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Original Paper

Physical property and hydrocarbon enrichment characteristics of tight oil reservoir in Chang 7 division of Yanchang Formation, Xin'anbian oilfield, Ordos Basin, China

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A B S T R A C T

Xin'anbian Oilfield of the Ordos Basin is the large tight oilfield to be first exploration discovery in china. The production of tight oil increased significantly in recent years. It shows great exploration potential of Chang7 tight oil. But the physical property and hydrocarbon enrichment characteristics of Chang 7 tight oil reservoirs were rarely studied, The forming conditions of tight oil reservoirs are systematically summarized and analyzed through the study of hydrocarbon generation, sedimentary reservoirs and hydrocarbon migration and accumulation based on production and core experimental data. The result shows that, The porosity of the Chang 7_2 reservoir mainly distributed in 5.0–11.0%, average at 7.9%, The permeability mainly distributed in 0.04–0.18 $\times$ 10^{-3} μm^2, average at 0.12 $\times$ 10^{-3} μm^2, The pore diameters of the tight oil reservoir distributed in 2–8 μm. The high-quality Chang 7_3 source rocks and the micropsammite of Chang 7_2 subaqueous distributary channel were widely distributed in the study area. The lenticular or banded sand bodies are distributed among mudstone or hydrocarbon source rocks and have the advantage of migration distance for hydrocarbon accumulation. The reservoir space is composed of micro-nanometer pores and throat, that is formed in the process of increasing pressure during hydrocarbon generation and hydrocarbon accumulation. The Chang 7 tight oil was generated in the early Cretaceous and injected into the sand of the subaqueous distributary channel driven by continuous hydrocarbon generation supercharging. The formation and accumulation of tight oil reservoirs are mainly controlled by source rocks, sedimentary microfacies and reservoirs of good quality.

1. Introduction

After the economic exploitation of shale gas in North America, the tight oil has become a new field for energy exploration and development (USGS, 2008; Liu et al., 2013), and has become a hot research field on global petroleum geology (Sun et al., 2011; Wang et al., 2013). Tight oil in China is mainly distributed in the Ordos Basin, the Sichuan Basin, the Songliao Basin, etc. (Zou et al. 2011, 2012; Jia et al., 2012a), and has a great exploration prospect. The exploration area of low-permeability oil, including tight sandstone and tight limestone oil, is 18 $\times$ 10^4 km^2, and the amount of geological resources is 74–80 $\times$ 10^8 tons (Zou et al., 2012). According to present studies, tight oil source rocks are mostly high-quality source rocks with strong hydrocarbon generation potentials and wide distribution (Zou et al., 2011). Tight oil reservoirs are characterized by diverse lithology and strong heterogeneity. The reservoir space is a complex and diverse pore network that composed of a large number of nanopores and micron pores (Zhao, 2012; Ren et al., 2014). In the process of hydrocarbon generation in source rocks, a certain volume of oil and gas was generated, and there was a large pressure difference with adjacent reservoirs (Jia et al., 2012b), The reservoir-forming dynamics of tight oil is dominated by overpressure (Yang and Zhang, 2005; Zhang et al., 2016a). Hydrocarbon-generating pressurization is the important

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factor leading to overpressure in source rocks (Yang et al., 2013; You et al., 2015). At present, there is less research on the source and reservoir structure formed by sandstone - mudstone interbed.

It is difficult to study the relationship between reservoir formation events such as fluid migration and accumulation system, reservoir formation age and oil accumulation. At present, the tight oil of Yanchang Formation in Ordos Basin has been successfully explored and developed (Li et al., 2015a, b), but the geological characteristics of tight oil have not been clearly studied. The explored tight oil reservoirs are mainly distributed in Chang 7 shale and tight sandstone of Yanchang Formation. Tight oil is mainly formed in semi-deep lacustrine facies and deep lacustrine sedimentary environment. The source rocks are thick and widely distributed. (Qin, 2005; Yang et al., 2010). In recent years, the ultra-low permeability reservoirs of 0.3–1 $\times$ $10^{-3}\mu m^2$ represented by Jiyuan and Huaqing oilfields have been successfully developed, and the exploration targets have been aimed at tight reservoirs with permeability less than 0.3 $\times$ $10^{-3}\mu m^2$. The tight oil reservoirs are characterized by poor physical properties, strong heterogeneity, complex geological conditions, and few studies on reservoir distribution and reservoir forming factors. In this paper, the Chang 7 tight oil reservoir is taken as a research object. The forming conditions of tight oil reservoirs are systematically summarized and analyzed through the study of hydrocarbon generation, sedimentary reservoirs and hydrocarbon migration and accumulation based on conventional and unconventional core experimental analysis. All conclusion will to guide the exploration of tight oil reservoir in Xin'anbian oilfield.

2. Regional geological condition

Xin'anbian Oilfield located in the western slope of Yishan in the Ordos Basin, with an area of about 5000 km^2 (Han et al. 2017, 2018) (Fig. 1). The formation structure is a gentle slope to the west with a gradient of 6–10 m/km and an inclination angle of less than 1°. The Yanchang Formation can be divided into 10 divisions — Chang 10 to Chang 1. The Chang 7 division was formed in a lacustrine sedimentary environment, and can be divided into Chang7_1, Chang7_2 and Chang7_3 reservoirs, the Chang7_3 black shale is widely developed and is a high-quality hydrocarbon source rock with great hydrocarbon generation potential (Jia et al., 2012a; Ren et al., 2014; Han et al., 2019a). During the sedimentary process of the Chang 7_3 and 7_2, the deep water in the lake basin gradually decreased, and due to river injection, a large river-lake delta system was constructed in Xin'anbian area. Underwater distributary channel sandstones in the delta front were developed, of which, the Chang 7_2 sandstone, thick, continuous and stably distributed, is the primary tight oil reservoir. The reservoir is mainly gray micropsammite, distributed interbed with black shale. The reservoir and the source rock are in direct contact with each other. The reservoir has poor physical properties (Yao et al., 2015a; Han et al., 2019b), but has three key factors for forming tight oil (Zou et al., 2012) (Fig. 2). The Xin'anbian Oilfield is first exploration and development for tight oil. The reservoir thickness is distributed between 4.0 and 28.6 m, with an average at 23.8 m and an oil-bearing area is 221.78 km^2. The proved geological oil reserves were 106.31 $\times$ 10^4 t and the geological reserves of dissolved gas were 69.06 $\times$ 10^8 m^3 in 2014. Tight oil reservoir formed in the gravity flow sedimentary environment, traps of tight oil reservoir include lithologic trap, diagenetic trap. The reservoir has no edge water or bottom water. The reservoir has the characteristics of continuous sand layer and vertical superposition. Reservoir distribution is not controlled by geological structure, but by sand distribution, reservoir physical properties and diagenesis (Fig. 2). The crude oil is characterized by low density, low viscosity, low freezing point, sulfur-free and high

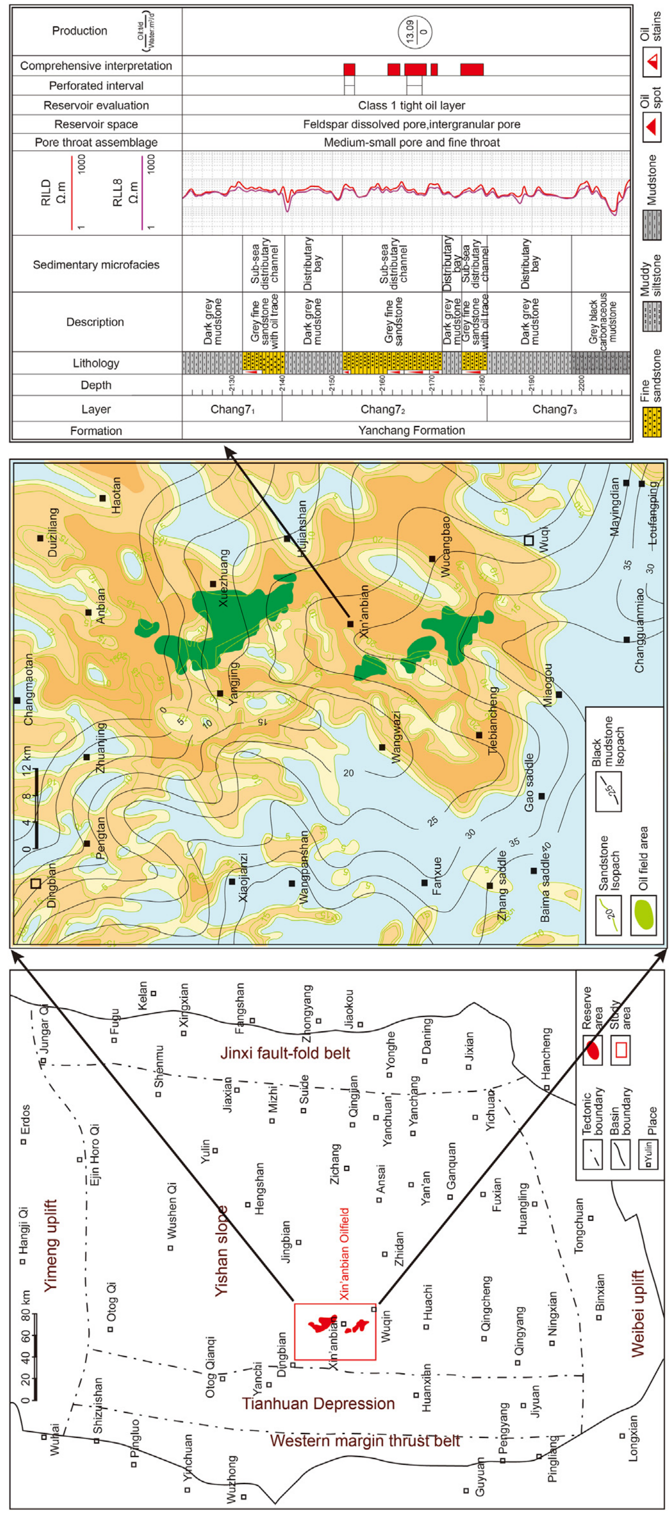

Fig. 1. Ordos Basin structure and location and plane distribution of Xin'anbian Oilfield (Chang 7_2 superposing on source rocks).

fluidity (Yao et al., 2015b). The average burial depth of the reservoir is 2256 m, the average formation temperature is 73.84 °C, the geothermal gradient is 3.27 °C/100 m, the original formation pressure is 16.9 MPa, and the pressure coefficient is 0.75, which belongs to low-pressure reservoir. Experimental date shows that the organic matter content of the Chang 7 source rock is high, the

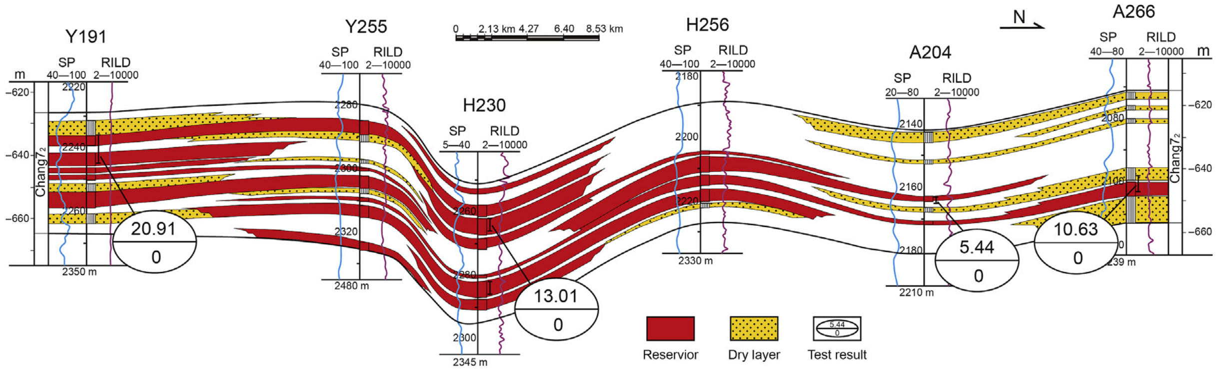

Fig. 2. Profile of Chang 7 tight oil in Xin'anbian oilfield.

average TOC of the black shale is 13.81%, and that of the dark mudstone is 3.75% (Fig. 3). The kerogen is composed mainly of amorphous lipids, and less hystrichosphaera and spores — the composition is simple, brown and light yellow under transmission light, bright yellow and brown fluorescence under ultraviolet and blue light excitation. Shale contains a large number of benthic algae and lake animals. The primary kerogen type is II_1 to I (Fig. 4), which belongs to sapropelic organic matter. The R_o value ranges from 0.9% to 1.2%. The degree of thermal evolution is in the stage of oil generation. The area of high-quality source rocks in Chang 7 is 5×10^4 km^2. The thickness of high-quality source rocks is between 10 and 50 m (Yang and Zhang, 2005) (Fig. 1). They are widely distributed and have favorable geological conditions for forming continuous tight oil reservoirs.

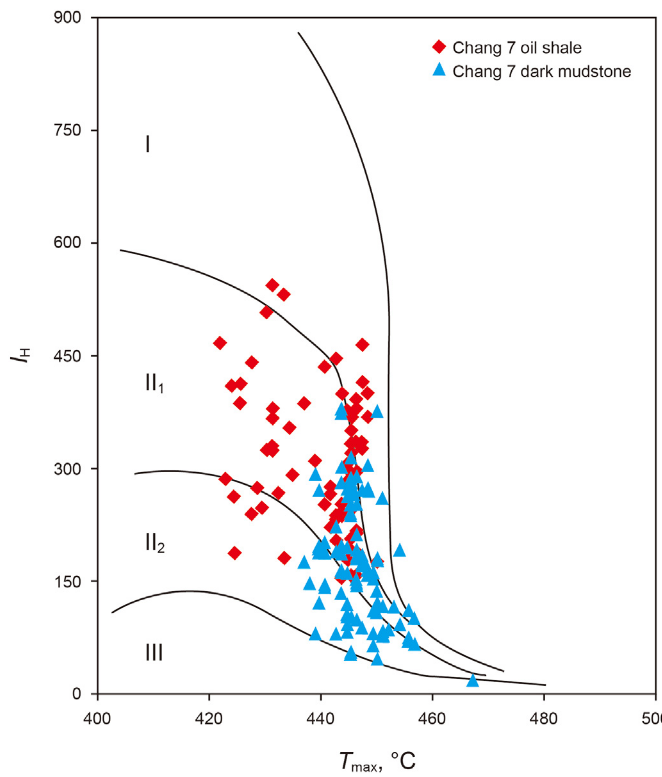

Fig. 4. Types of Chang 7 organic matter.

3. Reservoir

3.1. Mineral composition

The reservoir of Yanchang Formation has the characteristics of low compositional maturity, late diagenesis, fine clastic, poor sorting and high cement content (Yao et al., 2015c). According to the analysis of 122 rock samples of xin'anbian oilfield, the lithology of the Chang 7_2 reservoir is mainly light, dark, gray, fine, very fine-grained lithic arkose, and less arkose and feldspathic litharenite. The average content of quartz, feldspar and debris is 25.20%, 39.44% and 19.95% (Fig. 5, Table 1). The main composition of debris is metamorphic debris, followed by igneous debris, and the content of unstable and plastic debris is high. The average content of

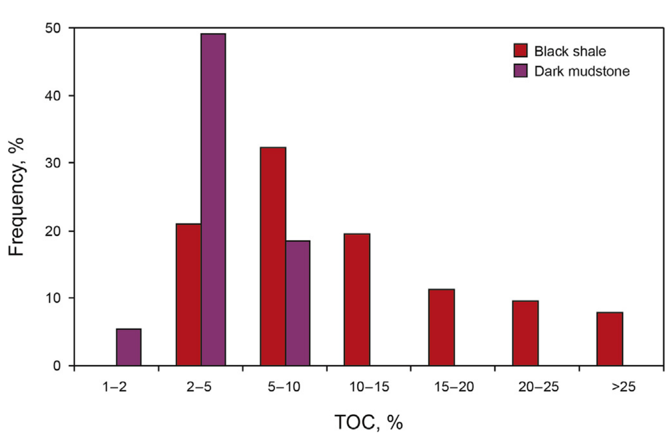

Fig. 3. TOC distribution of Chang 7 source rocks (213 samples).

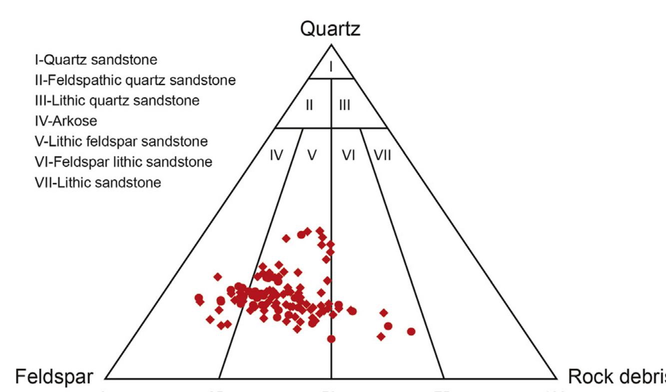

Fig. 5. Triangle of mineral composition of Chang 7_2 sandstone (122 samples from 55 wells).

Table 1
Statistical table of mineral composition and interstitial material of reservoir in An83 well area.

Number of samples (block)	Mineralization fraction (%)										
	Quartz	Feldspar	Debris	Interstitial material							
				Chlorite	Hydromica	Siliceous	Kaolinite	Calcite	Ferrocalcite	Other	Total
122	25.2	39.4	20.0	3.6	2.3	3.1	2.8	0.2	4.55	0.15	16.6

interstitial material is 15.41%. The interstitial materials are mainly iron calcite (4.55%), chlorite (3.65%) and kaolinite (2.78%) (Figs. 6 and 7). Most of the samples are micropsammite. The particle size is 0.03–0.60 mm. The grains are subangular, with poor roundness and good sorted. The cementation types are pore, enlarged pore and membrane pore types.

3.2. Physical properties

According to core experimental data from 145 wells, the porosity of the Chang 7_2 reservoir is distributed in the range of 3.55–17.12%, mainly 5.0–11.0%, average at 7.9% (Fig. 8); the permeability is distributed in the range of 0.006–0.99 $\times$ 10^{-3} μm^2, mainly 0.04–0.18 $\times$ 10^{-3} μm^2, average at 0.12 $\times$ 10^{-3} μm^2 (Fig. 9). The permeability of most samples is less than 0.3 $\times$ 10^{-3} μm^2, and the samples with permeability less than 0.2 $\times$ 10^{-3} μm^2 account for 87.7% of the total samples, indicating tight oil reservoir with strong heterogeneity. Comparing with the extra-low permeability and ultra-low permeability reservoirs in the Ordos Basin, the permeability of the Chang 7 tight oil reservoirs is quite different, but the porosity is similar, which indicates that the tight oil reservoirs in the Chang 7 division have characteristics of relatively high porosity and low permeability. The tight oil reservoirs of Chang 7 division are good in physical properties although they are of low permeability. The reservoir with low porosity ranging from 6% to 7% are mainly distributed at the edge of the underwater distributary channel, the reservoir with higher porosity ranging from 7% to 8% are mainly located in the middle of the channel, and distributed in strips along the underwater distributary channel, the reservoir with the highest porosity greater than 8% are mainly distributed in the thicker part of the delta front. The distribution of the

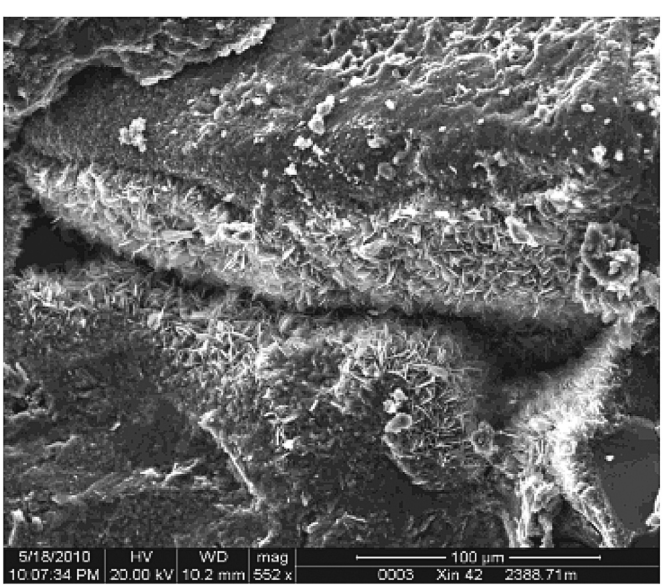

Fig. 6. Chlorite filled in residual pore throat; Chang 7_2; Well X42.

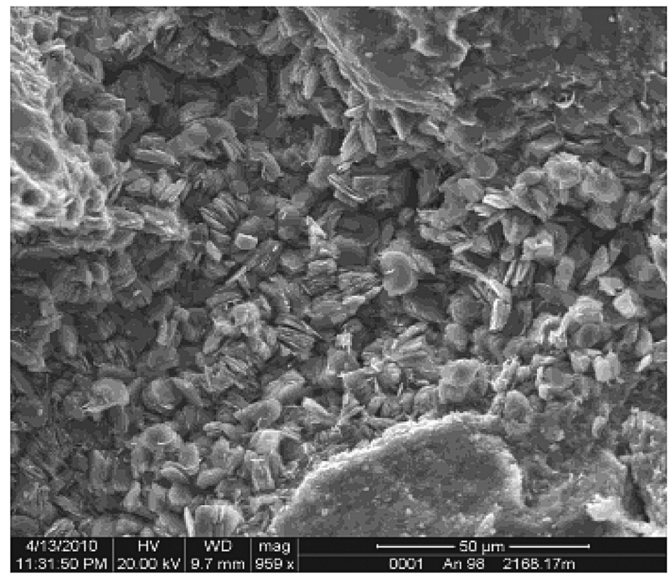

Fig. 7. Kaolinite filled in pores; Chang 7_2; Well A98.

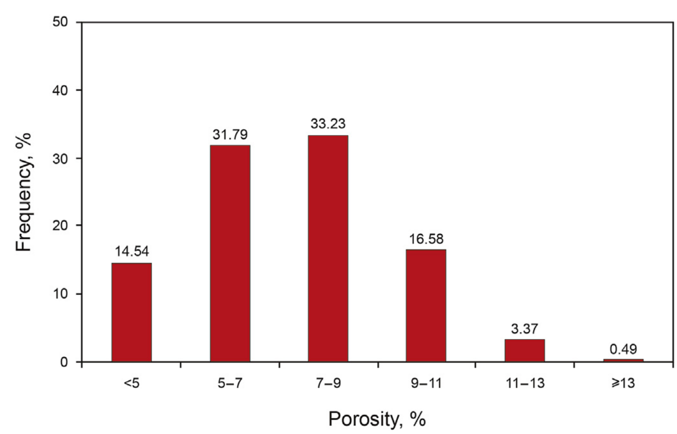

Fig. 8. Histogram of Chang 7_2 porosity distribution in Xin'anbian Oilfield.

permeability is well correlated with the porosity. Statistics show that the average permeability is greater than 0.13 $\times$ 10^{-3} μm^2, and the average porosity is about 9%, while the average permeability of poor oil, dry and tight oil reservoirs is lower than 0.1 $\times$ 10^{-3} μm^2, the average porosity is about 6.0%–8.0%.

3.3. Pore structures

According to the analysis of 122 casting thin sections of Chang 7_2 reservoir in Xin'anbian Oilfield, the total plane porosity is 2.05%. Feldspar dissolution pores accounted for 49.27% of the total pore volume, intergranular pores accounting for 35.12% of the total pore volume, lithic dissolution pores and intergranular dissolution

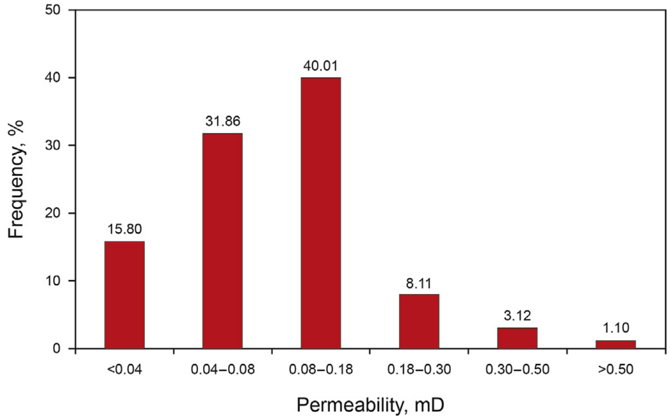

Fig. 9. Histogram of Chang 7_2 permeability distribution in Xin'anbian Oilfield.

pores, accounting for 6.83% and 0.49% of the total pore volume and the pore volume of intergranular pore and microfracture is the smallest. The reservoir pores space is mainly composed of secondary dissolution pores, feldspar dissolution pores are main pore type in the study area. Imaging logging analysis and core observation show that, large angle fractures and vertical fractures are also developed in the study area. The micron CT scanning results show that both tight oil and low permeability reservoirs are dominated by micropores with pore diameters ranging from 0 m to 12 m (Fig. 10). But the number of pores in tight oil reservoirs is several times more than that in low-permeability reservoirs. The main pore diameters of the tight oil reservoir are 2–8 μm, while the main pore diameters of the low-permeability reservoirs are larger than 8 μm.

According to the statistical analysis of mercury injection data from 20 wells, Chang 7_2 reservoir of Xin'anbian Oilfield has the characteristics of high displacement pressure (1.1976–5.277 MPa, average 2.16 MPa), good sorting of pores and throats, high median pressure (3.799–32.905 MPa, average 8.33 MPa), and small median radius (0.0224–0.1935 m, average 0.09 μm). The average maximum mercury saturation is 78.04%, and mercury retreat efficiency is 28.9%. The pore throat of tight oil reservoir is mainly distributed in the range of 25–250 nm (Fig. 11). The throat is mainly lamellar and

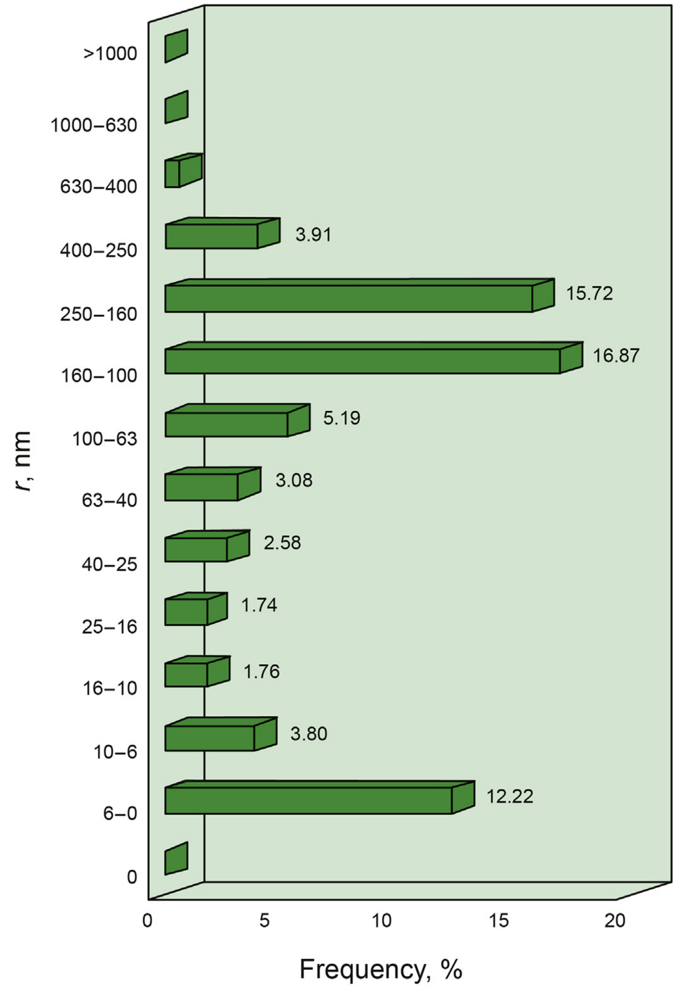

Fig. 11. Histogram of pore-throat radius distribution from mercury intrusion experiments on Chang 7 in Well H 210.

tubular (Yao et al., 2013; Yang et al., 2013), and less than 0.2 μm measured by constant rate mercury intrusion, and the average pore-throat ratio is 492 (Yao et al., 2015c). The reservoir space is

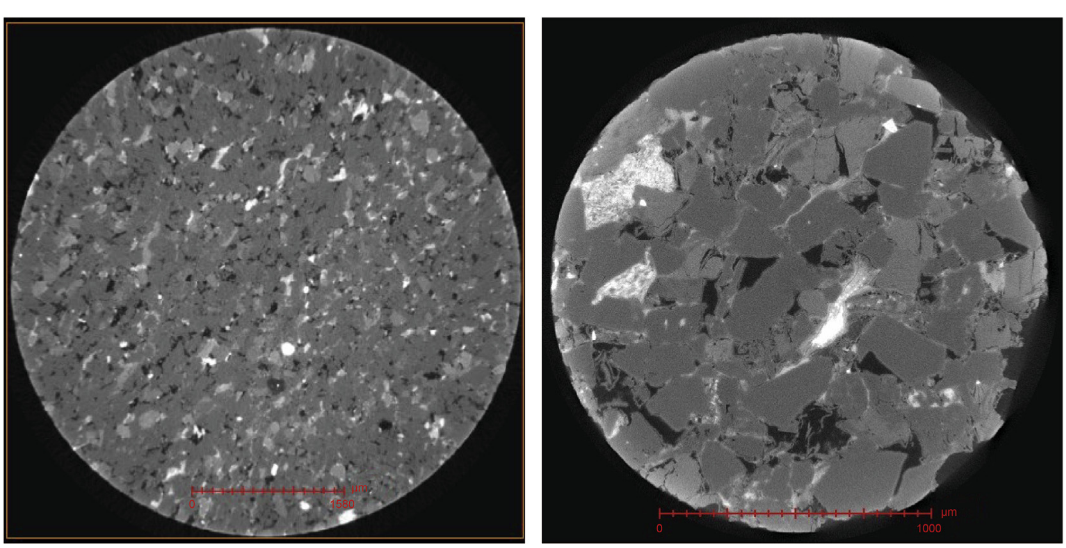

Fig. 10. Micron CT sections of Chang 7 tight oil and Chang 8 low-permeability reservoirs (sample: 2 mm).

mainly a pore network composed of nanometer-micron throat and micropores (Yao et al., 2015b). The oil can flow in the pores (Fig. 12).

4. Accumulation mechanism

4.1. Hydrocarbon migration and accumulation dynamics

According to previous studies (You et al., 2015), the abnormal overpressure is the main driving force of oil migration. The overpressure formation in Chang 7 shale is mainly caused by uncompacted and hydrocarbon-generating pressurization. The Chang 7 reservoir and its surrounding mudstone (source rock) under the same overlying sedimentary load, because the degree of compaction of shale is greater than sandstone, the fluid in shale filling to sandstone, which will increase the fluid volume in sandstone. Late Triassic Yanchang Formation, Jurassic and Lower Cretaceous are the strata with fast sedimentation. Rapid burial makes fluid in thick shale is difficult to expel in Chang 7 reservoir, and fluid pressure difference formed between the mudstone and the sandstone, the overpressure is created. In the early stage of thick shale sedimentation in Chang 7 division, the high pressure is mainly caused by uncompaction. The pore fluid volume can be increased by 25.4% when kerogen in the shale generates liquid hydrocarbon. When gaseous hydrocarbons are generated, the pore fluid volume can be increased by about 630 times. If the fluid produced during hydrocarbon generation added in shale pores cannot be discharged in time, overpressure will be generated (You et al., 2015). In Early Cretaceous, Chang 7 source rocks were at the maximum burial depth (about 3000 m). Most of the source rocks have reached the mature stage of thermal evolution. R_o reached 0.9%–1.1%. At the stage of maximum hydrocarbon generation and expulsion, kerogen was converted into oil and gas with low density, the volume expansion resulted in hydrocarbon generating overpressure. The study shows that the quantity of hydrocarbon generation in Chang 7 source rocks is high, and the cumulative hydrocarbon generation is much larger than the residual hydrocarbon, which indicates that a large number of hydrocarbons has been expelled, and when the amount of hydrocarbon generated reaches a certain value, it can produce significant pressure (Zhang et al., 2015). The volume expansion rate of hydrocarbon generation in Chang 7 source rocks can reach 3%–7%, which is much larger than the porosity of oil source rocks (Yang and Zhang, 2005; Zhang et al. 2015, 2016b). The resulting pressure growth is 0–0.6 MPa (Yao et al., 2015b). The hydrocarbon expulsion rate of Chang 7 source rocks reaches 72%. The hydrocarbon generation expansion is very significant, resulting in strong overpressure. The abnormal pressure generally reaches 8–20 MPa (Zhang et al., 2015). From the above analysis, it can be seen that shale has not entered the stage of abundant hydrocarbon generation at the early stage of deposition, and undercompaction has occurred in the shale due to rapid burial. With the increase of shale burial depth and the gradual rise of temperature, organic matter begins to generate a large number of hydrocarbons, which leads to the increase of pore volume and formation pressure. There is a distinct pressure difference between shale and sandstone, which provides dynamics for oil to migrate upward in a short distance. The well that produces more oil are mainly distributed in the adjacent areas with relatively low residual pressure and normal pressure. Micro-to nano-pore-throat systems are widely developed in the Chang 7_2 reservoir of Xin'anbian Oilfield, so buoyancy can not overcome migrating resistance. The main dynamics of oil migration and accumulation was hydrocarbon-generating pressurization, which is also the main dynamics for strong hydrocarbon expulsion and injection (Yao et al., 2013).

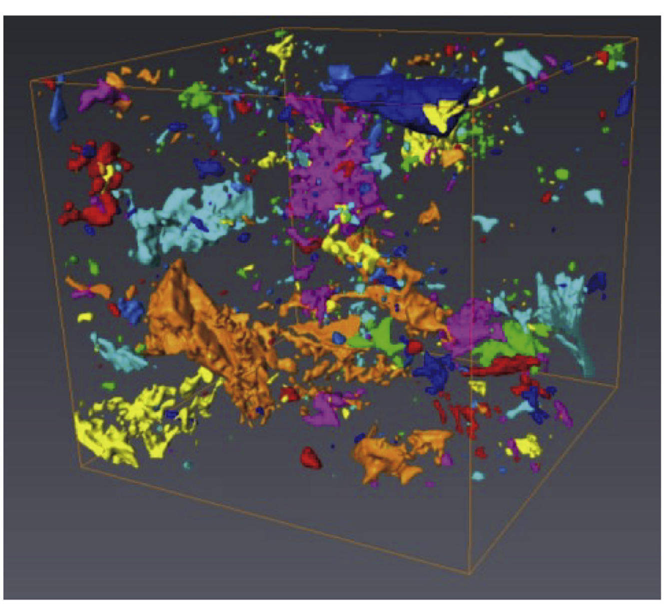

Fig. 12. Connected pore-throat volume of Chang 7 in Well H196.

When casting thin sections in the study area were observed, there is no obvious microcrack in the samples. The pores showed by industrial CT in Cheng 96 well were evenly distributed with good connectivity (Fig. 13). By fluorescence membrane observation, the fluorescence showed the pores as the channels for petroleum migration, and the matrix part did not emit fluorescence.

4.2. Hydrocarbon accumulation period

According to the homogeneous temperature test of fluid inclusions, The Chang 7 reservoir formed in the late early cretaceous and was continuously filled with hydrocarbons (Zhang et al., 2016a; Yang et al., 2017). Deng Xiuqin (Deng et al., 2009) identified three types of hydrocarbon inclusions, albite, enlarged quartz margin and calcareous cement in Yanchang Formation. respectively corresponding to the early filling in Late Jurassic, the peak of hydrocarbon generation and expulsion in Early Cretaceous and the uplifting at the end of Early Cretaceous. The accumulation period can be divided into two stages by the homogeneous temperature test of inclusions (Shi et al., 2012). Early homogeneous temperature is higher than late homogeneous temperature is the result of tectonic thermal events. The second stage is mainly the capture of inclusions during the reservoir-forming stage, corresponding to the late Early Cretaceous. It is generally accepted that Early Cretaceous was the peak of hydrocarbon generation and expulsion, and hydrocarbon migrated and accumulated on a large scale. Statistical analysis shows that the homogeneous temperature distribution is wide (Fig. 14), 70–150 °C, with two distinct temperature peaks, 100–110 °C and 130–140 °C, respectively. The homogeneous temperature distribution is continuous, reflecting that hydrocarbon migration and filling in the Chang 7 reservoir is a continuous process. The range of most inclusions homogeneous temperature is 100–110 °C, representing the main reservoir-forming temperature, corresponding to the middle and late Early Cretaceous (Fig. 15), indicating that the main reservoir-forming period of the Chang 7 reservoir is the middle and late Early Cretaceous. The hydrocarbon expulsion process of Chang 7 source rocks was simulated (Zhang et al. 2016). The Chang 7 reservoir, mainly composed of micro-to nano-pore-throat systems, can evolve into large-area oil-bearing reservoirs only undergoing a continuous high-pressure filling process.

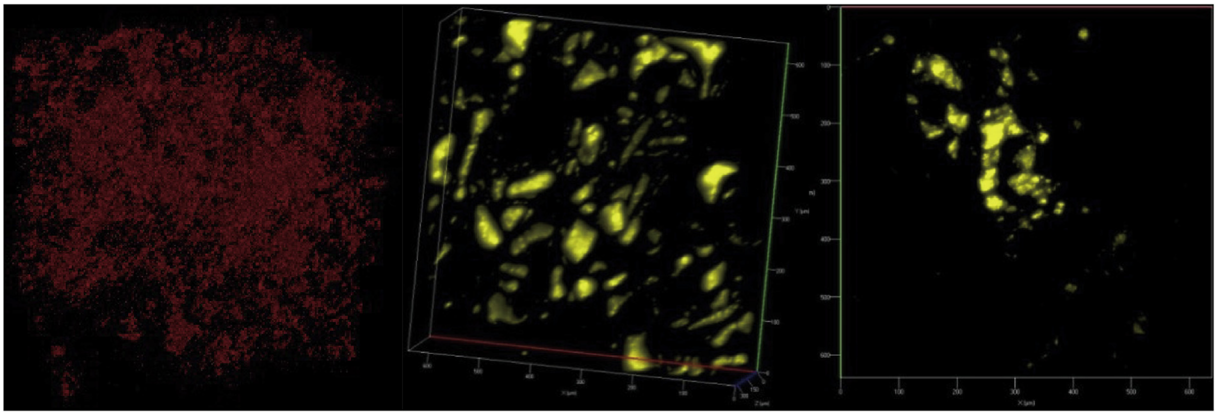

Fig. 13. Vertical and horizontal fractures in Chang 7 tight sandstone in well Cheng 96.

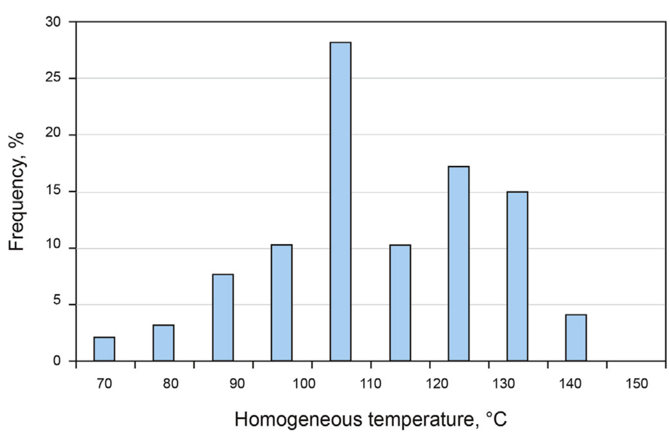

Fig. 14. Histogram of homogeneous temperature distribution of inclusions in Chang 7 reservoir of Yanchang Formation, Ordos Basin.

4.3. Hydrocarbon accumulation factor

4.3.1. Distribution of source rocks

The main force driving hydrocarbon to migrate and accumulate in small pores and throats is hydrocarbon expulsion pressure (Yang et al., 2017). The kerogen pore network, micropores and micro-fractures and overlapping sand bodies in source rocks constructed the three-dimensional pore network for hydrocarbon migration. The unbalanced distribution of excess pressure is the force for lateral hydrocarbon migration, and the area at low excess pressure is favorable for hydrocarbon migration and accumulation. The vertical source-reservoir pressure difference is large. The area at low excess pressure difference in adjacent layers becomes favorable for hydrocarbon migration and accumulation. In the sedimentary process of the Chang 7 reservoir, the interbeds of shale and tight sandstone are excellent source-reservoir combinations, and it is the primary place for oil accumulation. The analysis of hydrocarbon generation intensity and test oil production in source rocks show that the hydrocarbon generation intensity of three of the 21 wells in the study area is less than $300 \times 10^4/km^2$, with the maximum oil production of 5.4 t/d (Fig. 16). The analysis of the distance from the source rocks to the oil layer and the test oil production shows that there is an inverse correlation between the two, and the production tends to decrease with the increase of migration distance (Fig. 17). The hydrocarbon migrates continuously a short distance along fractures and overlapping sand bodies, and finally forms continuous tight oil reservoir in a large scale.

4.3.2. Favorable high permeability zone

The horizontal distribution of sedimentary facies controls the horizontal distribution of the Chang 7 reservoir. The underwater distributary channel in the delta front is a favorable facies zone, and the sand layers with relatively high quality physical properties are favorable reservoirs. The Chang 7 reservoir is formed in delta front sedimentary environment, which has thick source rocks interbedded with thicker sand layers. The oil enrichment area of tight oil is mainly distributed in the underwater distributary channels, which also shows that the sedimentary microfacies play an important role in controlling the distribution of tight oil.

The results of porosity, permeability and oil saturation test of Chang 7 reservoir shows that the porosity distributed in 6%–10% and the permeability distributed in 0.02–0.2 mD, both of which have good positive correlation (Fig. 18). The oil saturation distributed in 60%–80%, which increases with the increase of porosity and permeability. The diagenesis of the Chang 7 reservoir is strong, a large number of primary pores reformed and secondary pores developed. Under strong diagenesis, the reservoir properties are closely related to the diagenesis changes after burial. The most favorable cementation, microporous intergranular diagenetic facies, dissolution and solution-micropore diagenetic facies are less distributed in Chang 7_1 and more distributed in Chang 7_2 reservoir. The oil was more enriched in the Chang 7_2 reservoir than Chang 7_1 reservoir. The diagenesis is an important factor affecting the oil distribution in the Chang 7 reservoir.

4.3.3. Source rock-reservoir collocation

Geochemical parameters in Chang 7_1, Chang 7_2 and Chang 7_3 source rocks are higher than the lower limit of hydrocarbon generation. It shows that the three shales are high quality source rocks, especially the black shale of Chang 7_3. The sand layer of Chang 7 reservoir has a good reservoir quality, forming excellent source-reservoir-caprock combinations. The Chang 7_3 black shale is the main hydrocarbon source rock, which has the characteristics of stable distribution and more hydrocarbon expulsion. The oil generated by the hydrocarbon source rock is discharged upward into the overlying sand body, which is shielded by the overlying mudstone. It can be subdivided into 3 types of source reservoir combinations, such as A, B and C. Type A refers to excellent reservoir and cap conditions but poor hydrocarbon generation conditions, such as ZH 65 well (Fig. 19). Type B refers to excellent hydrocarbon generation and cap formation conditions and poor reservoir conditions, such as XI 102 well (Fig. 20). Type C refers to the hydrocarbon generating rocks and reservoir conditions are excellent, but the capping conditions are poor, such as Li 48 well

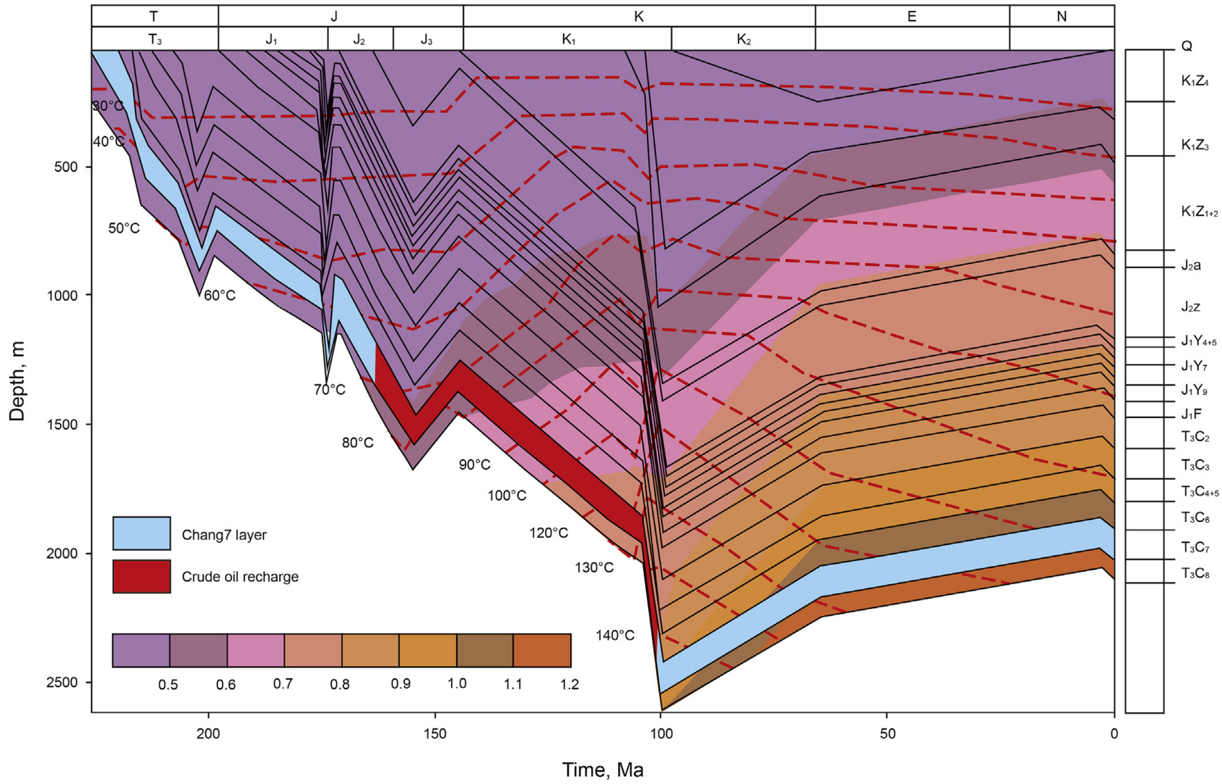

Fig. 15. Hydrocarbon generation evaluation, burial history, and thermal maturity of Yanchang Formation, Ordos Basin.

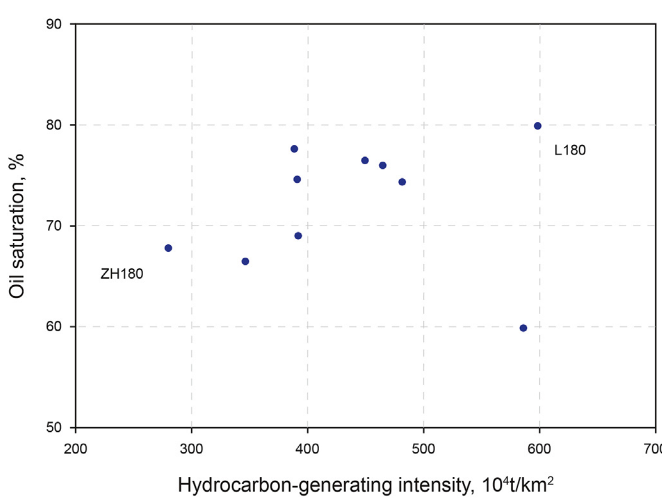

Fig. 16. Crossplot of hydrocarbon generation intensity and oil saturation of Chang 7 source rocks.

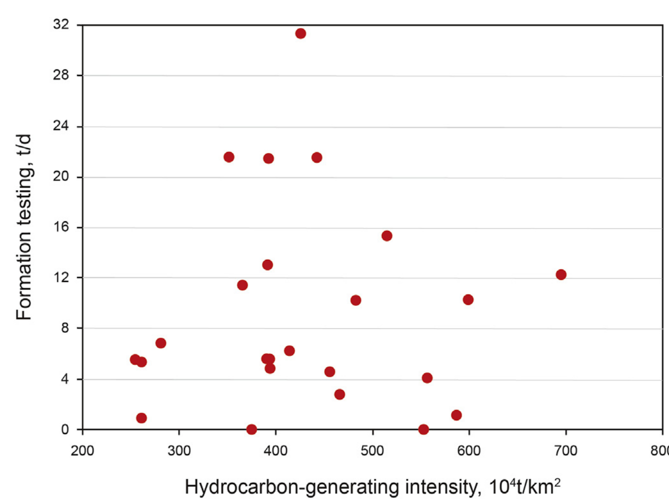

Fig. 17. Crossplot of hydrocarbon generation intensity and test oil production of Chang 7 source rocks.

(Fig. 20).

4.4. Accumulation characteristics

In Xin'anbian Oilfield, the internal heterogeneity of tight oil reservoir is strong, the reservoirs and source rocks are overlapped vertically, the underwater distributary channel sand bodies are separated by shallow lacustrine mudstone, the thickness of single sand layer is 5–15 m. The most tight oil distribution is in the main distributary channel sand layer in the delta front (Fig. 20). And the micro-heterogeneity of the sand layer is complex, micron-scale pores are developed, and the micron-scale pore-throat system restricts the buoyancy for fluid migration. The fluid migration force comes from hydrocarbon-generating pressurization, and the migration distance is short, mainly primary migration or short-distance secondary migration. The tight oil is basically stored in place after hydrocarbon generation. If the adjacent sand layer becomes dense due to compaction (more dark matter in sandstone) and calcareous cements, it is difficult for oil injected into sand layer. If early physical conditions are good and fractures are well developed, and source rocks become overpressure due to hydrocarbon generation and compaction, the fractures would be open and water

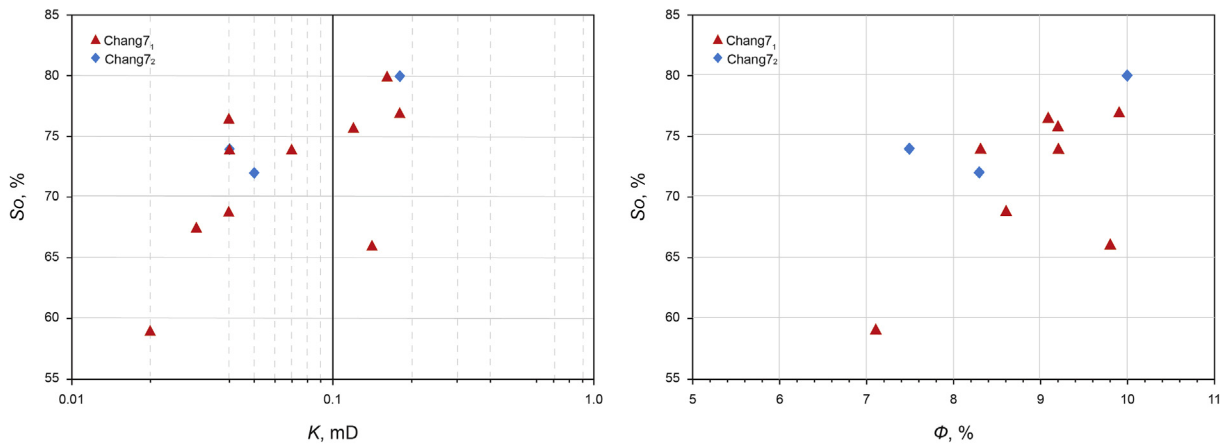

Fig. 18. Crossplot of porosity, permeability and oil saturation in Chang 7 reservoir.

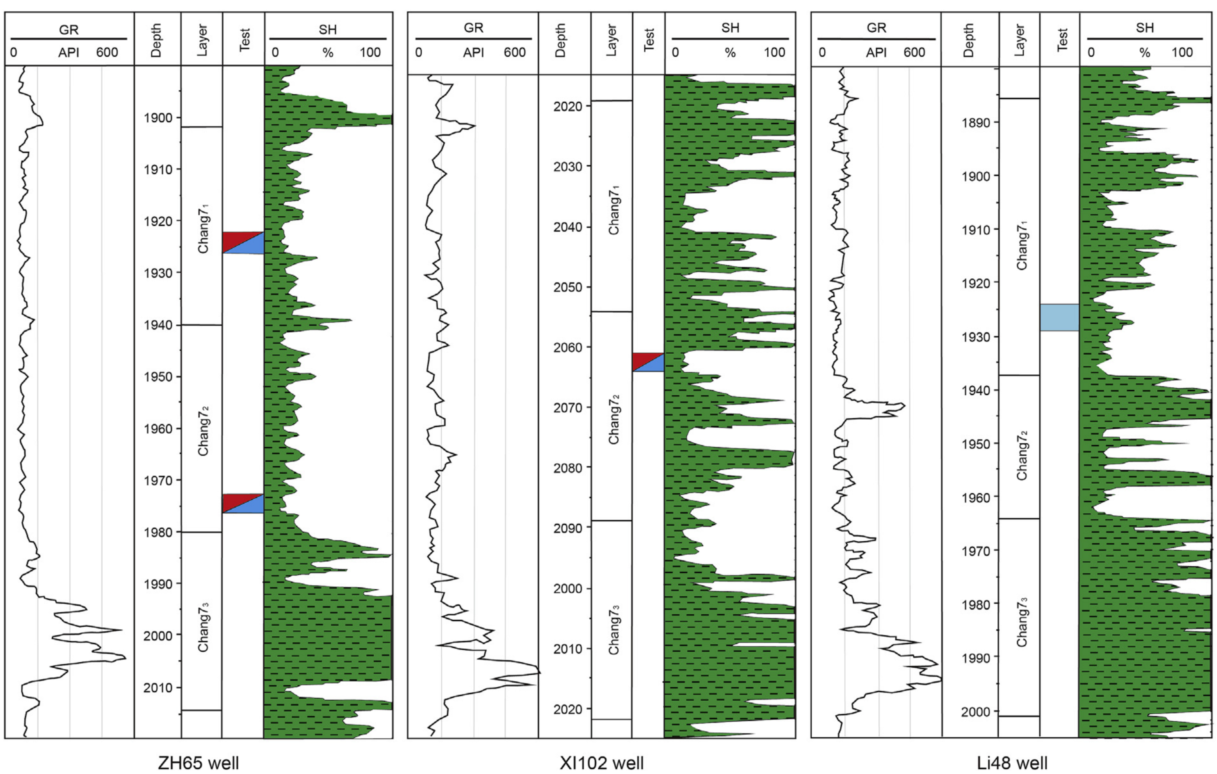

Fig. 19. Comprehensive bar chart of shale content in Chang 7 reservoir and oil test results.

originally filled in the sand layer. The oil would enter the sand layer under the action of buoyancy and source-reservoir pressure difference. With rapid burial in the middle and late period of Early Cretaceous, the reservoir was compact, but the physical properties of the reservoir were relatively good because the cementation was inhibited by the filling of oil. The Chang 7_2 reservoir of Well H119 and A98 belong to this type of reservoir-forming model.

5. Conclusions

(1) The Chang 7_3 high-quality source rocks are widely distributed in Xin'anbian Oilfield. The average TOC is 13.81%. The kerogen is mainly amorphous lipids, and the type of kerogen is mainly II_1–I, which belongs to partial sapropelic organic matter. The R_o is 0.9–1.2%, and the maturity is high.

(2) The porosity of the Chang 7_2 reservoir is mainly distributed in 5.0%–11.0%, averaging at 7.9%, The permeability is mainly distributed in 0.04–0.18 $\times$ 10^{-3} μm^2, averaging at 0.12 $\times$ 10^{-3} μm^2. The pore diameters of the tight oil reservoir are distributed in 2–8 μm, while the pore diameter of low-permeability reservoirs is generally greater than 8 μm. The pore space is dominated by micro-to nano-pore-throats. Micropores and nanothroats constructed a complex pore-throat network. A large number of micropores makes the reservoir quality equal to low-permeability reservoir.

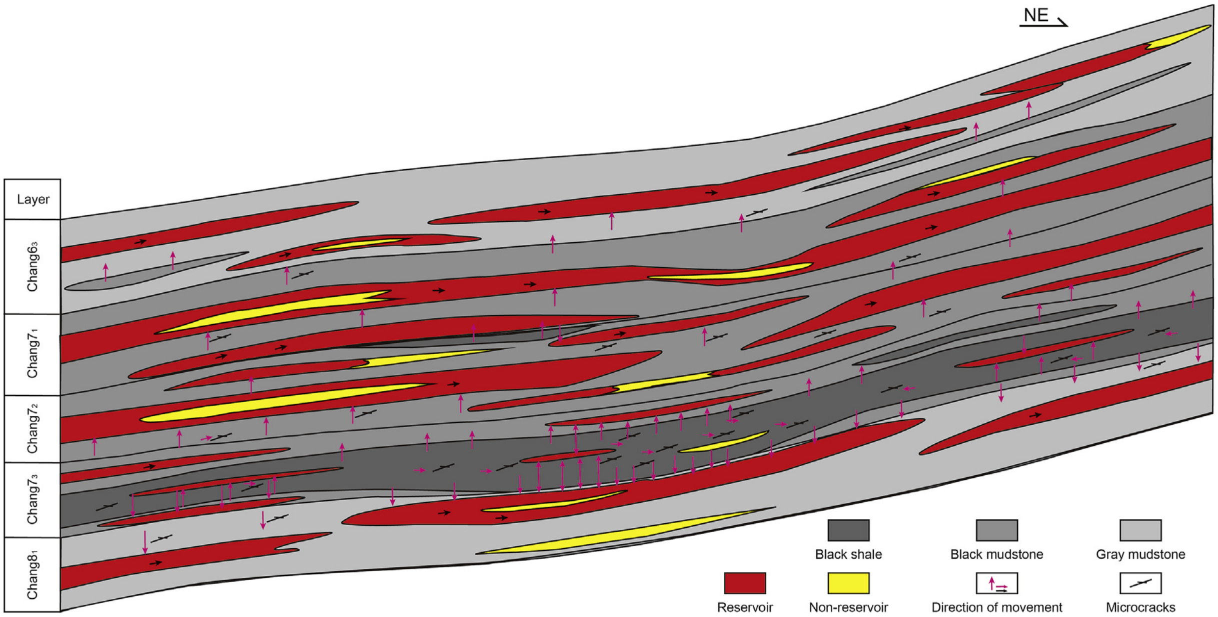

Fig. 20. Vertical distribution pattern of Chang 7 tight oil.

(3) Chang 7 tight oil reservoir has an excellent source-reservoir-caprock combinations. The distributary channel sand layer is mainly distributed in source rock with lenticular shape or strip, which has the advantage for preferential oil and gas accumulation. The primary period for reservoir formation is Early Cretaceous. Hydrocarbon-generating pressurization provide continuous and sufficient dynamics for oil accumulation, and favorable sedimentary microfacies and high-quality reservoirs contribute to the large-scale distribution of tight oil reservoirs.

Declaration of competing interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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References

Deng, X.Q., Liu, X.S., Li, S.X., et al., 2009. The relationship between compacting history and hydrocarbon accumulating history of ultra-low permeability reservoirs in Triassic Yanchang Formation in Ordos Basin. Oil Gas Geol. 30, 156–161. https://doi.org/10.11743/ogg20090205.

Han, W.X., Tao, S.Z., Hou, L.H., et al., 2017. Geochemical characteristics and genesis of oil-derived gas in the jingbian gas field, ordos basin, China. Energy Fuels 31, 10432–10441. https://doi.org/10.1021/acs.energyfuels.7b01179.

Han, W.X., Ma, W.J., Tao, S.Z., et al., 2018. Carbon isotope reversal and its relationship with natural gas origins in the Jingbian gas field, Ordos Basin, China. Int. J. Coal Geol. 196, 260–273. https://doi.org/10.1016/j.coal.2018.06.024.

Han, W.X., Chang, X.C., Tao, S.Z., et al., 2019a. Geochemical characteristics and genesis of pre-salt gases in the Ordos Basin, China. J. Petrol. Sci. Eng. 179, 92–103. https://doi.org/10.1016/j.petrol.2019.04.042.

Han, W.X., Chang, X.C., Ma, W.J., et al., 2019b. Geochemical characteristics and reasons for the carbon isotopic reversal of natural gas in the southern Jingbian gas field, Ordos Basin, China. Geol. Mag. 1–12. https://doi.org/10.1017/S0016756819000682.

Jia, C.Z., Zou, C.N., Li, J.Z., et al., 2012a. Assessment criteria, main types, basic features and resource prospects of tight oil in China. Acta Pet. Sin. 33, 343–350. https://doi.org/10.1016/0031-9384(73)90235-7 (in Chinese).

Jia, C.Z., Zheng, M., Zhang, Y.F., 2012b. Unconventional hydrocarbon resources in China and the prospect of exploration and development. Petrol. Explor. Dev. 39, 121–136. https://doi.org/10.1016/S1876-3804(12)60026-3.

Liu, X., Zhang, Y.W., Zhang, W., et al., 2013. Concept, characteristics, distribution and potential prediction of tight oil all over the World. Pet. Geol. Oilfield Dev. Daqing 32, 168–174 (in Chinese).

Li, Z.X., Qu, X.F., Liu, W.T., et al., 2015a. Development models of triassic Chang 7 tight oil in ordos basin, NW China. Petrol. Explor. Dev. 42, 217–221. https://doi.org/10.11698/PED.2015.02.11.

Li, H.B., Guo, H.K., Yang, Z.M., et al., 2015b. Tight oil occurrence space of triassic Chang 7 member in Northern Shaanxi area, ordos basin, NW China. Petrol. Explor. Dev. 42, 396–400.

Qin, J.Z., 2005. Source Rocks in China. Science Press, Beijing, pp. 32–33.

Ren, Z.L., Li, W.H., Liang, Y., et al., 2014. Tight oil reservoir forming conditions and controlling factors of Yanchang Formation in southeastern Ordos Basin. Oil Gas Geol. 35, 190–197. https://doi.org/10.11743/ogg20140203 (in Chinese).

Sun, Z.D., Jia, C.Z., Li, D.F., et al., 2011. Unconventional Oil & Gas Exploration and Development, ume I. Petroleum Industry Press, Beijing, pp. 1–150.

Shi, B.H., Zhang, Y., Zhang, L., et al., 2012. Hydrocarbon accumulation dating by fluid inclusion characteristics in Chang7 tight sandstone reservoirs of Yanchang Formation in Ordos Basin. Pet. Geol. Exper. 34, 599–603. https://doi.org/10.11781/sysydz201206599 (in Chinese).

USGS, 2008. Assessment of Undiscovered Oil Resources in the Devonian-Mississippian Bakken Formation, Williston Basin Province, Montana and North Dakota. USGS Fact Sheet.

Wang, F.Y., Meng, X.H., Feng Wei, P., et al., 2013. Techniques for evaluating resources and recoverability of lacustrine tight oil. Pet. Geol. Oilfield Dev. Daqing 32, 144–149. https://doi.org/10.3969/J.ISSN.1000-3754.2013.03.030 (in Chinese).

Yang, H., Zhang, W.Z., 2005. Controlling influences on high-quality Chang 7 source rocks in Ordos Basin during the enrichment of low-permeability reservoirs: geology and geochemistry. Geochimica 34, 147–154 (in Chinese).

Yang, H., Dou, W.T., Liu, X.Y., et al., 2010. Analysis on sedimentary facies of triassic Chang 7 in Yanchang formation in ordos basin. Acta Sedimentol. Sin. 28, 254–263. https://doi.org/10.1017/S0004972710001772 (in Chinese).

Yao, J.L., Deng, X.Q., Zhao, Y.D., et al., 2013. Characteristics of tight oil in triassic Yanchang formation, ordos basin. Petrol. Explor. Dev. 40, 150–158. https://doi.org/10.1016/S1876-3804(13)60019-1.

Yang, H., Li, S.X., Liu, X.Y., 2013. Characteristics and resource prospects of tight oil and shale oil in Ordos Basin. Acta Pet. Sin. 34, 1–11. https://doi.org/10.7623/syxb201301001 (in Chinese).

Yao, J.L., Xu, L., Xing, L.T., et al., 2015a. Fluid overpressure and oil migration in Chang 7 and Chang 8 of Yanchang formation in ordos basin,China. Nat. Gas Geosci. 26, 2219–2226. https://doi.org/10.11764/j.issn.1672-1926.2015.12.2219 (in Chinese).

Yao, Y.T., Li, S.X., Zhao, Y.D., et al., 2015b. Characteristics & controlling factors of Chang 7 tight oil in Xin'anbian area, Orods basin. Acta Sedimentol. Sin. 33, 625–632 (in Chinese).

Yao, J.L., Zhao, Y.D., Deng, X.Q., et al., 2015c. Controlling factors on tight oil reservior in triassic Yanchang formation in ordos basin. J. Jilin Univ. (Earth Sci. Ed.) 45, 983–992. https://doi.org/10.13278/j.cnki.jjuese.201504102 (in Chinese).

You, Y., Liu, J.P., Feng, S.B., et al., 2015. Heterogeneity of massive tight sandstones and its inspiration on exploration and development of tight oil. Pet. Geol. Oilfield Dev. Daqing 34, 168–174 (in Chinese).
Yang, H., Liang, X.W., Niu, X.B., et al., 2017. Geological conditions for forming continental tight oil and controlling factors on the enrichment: a case study on Chang 7 Member, Triassic Yanchang Formation, Ordos Basin, NW China. Petrol. Explor. Dev. 44, 12–20. https://doi.org/10.11698/PED.2017.01.02.
Zou, C.N., Tao, S.Z., Hou, L.H., et al., 2011. Unconventional Petroleum Geology. Geological Publishing House, Beijing, pp. 127–167.
Zou, C.N., Zhu, R.K., Wu, S.T., et al., 2012. Types, characteristics, genesis and prospects of conventional and unconventional hydrocarbon accumulations: a case study on tight oil and tight gas in China. Acta Pet. Sin. 33, 173–186 (in Chinese).
Zhao, J.Z., 2012. Conception, classification and resource potential of unconventional hydrocarbons. Nat. Gas Geosci. 23, 393–406 (in Chinese).
Zhang, W.Z., Yang, H., Li, J.F., et al., 2015. Controlling influence of high-quality Chang 7 source rock in Ordos Basin on enrichment of low-permeability hydrocarbon accumulation–Hydrocarbon generation and expulsion mechanism. Petrol. Explor. Dev. 20, 9–18.
Zhang, F.Q., Zhang, F.B., Zhong, H.L., et al., 2016a. Controlling factors on the enrichment of Chang 7 tight oil in Yanchang formation in southern Ganquan area, ordos basin. Lithol. Reserv. 28, 12–19 (in Chinese).
Zhang, Z.Y., Chen, S.J., Yang, H., et al., 2016b. Tight oil accumulation mechanisms of triassic Chang 7 member of Yanchang formation, ordos basin, China. Pet. Expl. Dev. 43, 590–599. https://doi.org/10.1016/S1876-3804(16)30075-1.