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Sedimentary Facies Characteristics and Hydrocarbon Accumulation Model of the Chang 2 Member in the Antaolin Area, Ordos Basin

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Abstract

The Chang 2 Member of the Triassic Yanchang Formation is an important oil-bearing interval in the Ordos Basin, and it serves as one of the key targets for tight oil exploration and development in China. The Antaolin area, located in the central part of the northern Shaanxi slope, exhibits relatively low well control but demonstrates good hydrocarbon potential based on drilling and testing results. In this study, core, well logging, thin section, and experimental data were comprehensively integrated to analyze the stratigraphic division, sedimentary facies, reservoir petrology and physical properties, and hydrocarbon accumulation characteristics of the Chang 2 Member in the Antaolin area. The results indicate that the Chang 2 Member was deposited during the stage of lake basin shrinkage and extinction, dominated by a delta depositional system, particularly the delta front subfacies. Subfacies types mainly include subaqueous distributary channels, mouth bars, interdistributary bays, and sheet sands, with sand bodies trending NE–SW. Subaqueous distributary channel and mouth bar sand bodies serve as the major reservoir units. Lithologically, the reservoirs are dominated by feldspathic sandstones, with cementation mainly by calcite and chlorite. Pore types include intergranular residual pores, dissolution pores, moldic pores, and microfractures. Reservoir properties are characterized by low porosity and low permeability, with strong heterogeneity. Hydrocarbon accumulation is controlled by the "source below, reservoir above" assemblage, with structural–lithological composite traps serving as the main trap type. Multiple charging events occurred, with late-stage charging playing a dominant role in accumulation. Based on the integration of depositional, structural, and diagenetic characteristics, a hydrocarbon accumulation model for the Chang 2 Member in the Antaolin area was established, providing a geological basis for future exploration and development.

Keywords

Ordos Basin; Antaolin Area; Chang 2 Member; Sedimentary Facies; Hydrocarbon Accumulation.

1. Introduction

The Ordos Basin, located on the western margin of the North China Block, is the second-largest inland sedimentary basin in China, covering an area of approximately 3.7×10^5 km^2. During the Paleozoic, it was characterized by marine and transitional deposits as a cratonic basin, and it later evolved into a continental lacustrine basin during the Mesozoic [1–4]. Structurally, it can be divided into six first-order tectonic units: the Yimeng Uplift, Weibei Uplift, Jinxi Flexural Fold Belt, northern Shaanxi Slope, Tianhuan Depression, and Western Thrust Belt. The basin hosts abundant hydrocarbon resources, with multiple oil-bearing intervals. In recent decades, the

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tight oil reservoirs of the Triassic Yanchang Formation have become the main focus of unconventional oil exploration and development in China [3,5,6].

The Antaolin area, located in the central part of the northern Shaanxi slope within the Zhidan oilfield, covers an area of about 231 km^2. Due to relatively low well control and limited systematic research on the Chang 2 Member, exploration success rates remain low. However, drilling and testing data, such as from wells YT8, Y802, and YT206, indicate good oil-bearing properties of the Chang 2 Member in the study area, highlighting its exploration potential [7]. Thus, it is necessary to systematically study the geological conditions of reservoir formation in this region, including stratigraphy, sedimentary facies, microstructures, reservoir petrophysical characteristics, and accumulation models, in order to provide a reliable geological basis for further exploration and efficient development.

Internationally, the concept of “reservoir description” was first proposed by Schlumberger in the 1970s, and early studies mainly focused on single-discipline methods, such as fault characterization and reservoir modeling, with relatively limited technical approaches [8,9]. In China, Qi Yinan first introduced the concept of “detailed reservoir description” in 1993, which emphasized the integration of geostatistics, seismic interpretation, and well logging. Since then, significant progress has been achieved in reservoir prediction, characterization, and modeling through multidisciplinary methods [9,10]. Modern reservoir description is characterized by comprehensiveness, integrativeness, and predictiveness, and it provides a scientific foundation for enhancing recovery efficiency and guiding exploration and development [9,10].

For low-permeability reservoirs, detailed reservoir characterization has evolved alongside field development, including single-sandbody prediction, fracture characterization, pore structure analysis, flow unit classification, and reservoir protection. Domestic studies have emphasized reservoir heterogeneity and flow mechanisms, and are relatively advanced compared with international efforts, while foreign studies maintain strengths in numerical simulation and laboratory experiments [3,5]. Reservoir evaluation methods mainly include quantitative integrated evaluation, classification-based evaluation, and real-time while-drilling evaluation [11–13]. These approaches, when combined, provide a more complete understanding of reservoir properties and performance.

Research progress in the Ordos Basin has also been significant. Zhang Jinshan (1982) highlighted the basin’s tectonic evolution, noting its location at the intersection of two geotectonic domains, and identified the Early to Middle Triassic as the main hydrocarbon generation period, with most petroleum in Jurassic basal sandstones sourced from the Yanchang Formation [14]. Yang Hua et al. (2007) demonstrated that the Yanchang Formation reservoirs are typical ultra-low permeability systems, weakly influenced by structural controls, with hydrocarbon distribution governed primarily by source and facies control [3]. Li Wenhou et al. (2009) further identified multiple depositional systems in the Late Triassic Yanchang Formation, including fluvial, braided delta, deltaic, lacustrine, and turbiditic systems [15]. Wang Jufeng (2010) showed that the Upper Yanchang Formation reservoirs are dominated by lithologic traps with low abundance and poor lateral continuity, with prospective resources concentrated in the northeastern, southwestern, and central lacustrine areas [16].

In the Antaolin area specifically, Xie Licheng et al. (2020) reported that reservoirs display different degrees of densification, mainly controlled by detrital composition, cementation, and dissolution, with some reservoirs exhibiting improved porosity due to secondary dissolution [7]. Wang Jianmin et al. (2011) concluded that Chang 2 reservoir accumulation in Zhidan is controlled by multiple factors, including stratigraphy, paleogeomorphology, unconformities, local structures, and sedimentary features, with trap types dominated by structural–lithological and structural–stratigraphic traps [17]. Xie Wei et al. (2017) showed that the Chang 2 Member in the Yongning area is dominated by meandering river deposits, with the Chang 21 and Chang 23 submembers having the best reservoir quality, mainly consisting of intergranular and

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dissolution pores, and diagenesis characterized by chlorite film cementation, authigenic kaolinite cementation, and feldspar and lithic dissolution [18]. Li Jianxin et al. (2019) argued that hydrocarbon accumulation in Chang 2 reservoirs is controlled by a combination of multiple factors, and cannot be attributed to a single factor [19].

In summary, while significant progress has been made in reservoir characterization, depositional facies analysis, and hydrocarbon accumulation in the Ordos Basin, systematic studies of the Chang 2 Member in the Antaolin area remain insufficient. This study integrates core, well log, and laboratory data to investigate depositional facies, reservoir characteristics, and hydrocarbon accumulation models of the Chang 2 Member, aiming to clarify hydrocarbon enrichment patterns and provide a basis for exploration deployment.

2. Geological Setting

2.1. Geographical Location and Structural Characteristics

The Antiaolin area is located in the central part of the Northern Shaanxi Slope within the Ordos Basin, affiliated with the Zhidan Oil Region, covering an area of approximately 231 km^2. It is situated in the Yongning Town area of Zhidan County, Shaanxi Province (Figure 1). This area holds a unique structural position, lying within the basin's overall westward-dipping monoclinal framework. The Northern Shaanxi Slope, an important first-order structural unit of the Ordos Basin, trends approximately north-south, with a broad and gentle eastern flank and a relatively steeper western flank. Structurally, it belongs to a platform depression-type sedimentary environment [1–4]. Within this context, the study area has developed an overall westward-dipping monoclinal structure, with local development of low-amplitude nose-like structures formed by differential compaction. These nose-like structures played a significant role in the process of hydrocarbon migration and accumulation, serving as crucial geological conditions for the formation of local hydrocarbon enrichment zones.

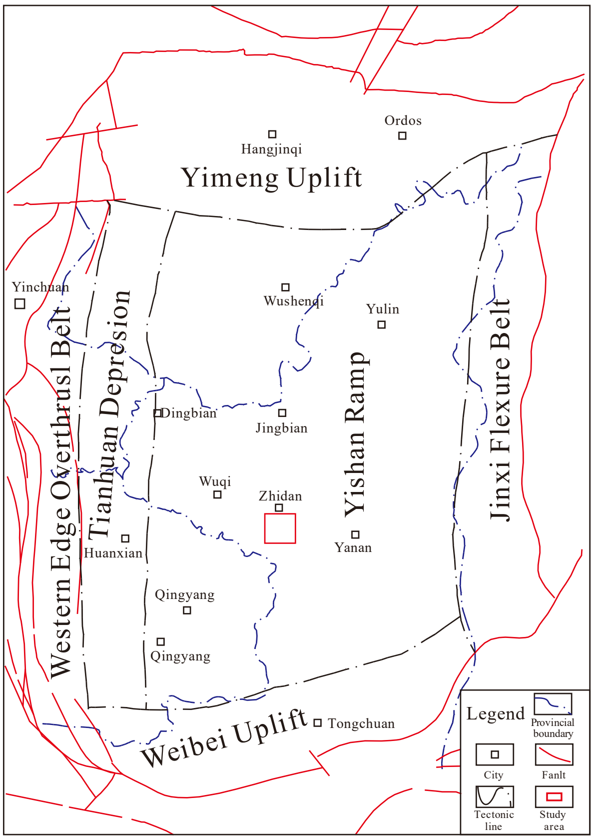

Figure 1. Structural Location Map of the Zhidan Oil Region

2.2. Stratigraphic Characteristics

The stratigraphic sequence in the study area, from top to bottom, consists of the Quaternary System, the Cretaceous Luohe Formation, the Jurassic Yan'an Formation, Zhiluo Formation, Anding Formation, and the Triassic Yanchang Formation. The Yanchang Formation is the main oil-bearing strata in this area and can be subdivided from top to bottom into multiple oil layer groups from Chang 10 to Chang 1. Among these, the Chang 2 oil layer group is the most important exploration target in the Antiaolin area and can be further subdivided into three sub-layers: Chang 2^1, Chang 2^2, and Chang 2^3 (Table 1, Figure 3). The depositional period of this layer was the shrinking and extinction stage of the lake basin, dominated by a delta sedimentary system. Sand bodies are widely distributed, indicating significant reservoir potential [5–7].

Table 1. Simplified Stratigraphic Division Table for the Antiaolin Area

System	Series	Group	Member	Oil Layer Group	Subgroup	Lithology Description
Jurassic System	Lower Series	Yan'an Formation		Yan 10		Grey-white medium to coarse-grained massive sandstone, developing large-scale tabular or trough cross-bedding.
			Fifth Member (T3y5)	Chang 1		Light grey-green, grey-white medium- to fine-grained sandstone, siltstone, dark grey sandy mudstone, mudstone, and argillaceous siltstone interbedded, with black carbonaceous shale and thin coal seams.
					Chang 2^1	Top part consists of mudstone and silty mudstone; middle and lower parts consist of massive sandstone interbedded with mudstone.
			Fourth Member (T3y4)	Chang 2	Chang 2^2	Grey, light grey massive feldspathic sandstone interbedded with mudstone, argillaceous siltstone, and siltstone.
					Chang 2^3	Grey, light grey massive sandstone interbedded with mudstone and siltstone.
				Chang 3		Light grey, grey-brown fine sandstone interbedded with dark mudstone, siltstone, and silty mudstone.
				Chang 4+5	Chang $4-5^1$	Consists of dark mudstone, carbonaceous mudstone, and coal seams interbedded with thin layers of fine to very fine sandstone.
					Chang $4-5^2$	Light grey siltstone, fine sandstone interbedded with dark mudstone.
Triassic System	Upper Series	Yanchang Formation			Chang 6^1	Green-grey, grey-green fine sandstone interbedded with dark mudstone.
			Third Member (T3y3)	Chang 6	Chang 6^2	Siltstone to fine sandstone, grey-black mudstone, and argillaceous siltstone in unequal thickness interbeds, with thin tuff layers.
					Chang 6^3	Consists of light grey-green siltstone to fine sandstone interbedded with dark mudstone.
					Chang 6^4	Dark mudstone interbedded with siltstone, argillaceous sandstone, and thin tuff layers.
				Chang 7		Dark mudstone interbedded with thin layers of siltstone to fine sandstone, with black shale developed at the bottom.
			Second Member (T3y2)	Chang 8	Chang 8^1 Chang 8^2	Dark mudstone, sandy mudstone, shale interbedded with grey siltstone to fine sandstone.
				Chang 9		Dark mudstone interbedded with grey siltstone to fine sandstone, with black shale developed at the top.
			First Member (T3y1)	Chang 10		Massive feldspathic sandstone interbedded with silty mudstone.

2.3. Exploration Status

Well control in the Antiaolin area is relatively low, and research targeting the Chang 2 oil layer group is still insufficient. However, drilling results indicate that the Chang 2 oil layer group in this area has good oil-bearing properties and exploration prospects. For example, wells such as Yongtan 8, Yong 802, and Yongtan 206 have all obtained industrial oil flow, demonstrating the realistic potential for oil and gas exploration in this area [7,8]. Therefore, further research on the distribution of sedimentary facies, reservoir heterogeneity, and hydrocarbon accumulation characteristics is of great significance for improving exploration success rates and resource utilization.

3. Lithostratigraphy and Sedimentary Facies

3.1. Stratigraphic Division and Correlation

The Chang 2 Member of the Triassic Yanchang Formation can be subdivided into three submembers: Chang 21, Chang 22, and Chang 23. These submembers are identified and correlated based on logging responses, sedimentary cycles, and core observations (Figure 2). The Chang 21 submember is dominated by medium- to fine-grained sandstones interbedded with mudstones, showing upward-fining cycles, indicative of delta front deposits. The Chang 22 submember exhibits relatively thicker sandstone bodies with upward-coarsening cycles, reflecting distributary channel and mouth bar development. The Chang 23 submember consists primarily of mudstones with interbedded thin-bedded sandstones, representing interdistributary bay deposits[11].

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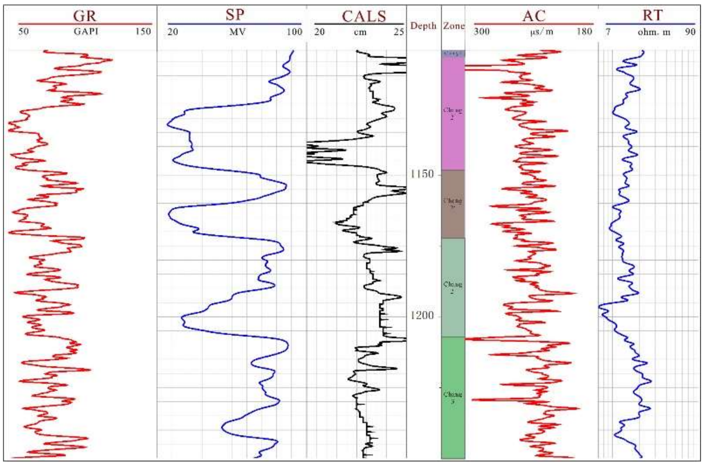

Figure 2. Electrical characteristic responses of the Chang 2^1/Chang 2^2, Chang 2^2/Chang 2^3, and Chang 2^3/Chang 3 boundaries

3.2. Sedimentary Facies Types

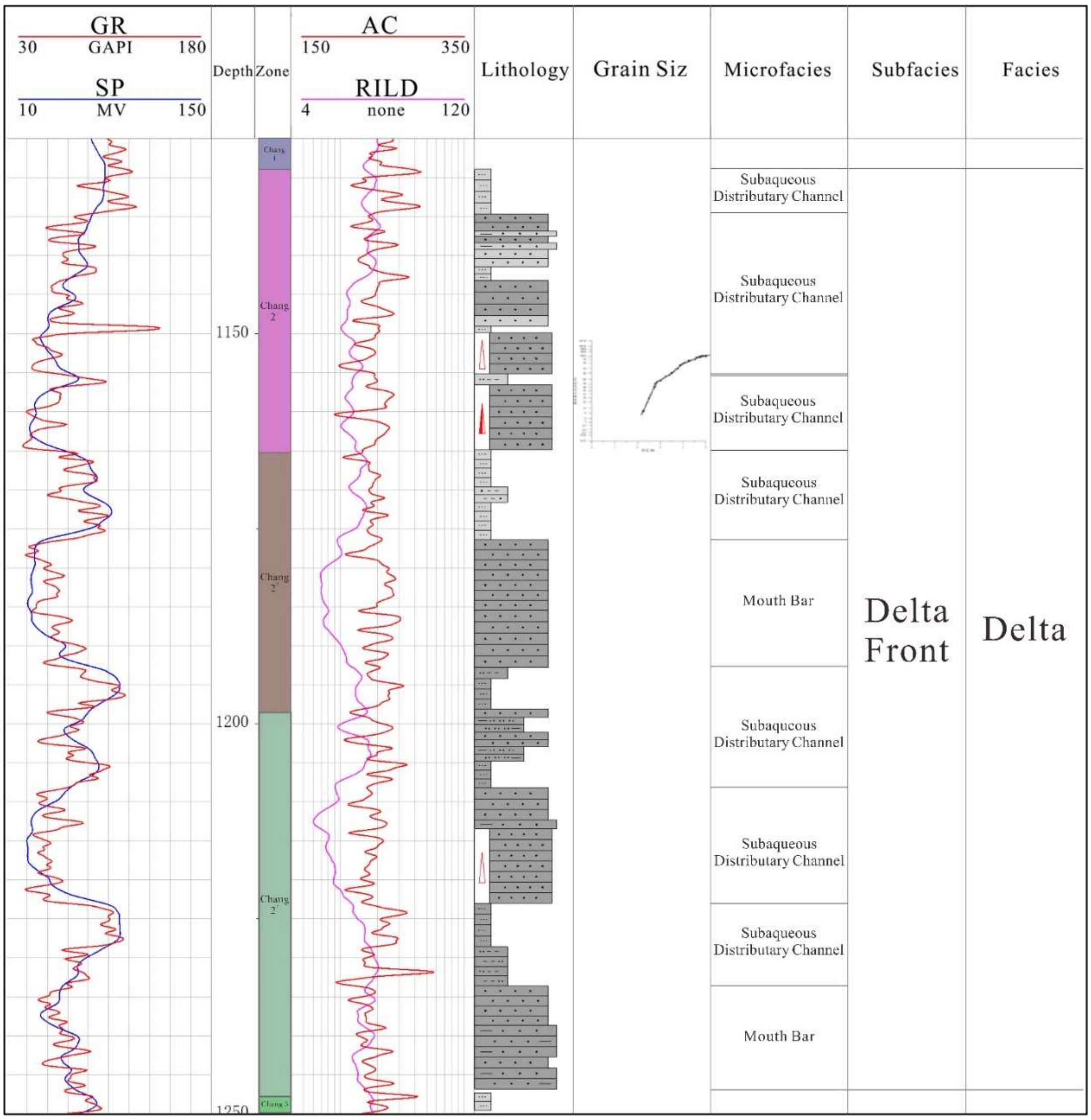

Figure 3. Characteristics of Sedimentary Microfacies Assemblages in the Chang 2 Reservoir

Sedimentation during the Chang 2 period was dominated by a delta depositional system, particularly delta front facies. The main microfacies types include[12]:

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Subaqueous distributary channels: Characterized by thick-bedded, upward-fining sandstones with erosion bases, high gamma-ray variability, and blocky or bell-shaped logging curves.

Mouth bars: Composed of medium- to fine-grained sandstones with cross-bedding, upward-coarsening cycles, and funnel-shaped logging curves.

Interdistributary bays: Dominated by mudstones with thin interbedded sandstones, showing high gamma-ray readings and serrated curves.

Sheet sands: Thin, laterally extensive sandstone layers with low thickness but wide distribution, often capping bay deposits.

3.3. Sandbody Distribution

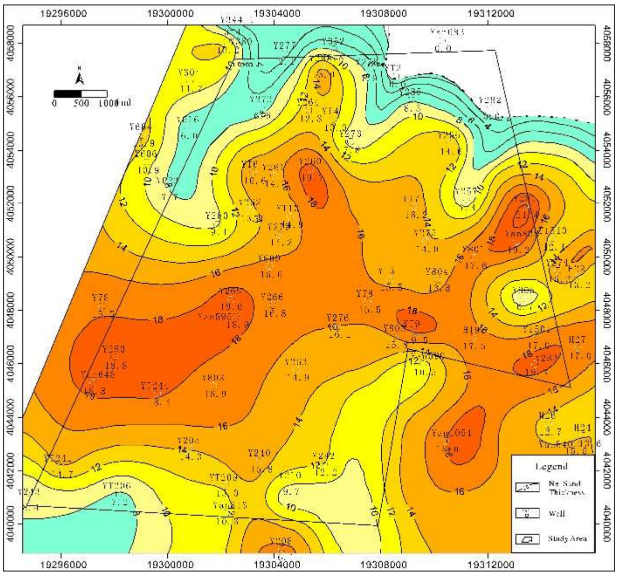

Figure 4. Stratigraphic Thickness Map of the Chang 2^1 Subunit

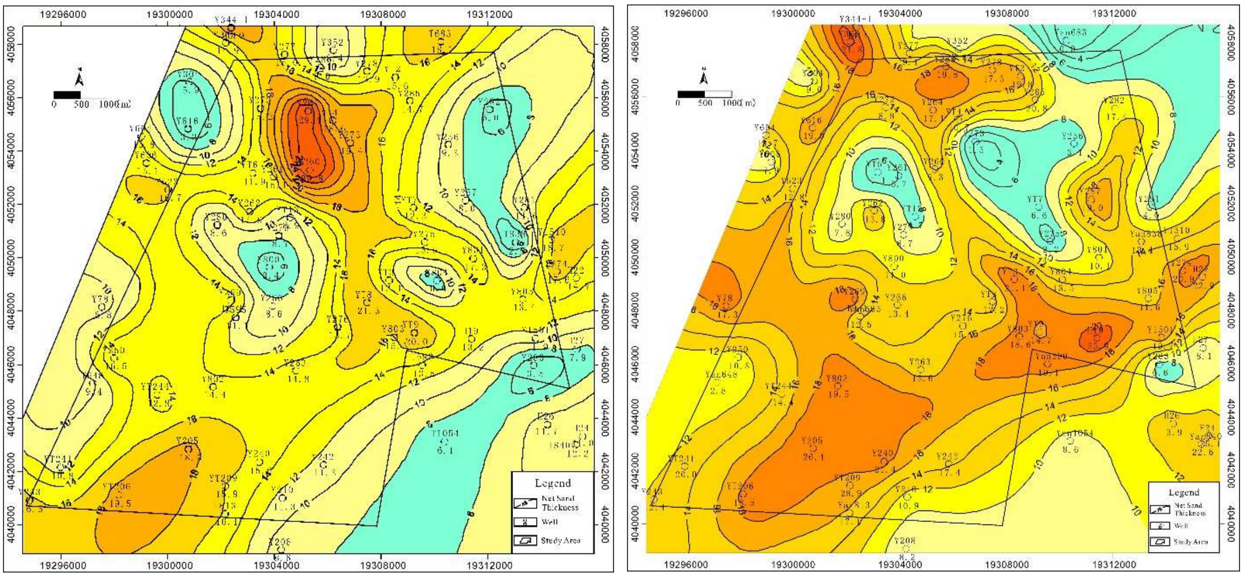

Figure 5. Stratigraphic Thickness Maps of the Chang 2^2 and Chang 2^3 Subunits, Respectively

The sand bodies exhibit an overall NE-SW trending distribution, controlled by sediment provenance supply and paleogeomorphology. The sandstone thickness of the Chang 2^1 subunit ranges from 12 to 46 m and is locally absent. The thickness of Chang 2^2 ranges from 28 to 40 m, while that of Chang 2^3 generally ranges from 33 to 50 m, with some areas exceeding 50 m

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(Figures 4, 5). The widely distributed distributary channel sand bodies serve as favorable zones for hydrocarbon accumulation.

4. Reservoir Characteristics

4.1. Petrological Characteristics

The Chang 2 reservoir is predominantly composed of feldspathic sandstone, with minor amounts of lithic arkose. The detrital composition is dominated by feldspar, followed by quartz and minor rock fragments (Figures 6). The primary cements include calcite, ferroan calcite, and chlorite, with contents ranging from 3% to 29% and averaging approximately 10% (Table 2). Chlorite coatings play a beneficial role in porosity preservation [13].

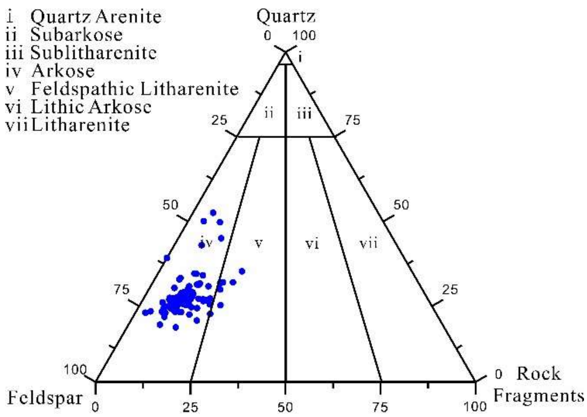

Figure 6. Ternary Diagram of Sandstone Rock Composition in the Chang 2 Reservoir

Table 2. Statistical Analysis of Cement Types and Their Abundance

Mineral	Range (%)	Average (%)
Kaolinite	0-2	0.11
Hydromica / Illite-Smectite Mix	0	0
Chlorite	0-6	2.49
Illite	0-8	0.9
Argillo-Ferruginous Material	0-5	0.74
Calcite	0-23	3.11
Ferroan Calcite	0-5	0.35
Dolomite	0-3	0.18
Siderite	0-15	0.41
Laumontite	0	0
Siliceous Material / Quartz	0-3	0.83
Feldspar	0-3	0.41

4.2. Pore Types and Pore Structure

The main pore types include relict intergranular pores, intragranular dissolution pores, moldic pores, and microfractures. Intergranular pores are the dominant type, accounting for over 70% of the total porosity. Dissolution pores comprise approximately 30%, primarily formed by the dissolution of feldspar and carbonate grains. Microfractures are mostly tectonic in origin and play a beneficial role in enhancing permeability (Figures 7, 8) [14].

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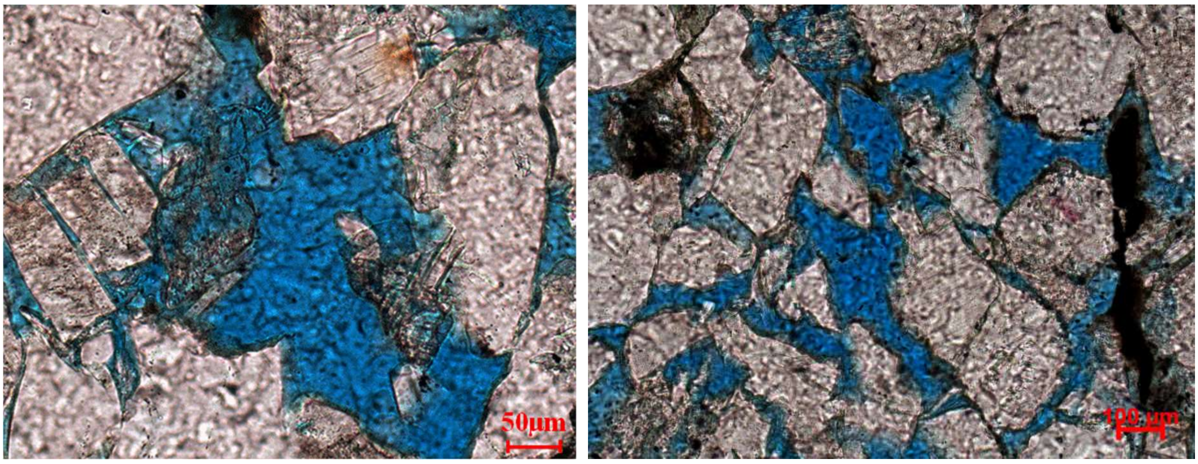
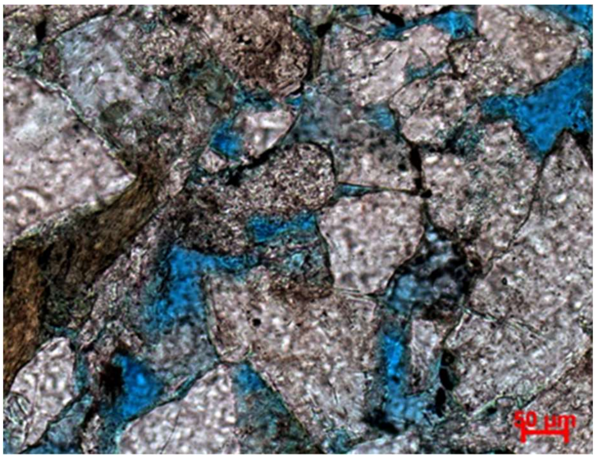
Mercury injection and nuclear magnetic resonance (NMR) experiments indicate that the pore-throat structure is predominantly fine to medium-fine, with uneven pore size distribution and strong heterogeneity (Figure 9) [15].



a. Intergranular dissolution pores, moldic pores. b. Intergranular dissolution pores, moldic pores.

Well Yong 803, 1141.1 m, Chang 2 Member. Well Yong 659, 1081.55 m, Chang 2 Member.



c. Dissolution pores in matrix, mica, and feldspar. Well Yong 659, 1081.55 m, Chang 2 Member.

Figure 7. Characteristics of Intergranular Pores in Chang 2 Sandstone, Study Area

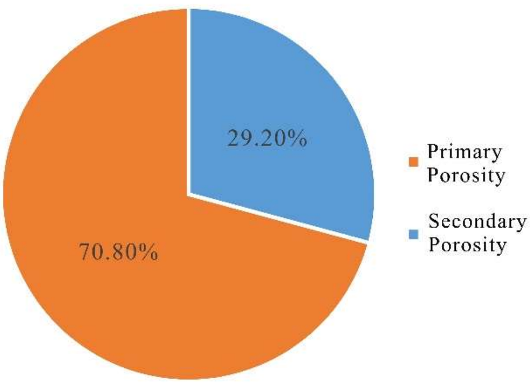


Figure 8. Sandstone Pore Types and Their Relative Content (Percentage)

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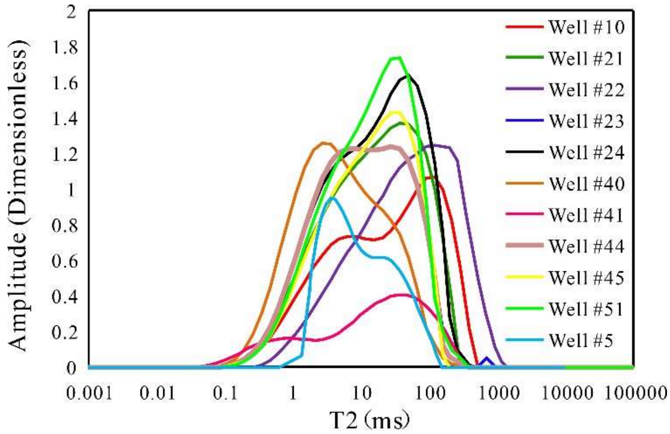

Figure 9. NMR T_2 Spectrum Test Results of the Reservoir

4.3. Petrophysical Properties

The Chang 2 sandstone generally exhibits porosity ranging from 5% to 12% and permeability mostly less than 1×10^{-3} μm^2, classifying it as a low-porosity and low-permeability reservoir. In local areas where dissolution is strong, porosity can exceed 15% with significantly improved permeability, making these zones favorable exploration targets (Figure 10) [16].

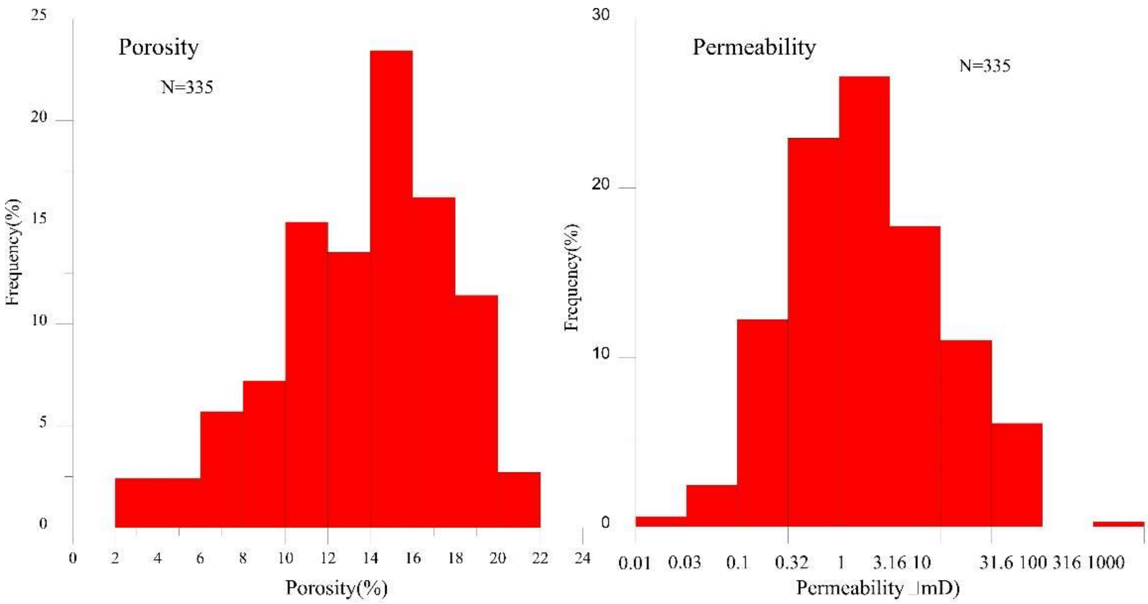

Figure 10. Petrophysical Property Statistics of the Chang 2 Sandstone

5. Petroleum System and Hydrocarbon Accumulation

5.1. Reservoir and Trap Characteristics

The Chang 2 oil layer group overall exhibits a west-dipping monoclinal structure, with locally developed subtle nose-like structures. The oil-water contact is controlled by both structure and fluid potential, converging from the high-potential area in the west to the low-potential area in the east (Figure 11). The reservoir type is primarily a structural-lithologic composite reservoir. The crude oil is relatively light, and its distribution is jointly controlled by sand body distribution and the structural framework [17].

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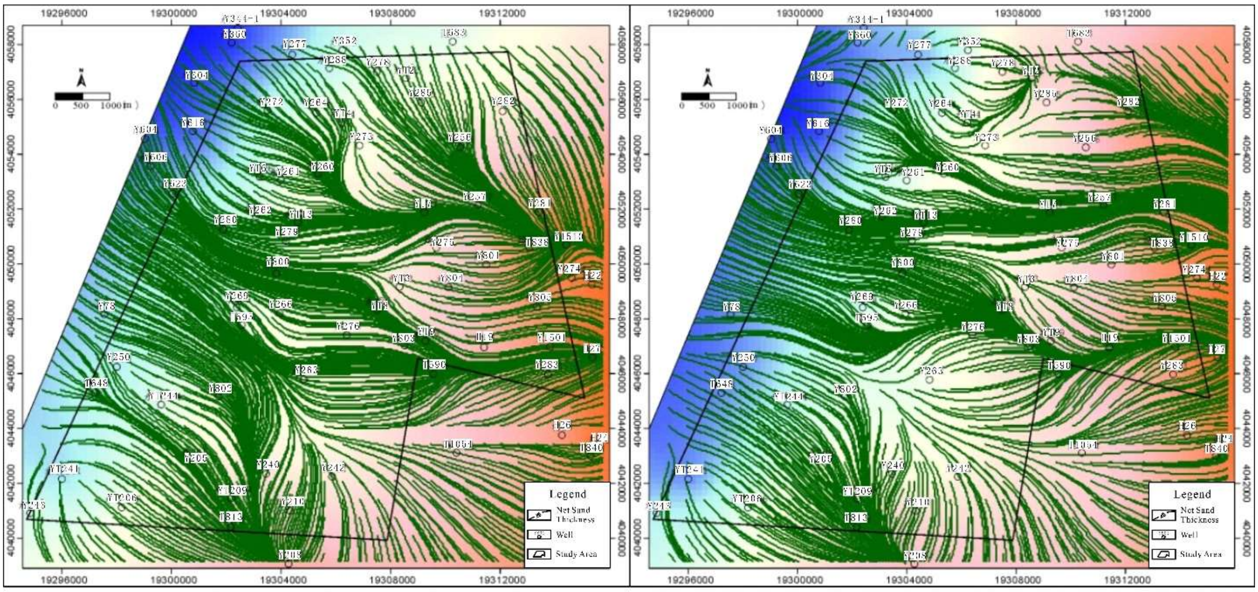

Figure 11. Structural Map (Top of Chang 2) Overlaid with Fluid Potential Map

5.2. Hydrocarbon Source and Migration

The main controlling factors for hydrocarbon accumulation include [18]:

Source Rock Conditions: Underlying source rocks provided sufficient hydrocarbons, creating a "lower-generation, upper-accumulation" configuration.

Reservoir Conditions: Well-developed sand bodies, with dissolution significantly improving reservoir quality.

Trap Conditions: Local nose-like structures and lithologic sand bodies form composite traps.

Sedimentary Facies Control: Distributary channels and mouth bar sand bodies are the most favorable enrichment facies.

5.3. Hydrocarbon Accumulation Model

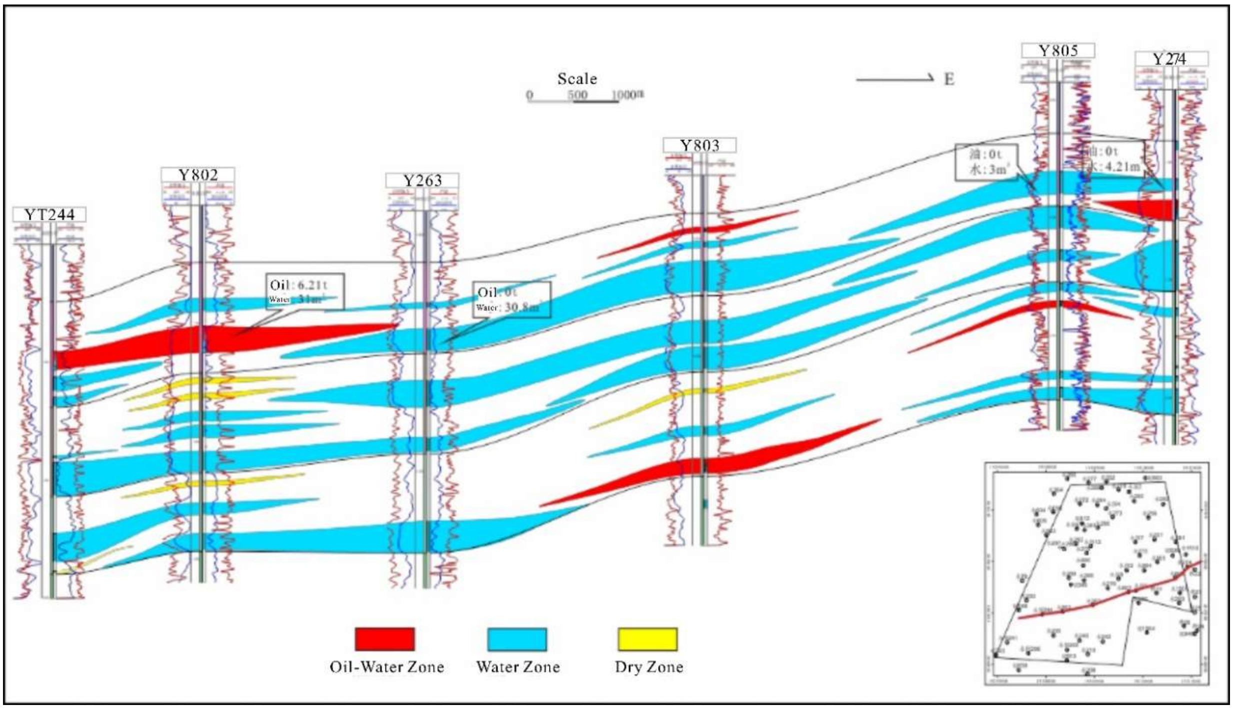

Figure 12. Hydrocarbon Accumulation Model of the Chang 2 Oil Layer Group in the Antiaolin Area

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Comprehensive analysis suggests that the hydrocarbon accumulation model for the Chang 2 oil layer group in the Antiaolin Area can be summarized as a "lower-generation, upper-accumulation, structural-lithologic composite control" model. Hydrocarbon charging occurred in three phases, with the final phase being the largest in scale and decisive for the formation of the current reservoirs (Figure 12) [19].

6. Conclusion

(1) The depositional period of the Chang 2 oil layer group in the Antiaolin Area corresponded to the shrinking and extinction stage of the lake basin. The sedimentary system was predominantly delta front, developing sedimentary microfacies such as subaqueous distributary channels, mouth bars, and interdistributary bays.

(2) The reservoir is primarily composed of feldspathic sandstone. The main pore types are relict intergranular pores and dissolution pores. Diagenesis significantly controls the reservoir's physical properties. The reservoir is generally characterized by low porosity and low permeability, but significant local improvement exists.

(3) The hydrocarbon accumulation conditions manifest as a "lower-generation, upper-accumulation" source-reservoir configuration. Structural-lithologic composite traps are the main accumulation type.

(4) A hydrocarbon accumulation model of "lower-generation, upper-accumulation, structural-lithologic composite control" has been established. Distributary channel and mouth bar sand bodies are identified as preferred exploration targets.

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