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Research paper

Formation, distribution and resource potential of the "sweet areas (sections)" of continental shale oil in China

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ABSTRACT

Shale oil refers to oil stored in organic-rich shale. It is an important part of unconventional oil and provides a large amount of resources. Based on the systematic study of the geological characteristics of shale oil in China's major continental basins, the geological connotation of the “sweet area (section)” in shale oil is proposed in this paper, and it refers to areas (sections) that can be preferentially explored and developed in oil-bearing shale formations under current economic and technical conditions. The formation conditions and distribution characteristics of continental shale oil in China are analyzed with a focus on the geological properties of the Triassic Yanchang Formation in the Ordos Basin, the Cretaceous Qingshankou Formation in the Songliao Basin and the Permian Lucaogou Formation of the Jimusar Sag in the Junggar Basin. It is found that the “sweet areas” of shale oil with medium-high maturation are mainly located in thick shales with a Ro greater than 0.9%, and the “sweet sections” are mainly located in the middle and lower parts of the shale formation. The geological resources of continental shale oil in the major continental basins in China are estimated to be approximately 3700×10^8 tons. The in situ conversion process (ICP) may be a key technology for the effective development of medium-to low-mature shale oil. The scale, maximum burial depth and present depth of the organic-rich shale are proposed as the three key parameters for the optimization of pilot sites by taking the Triassic Yanchang Formation in the Ordos Basin as an example. Using ICP, it is expected that the recoverable resources of China's continental shale oil will be approximately $(400–500) \times 10^8$ tons. The terminology of "man-made reservoir" is proposed in this paper. In an "man-made reservoir", the overall industrial output of the "sweet areas (sections)" is formed by artificial intervention and the construction of an underground fracture network system with "man-made permeability". Continental shale oil may be another revolutionary source of unconventional oil and is expected to be first successfully produced in China.

1. Introduction

The oil industry is continuously expanding beyond conventional oil, which accounts for 20% of total oil resources, to unconventional oil, which accounts for 80% of total oil resources (Zou et al., 2013a, 2013b). The target type of oil exploration is constantly expanding from structural reservoirs to stratigraphic and lithologic reservoirs located at slopes or even to the “sweet areas (sections)” of unconventional reservoirs in the central part of a basin (Zou et al., 2013a; Yang et al., 2015). The residual liquid hydrocarbon in black organic-rich shale is the focus of current unconventional oil development and research (Pollastro et al., 2010; Jarvie, 2011, 2012; Cander, 2012; Harris, 2012; Zou et al., 2013a; Yang et al., 2015). Shale oil is an important component of oil resources that is developed in shale and is a petroleum accumulation in “source rock”. “Exploring oil into source kitchen” will become the core method of unconventional oil development. Oil exploration has included searches for oil from “structural highs” to “slopes” and then to “source rock areas” (Jarvie, 2011, 2012; Cander,

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2012; Harris, 2012; Zou et al., 2013a; Yang et al., 2015; Hackley and Cardott, 2016; Sieminski, 2016).

In this paper, shale oil refers to oil stored in organic-rich shale formations, and mainly refers to oil in organic shale with medium to high maturity (R_o ranges from 0.9% to 1.7%). Shale is both a source rock and reservoir rock, and shale oil is sometimes called "source rock oil". Shale oil exists in adsorbed and free states and is generally light oil with a low viscosity (Seifert and Moldowan, 1978; Tissot, 1984; Peters et al., 1990, 2005; Krooss et al., 1991; Hill, 2007; Han et al., 2015, 2017; Dong et al., 2018). It is mainly stored in nano sized pores, throats and fractures, mostly in flaky beddings or parallel microfractures. Usually, organic-rich shale accumulates continuously in a large area in the center of a basin and generally contains oil universally. Abundant oil has been found in many organic-rich shales that have been drilled, indicating the existence of large-scale shale oil resources. Shale oil has no obvious trapping limit, and its geological characteristics are obviously different from conventional oil. A shale oil well generally has no natural production capacity, or its natural production capacity does not reach the lower limit of industrial oil output. Exploring "sweet areas (sections)" where industrial oil flow is enriched is the main task of shale oil exploration. The successful exploitation of shale gas provides a technical reference for the exploitation of shale oil. "Man-made permeability" technologies such as volume fracturing stimulation and refracturing stimulation in horizontal wells are key technologies for the effective development of shale oil (Zou, 2017; Yang et al., 2016a, 2017a,b; Gao et al., 2017; Wang et al., 2018). Currently, fractured shale oil and light to condensate shale oil have succeeded in industrial production, and fractured shale oil and gas were found in the Appalachian Mountains, the Gulf of Mexico, West Siberia, the Songliao Basin, etc. As a result, a consensus that oil can be found in special fractures in shale has been reached. Theoretically, condensate oil and light oil may be stored in nano sized pores and throats in shale. Hydrocarbon-bearing shale with medium to high maturity is widely distributed around the world, which provides favorable geological conditions for the storage of condensate or light oil.

Based on studies of the shale formations in China's lacustrine basins including the Triassic Yanchang Formation in the Ordos Basin, the Cretaceous Qingshankou Formation in the Songliao Basin, and the Permian Lucaogou Formation in the Junggar Basin, this paper systematically details the geological characteristics of the shale oil, the formation conditions and the vertical and horizontal distribution of the "sweet area (section)", and predicts the resource potential of shale oil in China.

2. Geological characteristics of shale oil

Shale oil discoveries that have been found in China are distributed in continental shale formations at different scales ranging from 0.1×10^4 to $10 \times 10^4\,km^2$ (Fig. 1). Oil-bearing continental shales in China span a large extent of geologic time. Shales in the eastern Songliao and Bohai Bay Basins are mainly distributed in the Cretaceous and Paleogene. While shales in the central Ordos basin and Sichuan Basins are mainly distributed in the Triassic and Jurassic. Shales in the northwestern regions such as Junggar, Santanghu, and Qaidam Basins are mainly distributed in the Permian, Paleogene, and Jurassic (Fig. 2). The effective thickness of continental shales is generally more than 30 m and the maximum is more than 1000 m. The main organic matters are types I-II. As a result of strong heterogeneity, the abundance of the organic matter varies greatly with the TOC from 0.01 to 25.27%, S_1 from 0.01 to 45.44 mg/g • rock, S_2 from 0.01 to 114.71 mg/g • rock, and $S_1 + S_2$ from 0.01 to 97.27 mg/g • rock. The thermal maturity is relatively low with Ro from 0.6 to 1.1% and T_{max} from 430 to 450 °C (Figs. 2 and 3, and Table 1). It should be noted that although the shale oil generating conditions in the Qaidam Basin and the Sichuan Basin are poor (Figs. 2 and 3, and Table 1), there has been large-scale industrial production in these shales.

In general, China's continental organic-rich shale formations are characterized by young stratigraphic age, limited distribution, frequent facies variation, multiple types of organic matter, low thermal evolution, low brittle mineral content, and high clay content (Qiu et al., 2004; Xiao et al., 2010; Lin et al., 2013; Yang et al., 2015, 2016a,b; 2017a,b; Pan et al., 2017; Hou et al., 2017). Particularly, the maturity of organic matter is generally low, while the area with highly mature shale is relatively deeply buried. Therefore, the accumulation mechanism and conditions are unfavorable for subsequent stimulation and the oil is characterized by high density, high viscosity, and high wax content. All these factors restrict the exploration and development of shale oil in China.

3. Formation and distribution of "sweet areas (sections)" of shale oil

3.1. Geological connotation

"Sweet areas (sections)" of shale oil refer to the target areas (sections) that can be preferentially explored and developed in the oil-bearing shale formations under current economic and technical conditions. Generally, they are extensively distributed (several thousands of square kilometers) and relatively thick (usually more than 15 m). Moreover, they possess the characteristics of high-quality source rock (TOC greater than 2%), large reservoir space (porosity usually greater than 3%), high oil saturation (often more than 50%), high-quality light oil, a high formation energy (high gas-to-oil ratio and high formation pressure), and a high brittleness index (often more than 40%) (Sarg, 2012; Beau, 2014; Yang et al., 2015). In addition, natural fractures and local structures are developed.

Shale oil has two basic characteristics: (1) oil is continuously distributed over a large area, while the resource abundance is low; and (2) it has no natural industrial capacity, and "artificial" stimulation is needed for oil production. Therefore, the evaluation of "sweet areas (sections)" of shale oil involves the search for "areas (sections) with higher resource abundance" and "areas (sections) that can easily create man-made permeability". Under current technological conditions, relying on technologies such as volume fracturing of horizontal wells and platform-based "factory" operation, "areas (sections) with higher resource abundance" generally refer to those with a large distribution, great thickness, high organic abundance and high maturity. These are the geological attributes for the evaluation of "sweet areas (sections)". "areas (sections) with man-made permeability" generally are favorable areas (sections) with developed natural fractures, high brittle mineral content and a small horizontal stress difference. These are the engineering attributes for "sweet areas (sections)" evaluation. This paper mainly discusses the geological attributes of shale oil.

3.2. Formation and distribution of "sweet areas (sections)"

The sedimentary environments of continental shale oil in China can be mainly divided into continental freshwater lakes and continental saline lakes. In these sedimentary environments, oil-generating rocks mainly include siliceous shale and calcareous shale. The area of the lake water is limited, usually thousands of square kilometers, but varies greatly. The long-term continuous subsidence is conducive to the preservation of organic matter and the formation of high-quality source rocks. The semideep and deep lacustrine facies are the most favorable facies for the formation of source rocks. This is because a large amount of organic matter has been deposited and favorable shale areas (sections) could be formed. Most of the lacustrine shale was formed in deep or large permanent lakes. In warm and humid climates, lakes tend to maintain a certain water depth with abundant organic matter, where the water has a certain degree of salinity, which is conducive to the formation of organic-rich shale. During the sedimentation of the Seventh Member of the Triassic Yanchang Formation in the Ordos

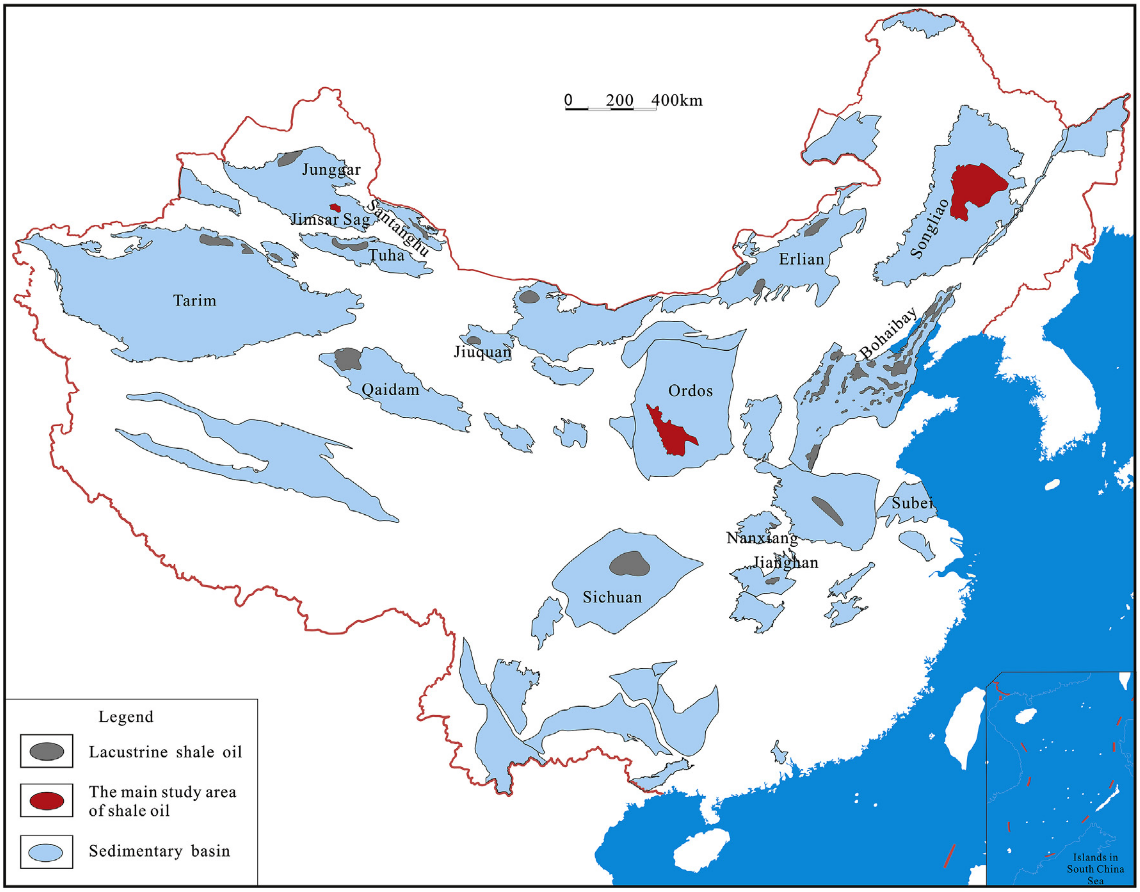

Fig. 1. Oil-bearing lacustrine shale distribution in the main basins in China.

Basin, the First Section of the Qingshankou Formation in the Songliao Basin, and the Third Member of the Shahejie Formation in the Bohai Bay Basin, the areas of the basins, climatic conditions, and preservation conditions all contributed to the formation of the world-class continental organic-rich shales.

The generation process of continental shale oil in China can generally be divided into two phases. (1) During the low maturity stage (R_o from 0.5% to 0.7%), the oil generated is characterized by a high wax content and poor fluidity and is mainly dominated by high density crude oil. The liquid petroleum is similar to immature oil in composition and properties. The n-alkanes are mainly C_{22}—C_{34}, which have a relatively high molecular weight and show an obviously predominant odd-carbon number. There are 1–6 rings of alkanes in the cycloalkanes, and the 4-ring cycloalkane features the odd peak. Aromatic hydrocarbons are also dominated by compounds with relatively high molecular weight, and two peaks are presented at the naphthalene and the polynuclear aromatic hydrocarbon. (2) At the mature oil stage (R_o between 0.7% and 1.3%), as the maturity increases, the ratio of gas to oil rises dramatically; the oil density decreases; the viscosity decreases drastically, and the fluidity increases greatly. In addition, the proportions of light oil and condensate oil increase. The liquid petroleum generated in this stage is significantly different from immature oil in its composition and properties. The carbon number and molecular weight of n-alkanes decreases, the predominant odd-carbon number disappears, the carbon atoms of naphthenes and aromatics decrease, and the number of polycyclic and polyaromatic compounds decreases significantly. Within the depth range of shale oil exploration in the continental basins in China, the maturity of organic matter is generally between 0.5 and 1.0%. As a result, shale oil generally has the features of high density, high wax content, and high viscosity.

Organic-rich continental shale formations in China are characterized by multiple types, a wide age span, and a large distribution, which provide a good basis for the formation of shale oil. The organic-rich black shale formations formed in the lacustrine environment were found in the continental rift basins and depression basins of the Permian, Triassic, Jurassic, Cretaceous, Neogene, and Paleogene age. Permian lacustrine organic-rich black shale formations, including the Fengcheng Formation (P_1f), the Xiazijie Formation (P_2x), and the Wuerhe Formation ($P_{2-3}w$), are developed in the Junggar Basin and are distributed in the western-southern depression of the Junggar Basin. Triassic lacustrine shale formations are developed in the Ordos Basin, and the Ninth Member of the Triassic Yanchang Formation (T_3ch^9) and the Seventh Member of the Triassic Yanchang Formation (T_3ch^7) shale formations that are distributed in the south-central Basin are the best. Jurassic coal-bearing formations are widely distributed in central and western China, but in the Sichuan Basin, they were deposited in a shallow lacustrine to semideep lacustrine environment where the Ziliujing shale Formation ($J_{1-2}z$) that developed in the Middle and Upper Jurassic is widely distributed in Central, Northern and Eastern Sichuan. The Cretaceous lacustrine shale formations that developed in the Songliao Basin include the lower Cretaceous Qingshankou Formation, Nenjiang Formation, Shahezi Formation and Yingcheng Formation, which are distributed throughout the basin. Paleogene lacustrine shale formations that are widely developed in the Bohai Bay Basin mainly include the E_3s^1, E_3s^3, and E_3s^4 of the Shahejie Formation, and the Kongdian shale Formation (E_3k) is developed in the Huanghua and Jiyang Depression. The lacustrine black organic-rich shale is the primary oil source rock in the Songliao, Bohai Bay, Ordos, Junggar and other large oil production areas in onshore China.

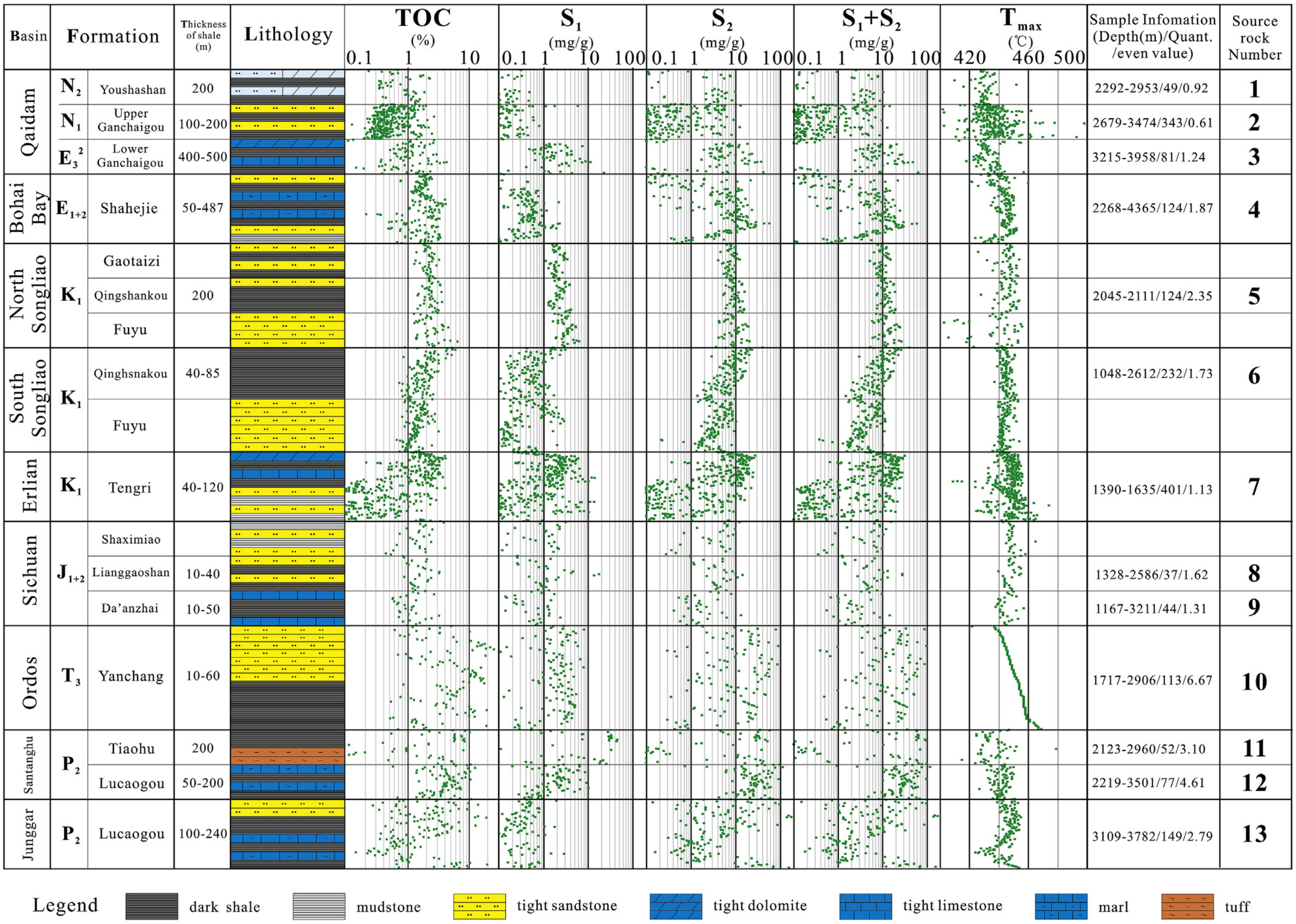

Fig. 2. Geochemical profile of lacustrine shale in the main basins in China.

3.3. Typical examples

Taking the oil-bearing shale of the Seventh Member of the Triassic Yanchang Formation in the Ordos basin, the First Section of the Cretaceous Qingshankou Formation in the Songliao basin and the Permian Lucaogou Formation in the Jimusaer Depression, and the Jungar basin, as examples, this paper briefly describes the particular geological characteristics of the "sweet areas (sections)" in the study area.

Continuous distribution in a large area is an identifiable feature of

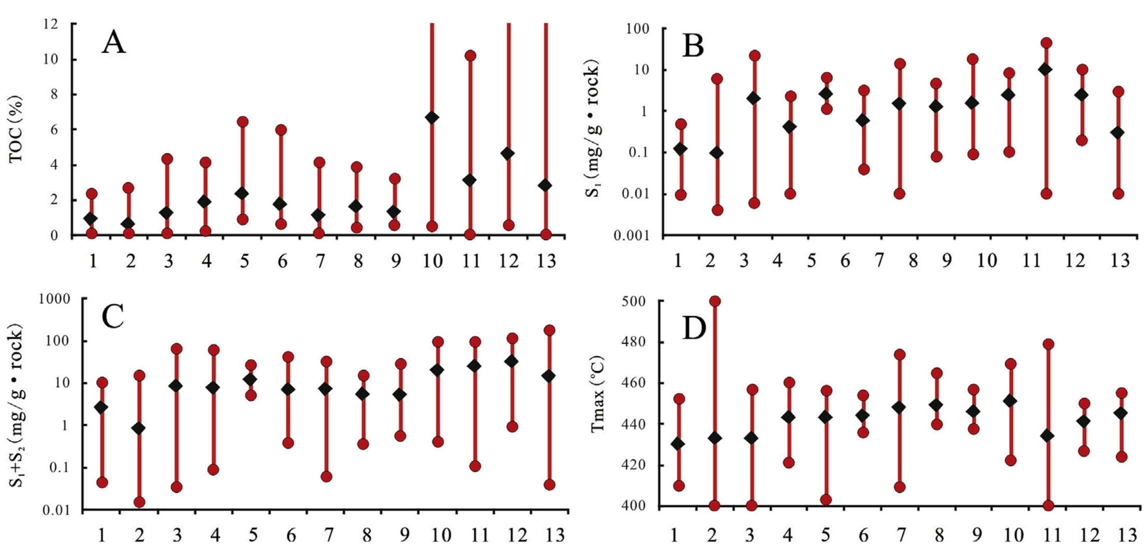

Fig. 3. Geochemical parameter cross-plot of lacustrine shale in the main basins in China.
Note: The numbering in the X-axis is detailed in Fig. 2.

Table 1
Geochemical parameter statistics of lacustrine shale in the main basins in China.

Number	Basin	Formation	Sample numbers	Depth (m)	TOC (%)	S_1 (mg/grock)	S_2 (mg/grock)	S_1+S_2 (mg/grock)	Tmax (°C)
1	Qaidam	N_2(Youshashan)	49	2292–2953	0.09–2.38(av.0.92)	0.010–0.491(av.0.121)	0.035–9.927(av.2.491)	0.046–10.418(av.2.612)	410-452(av.430)
2	Qaidam	N_1(Upper Ganchaigou)	343	2679–3474	0.10–2.68(av.0.61)	0.004–5.955 av. (0.096)	0.011–12.874(av.0.751)	0.015–14.660(av.0.847)	301-565(av.433)
3	Qaidam	E_3^2(Lower Ganchaigou)	81	3215–3958	0.11–4.32(av.1.24)	0.006–22.74(av.2.013)	0.028–41.416(av.6.492)	0.034–64.157(av.8.51)	386-457(av.433)
4	Bohaibey (Shulu Sag)	E_{1-2}(Shahejie)	181	2268–4365	0.21–4.13(av.1.87)	0.01–2.32(av.0.41)	0.07–57.08(av.7.31)	0.09–59.4(av.7.72)	421-460(av.443)
5	North Songliao	K_1(Qingshankou)	124	2045–2111	0.88–6.41(av.2.35)	1.13–6.31(av.2.59)	3.7–20.43(av.9.18)	5.24–26.74(av.11.77)	403-456(av.443)
6	South Songliao	K_1(Qingshankou)	232	1048–2612	0.66–6.01(av.1.73)	0.04–3.11(av.0.59)	0.38–40.14(av.6.45)	0.38–40.14(av.7.04)	436-454(av.444)
7	Erlian (Anan Sag)	K1(Tengri)	401	1390–1635	0.08–4.13(av.1.13)	0.01–13.91(av.1.47)	0.04–27.31(av.5.65)	0.06–31.52(av.7.13)	409-474(av.448)
8	Sichuan	J(Lianggaoshan)	37	1328–2586	0.44–3.86(av.1.62)	0.08–4.64(av.1.28)	0.28–12.38(av.4.19)	0.36–15.51(av.5.47)	440-465(av.449)
9	Sichuan	J(Daanzhai)	44	1167–3211	0.56–3.23(av.1.31)	0.09–17.75(av.1.54)	0.42–14.44(av.3.66)	0.56–28.09(av.5.20)	438-457(av.446)
10	Ordos	T_3(Yanchang)	113	1717–2906	0.52–25.27(av.6.67)	0.10–8.14(av.2.45)	0.3–91.38(av.17.43)	0.4–97.27(av.19.88)	422-469(av.451)
11	Santanghu	P_2(Tiaohu)	52	2123–2960	0.01–10.2(av.3.10)	0.01–45.44(av.10.11)	0.01–58(av.14.59)	0.01–94.39(av.24.71)	389-479(av.434)
12	Santanghu	P_2(Lucaogou)	77	2219–3501	0.57–12.57(av.4.61)	0.2–10.18(av.2.43)	0.74–114.71(av.30.82)	0.94–116.42(av.32.25)	427-450(av.441)
13	Junggar	P_2(Lucaogou)	149	3109–3782	0.03–19.77(av.2.79)	0.01–2.91(av.0.30)	0.02–176(av.14.23)	0.04–176.65(av.14.54)	424-455(av.445)

Note: The number in the first column is shown in Fig. 2.

shale oil accumulation. Large-scale reservoirs have continuous microscale and nanoscale reservoir spaces, which are the basis for continuous shale oil distribution (Fig. 4). In the shale reservoirs of the Upper Triassic Yanchang Formation of the Ordos Basin (Fig. 4-A, 4-B), the Lower Cretaceous Qingshankou Formation in the Songliao Basin (Fig. 4-C, 4-D) and the Middle Permian Lucaogou Formation in Jimsar Sag in the Junggar Basin (Fig. 4-E, 4-F), the nanoscale pores include organic pores, intragranular pores, intergranular pores, and microfractures (Fig. 4). The main pore size of the shale reservoirs is 30–400 nm. The organic pores primarily occur along the edges of organic matter and mineral matrixes, taking the form of long strips or bended flakes. Few networked organic pores are detected. The pores sizes are mainly between 30 and 200 nm. The intragranular pores are chiefly dolomite intragranular pores and illite/smectite mixed-layer intragranular pores with various forms. The intergranular pores include pyrite intercrystalline pores and gypsum intercrystalline pores with stripped, circular, or elliptic forms. The pore sizes mainly range from 40 to 300 nm. The organic pores in lacustrine shale oil reservoirs are less developed than those in marine shale gas reservoirs, which can be attributed to the degree of thermal evolution.

A. Dark shale sample from the 7th Member of Triassic Yanchang Formation in the Ordos Basin, SEM, organic matter (OM) surrounded by clays. **B**. Dark shale sample from the 7th Member of Triassic Yanchang Formation in the Ordos Basin, SEM, organic matter (OM) in the pyrite. **C.** Dark shale sample from the Cretaceous Qingshankou Formation in the Songliao Basin, SEM, organic matter (OM) surrounded by quartz and clays. **D.** Dark shale sample from the Cretaceous Qingshankou Formation in the Songliao Basin, SEM, organic matter (OM) surrounded by clays. **E.** Dark shale sample from the Permian Lucaogou Formation in Jimsar Sag in the Junggar Basin, SEM, organic matter (OM) surrounded by the grains. **F**. Dark shale sample from the Permian Lucaogou Formation in Jimsar Sag in the Junggar Basin, SEM, intergranular pores between dolomites, organic matter (OM) surrounded by minor grains.

During the sedimentation of the Late Triassic Yanchang Formation in the Ordos Basin, which was affected by the Indosinian Movement, a freshwater lake basin with a large area and a wide water area was created. The lake basin reached its peak area in the depositional period of the Seventh Member of the Triassic Yanchang Formation, when the primary oil-generating rocks that were dominated by black shale and dark mudstone were developed. Distributed in the NW-SE direction, the widely developed black shale is the primary source rock in the basin, with an effective distribution of approximately $5 \times 10^4\ km^2$ (Fig. 5). Semideep lake and deep lake subfacies are the sedimentary environments of the black shale whose distribution is consistent with that of the lake basin. The black shale was mainly developed at the bottom of the Seventh Member of the Triassic Yanchang Formation with a great and continuous thickness. The sandstone or tuff interlayers are relatively thin with a thickness generally from 30 to 60 m and the maximum thickness of 130 m. The black shale in the Seventh Member of the Triassic Yanchang Formation of the Yanchang Formation is rich in organic matter with TOC from 6% to 22%, with an average of 13% (Fig. 6). Ro ranges from 0.85% to 1.15%, and T_{max} is mainly distributed between 450 °C and 470 °C, which indicates that the shale formation is in the medium maturity stage (Fig. 5). The average hydrocarbon generation intensity is $560 \times 10^4\ t/km^2$, and the total effective hydrocarbon generation volume is approximately 1300×10^8 tons. Shaly, sandy and microscopic lamellae are developed with flaky clay minerals, carbonate rock and organic matter, pyrite, etc. The TOC content has a positive correlation with the development level of the shale lamellae, and shale oil is extensively present in these lamellar planes or parallel microfractures (Fig. 7). The "sweet spot zone" of the shale oil in the Seventh Member of the Triassic Yanchang Formation of the Ordos Basin is mainly located where the thickness is greater than 15 m and Ro is greater than 0.9%. The "sweet section" is mainly located in the lower part of the Seventh Member of the Triassic Yanchang Formation (Figs. 5 and 6).

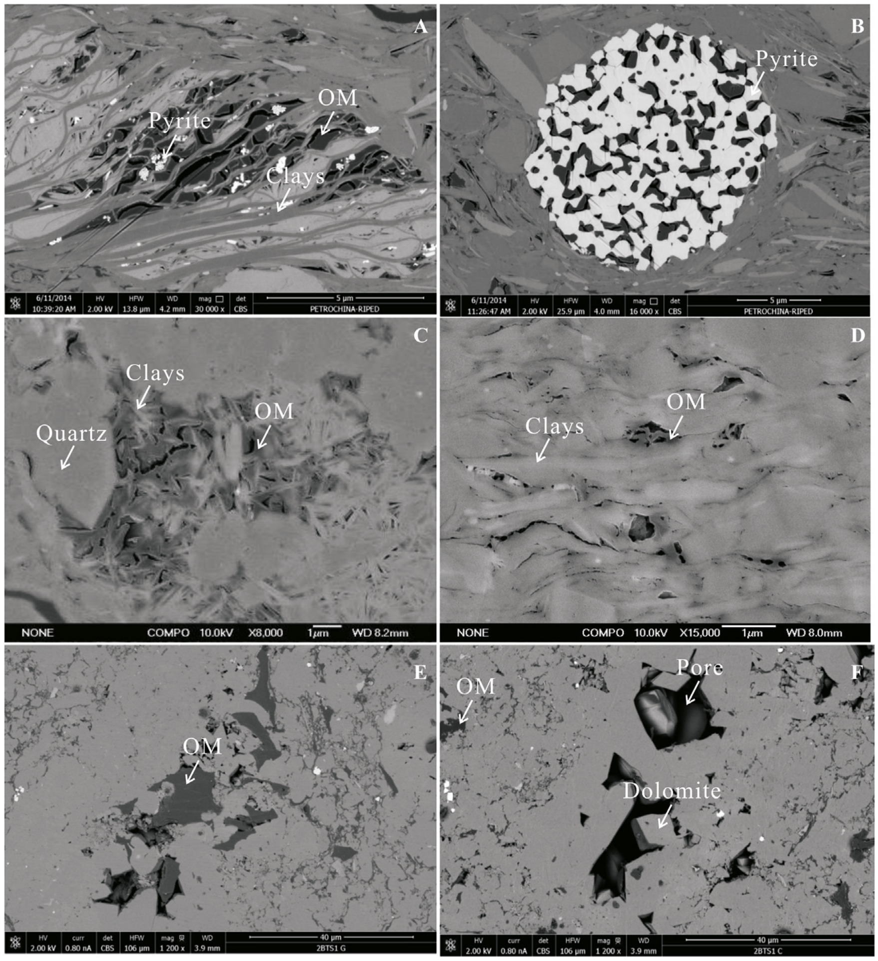

Fig. 4. SEM images of typical continental oil-bearing shale in China.

A. Dark shale sample, under polarized light, TOC = 0.75%, S_1 = 0.96 mg/g. **B**. Dark shale sample, under polarized light, TOC = 1.42%, S_1 = 0.81 mg/g. **C.** Dark shale sample, under polarized light, TOC = 2.23%, S_1 = 0.66 mg/g. **D.** Dark shale sample, under polarized light, TOC = 3.38%, S_1 = 1.03 mg/g. **E.** Dark shale sample, under polarized light, TOC = 4.96%, S_1 = 2.69 mg/g. **F**. Dark shale sample, under polarized light, TOC = 5.54%, S_1 = 2.81 mg/g. **G**. Dark shale sample, under polarized light, TOC = 10.17%, S_1 = 4.72 mg/g. **H**. Dark shale sample, under polarized light, TOC = 25.27%, S_1 = 3.23 mg/g.

During the depositional period of the Qingshankou Formation in the Songliao Basin, eastern China, large-scale continental depression and lake basins stably subsided under the hot and humid climate. An extensive lacustrine transgression occurred, resulting in a large area of semideep to deep lacustrine black shale, with an area larger than 8×10^4 km^2 (Fig. 8). The thick mudstone/shale at the lower part of the First and Second Sections of the Qingshankou Formation is primarily distributed in the main depressions of Qijia-Gulong, Sancha, Changling, etc. The lateral distribution of the shale is stable, and the thickness is generally between 30 m and 80 m (Fig. 9). It is a world-class oil source rock in the Daqing Oilfield. The shale in the Qingshankou Formation is a set of high-quality source rocks with abundant organic matter. The TOC is between 1% and 8%, and the average is more than 2%. Overall, the organic matter is of a sapropel type. In the Qingshankou Formation, the organic matter in the first member is types I to II_1, and the second and third members are types I to II_2. The R_o is mainly between 0.6% and 1.2% and the T_{max} value ranges from 440 °C to 455 °C (Figs. 8 and 9), suggesting a medium mature stage. The average hydrocarbon generation intensity of the first member is 500×10^4 t/km^2, and that of the second and third members of the Qingshankou Formation is approximately 350×10^4 t/km^2, which results in an effective hydrocarbon generation of approximately 1100×10^8 tons. The black shale interbeds have widely distributed thin sandstone layers, which forms a typical "shale-in-sandstone" structure where various levels of hydrocarbon indications have been found in most wells. The shale oil "sweet spot zone" of the Qingshankou Formation in the Songliao Basin is mainly distributed where the thickness is greater than 40 m and R_o is higher than 0.9%. The "sweet section" is mainly located in the middle and lower parts of the Qingshankou Formation (Figs. 8 and 9).

The Permian Lucaogou Formation in the Junggar Basin is one of the oldest strata with continental liquid hydrocarbon-bearing shale. It is composed of offshore mixed sediments in the salty lake, and has abundant shale oil resources. The Jimusar sag in the Junggar basin is a typical sag enriched in shale oil resources. In the depositional environment of the offshore lake in the Jimusar sag, the intermittent injection of seawater caused the death of biological groups in the lake, which was conducive to the accumulation and conservation of organic matter. The whole section is subdivided into six layers with 2.5 third-order cycles (Fig. 11). The organic-rich shale is mainly developed in P_2l_2 and P_2l_5, which is composed of carbonate mudstone and shale, and the TOC is generally above 4%. The dominant kerogen is type II, and the Ro is between 0.6% and 1.2% in the oil window (Fig. 11). The reservoir properties of the shale are generally poor: the porosity is between 6% and 12%, the air permeability is less than 0.1 mD, and the oil saturation is between 80% and 90%. The formation fluid pressure system is dominated by normal pressure to weak overpressure. The

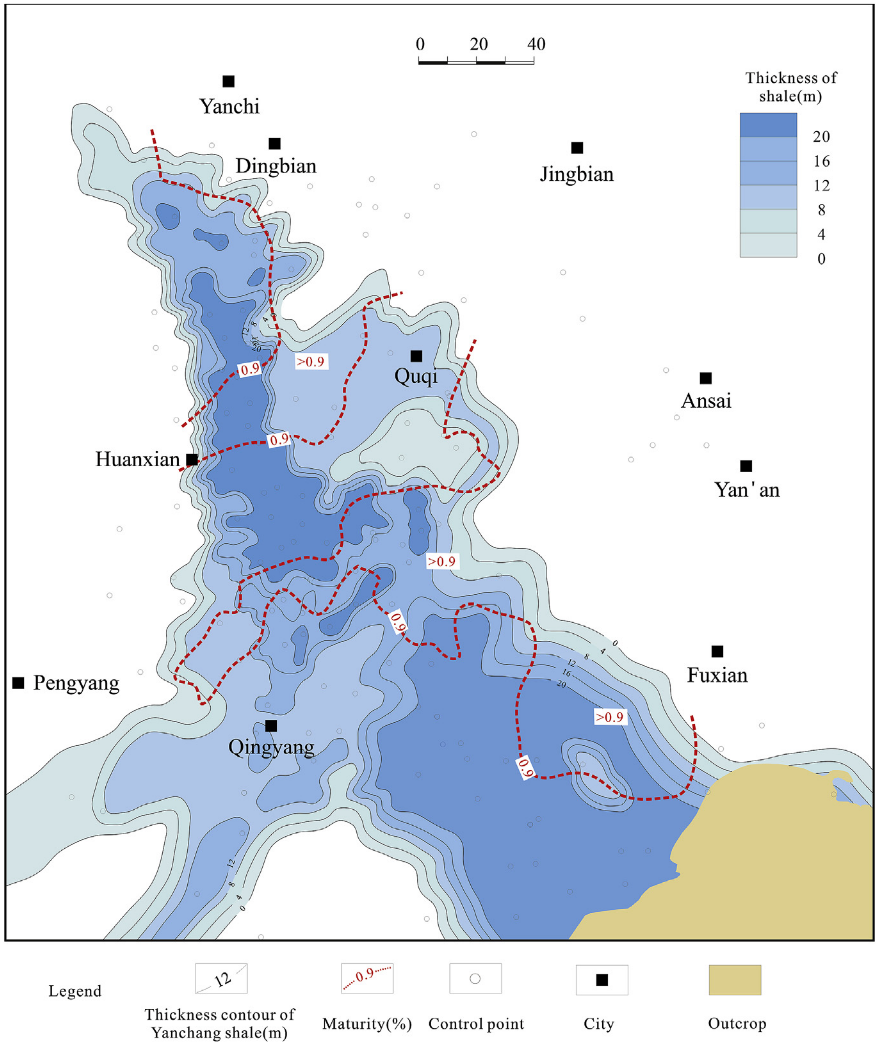

Fig. 5. Overlay of the shale thickness and vitrinite reflectance of the Triassic Yanchang Formation in Ordos basin, China.

crude oil has an average density of 0.8971 g/cm3 and an average viscosity of 165.2 mPa s at 50 °C, indicating a low to medium thermal evolution and poor flow capacity in the reservoir. There are abundant shale oil resources in the Lucaogou Formation in the Jimusar sag. P_2l_5 and P_2l_2 are "sweet sections", and the "sweet areas" are mainly distributed in the middle of the sag (Figs. 10 and 11).

In addition, the Paleogene section in the Bohai Bay Basin contains world-class oil shale layers, of which the shales in the upper Fourth Member and the lower Third Member of the Shahejie Formation, and Second Member of the Kongdian Formation have favorable geological conditions. In previous drilling and recent shale oil exploration activities, plentiful hydrocarbon shows and productivity have been obtained from these members where 1400 × 10^8 tons of hydrocarbons have been effectively generated. The upper Fourth Member and the lower Third Member of the Shahejie Formation are dominated by organic-rich, laminate lime mudstone or argillaceous limestone, with a large cumulative thickness (400–1500 m), high TOC (between 1% and 6%, with an average above 3%) and good kerogen (mainly types I-II_1). According to the discovered shale oil, a large amount of free oil exists in the organic-rich, laminate shale with the R_o of more than 0.8%. It may be the main target for the development of shale oil in this basin.

4. The development potential of shale oil

The resource potential of shale oil is mainly determined by the amount of retained hydrocarbons that have not yet been discharged. Under current economic and technological conditions, medium to high mature and organic-rich shale formations are ideal targets for shale oil exploration and development. According to the thermal evolution model of the continental type I kerogen, the amount of retained hydrocarbons in medium to high mature organic-rich shale (0.9% < Ro < 1.3%) can reach 20%–50%. In these shale formations, pores are well developed, and the content of light oil and condensate oil is high with a high gas-to-oil ratio. As a result, the formation energy and the fluid flowing capability are strong. According to the author's research on the hydrocarbon generation potential of source rocks in major basins of China, combined with the results of China's third round hydrocarbon resources evaluation and relevant studies, this paper evaluates the resource potential of shale oil in major continental basins in China (Table 2). The oil generated in continental shale formations in China is approximately 5722 × 10^8 tons, and the retained hydrocarbon is approximately 3702 × 10^8 tons; these retained oil recourses are shale oil. However, due to the limitation of available technologies, only 2%–5% of the shale oil may be produced (Table 2). Since 2010, inspired by "the unconventional oil and gas revolution" in North America, Changqing, Daqing, Shengli, Dagang and other oil companies in China have continued to develop key technologies such as predictive technology for "sweet areas (sections)", as well as develop cost reduction and stimulation technologies for well drilling and completion. At the same time, development pilots were conducted in porous shale

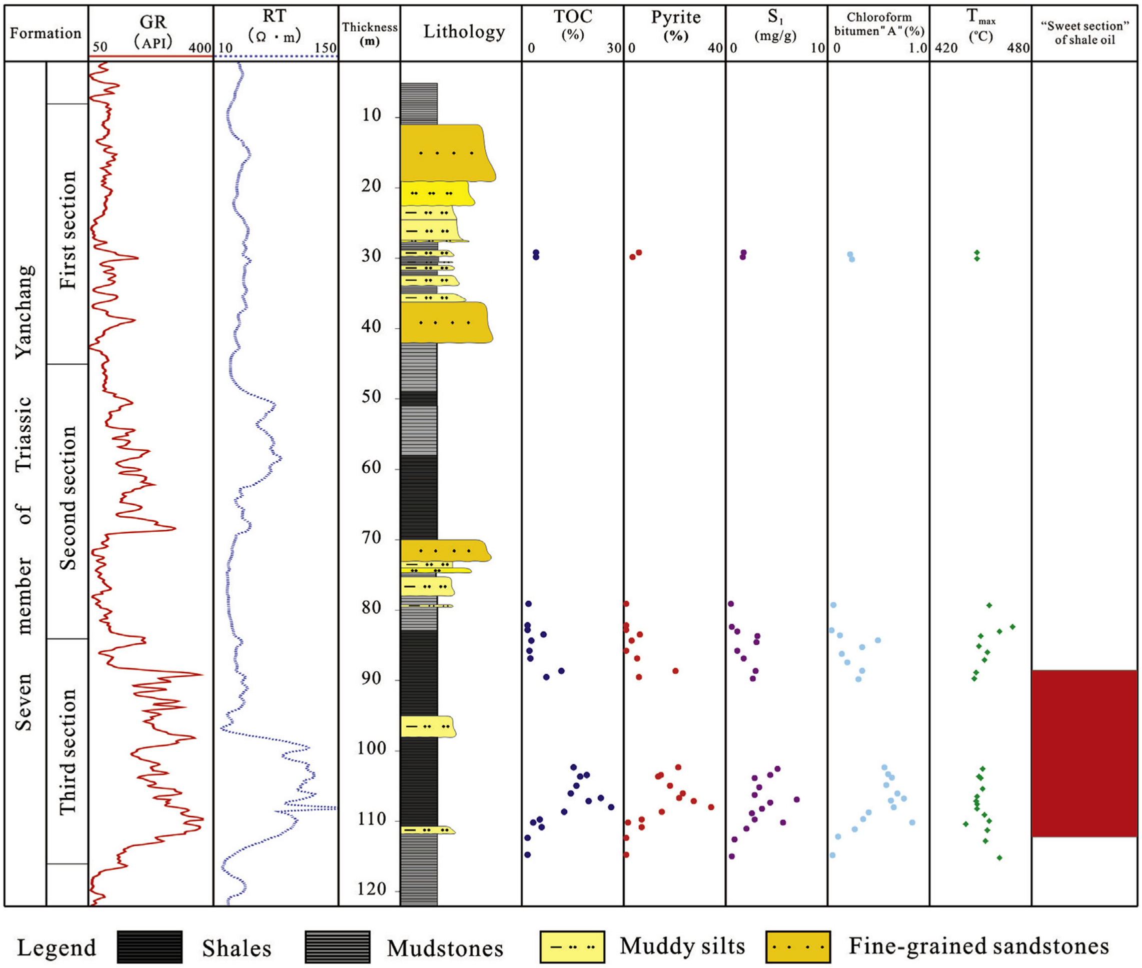

Fig. 6. Geochemical depth profile of Triassic Yanchang Formation lacustrine shale in Ordos basin, China.

formations with medium to high maturity. As a result, progress has been made in multiple shale formations. Industrial oil flow has been achieved at the Kong 2 Member shale when two wells in the Cangdong Depression of the Bohai Bay Basin were tested. Additionally, industrial oil flows have been archived in 8 wells drilled in the Seventh Member of the Triassic Yanchang Formation in the Ordos Basin, as well as 2 wells drilled in the First Section of the Qingshankou Formation in the Gulong depression of the Songliao Basin; 8 vertical wells and 4 horizontal wells that were drilled in the Jiyang depression delivered industrial oil flows or good shows, while good hydrocarbon shows were found in the Qianjiang Formation in the Jianghan Basin. Porous shales show resource potential, but the single well output is low and technologies for stable production are still in development.

The oil resources in medium-to-low mature shales are also very abundant. According to the thermal evolution model of continental type I kerogen, the amount of retained hydrocarbons in medium to low mature organic-rich shale (0.5% < Ro < 0.9%) can reach 40%–60%, and the percent of unconverted organic matter can reach 40%–100%.

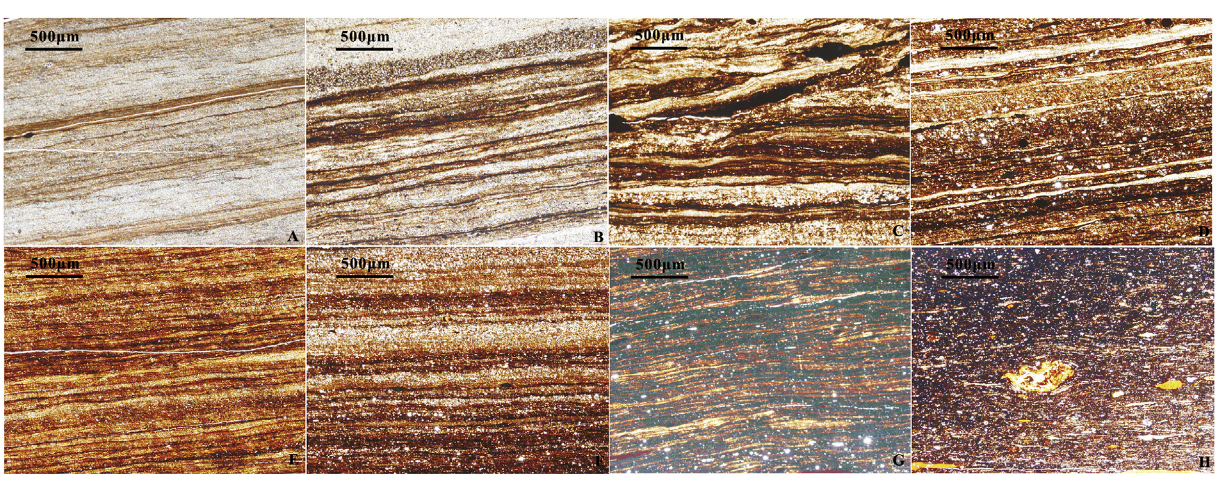

Fig. 7. Microscopic photos under polarized light of lamina and organic matter in the Triassic Yanchang Formation in the Ordos Basin.

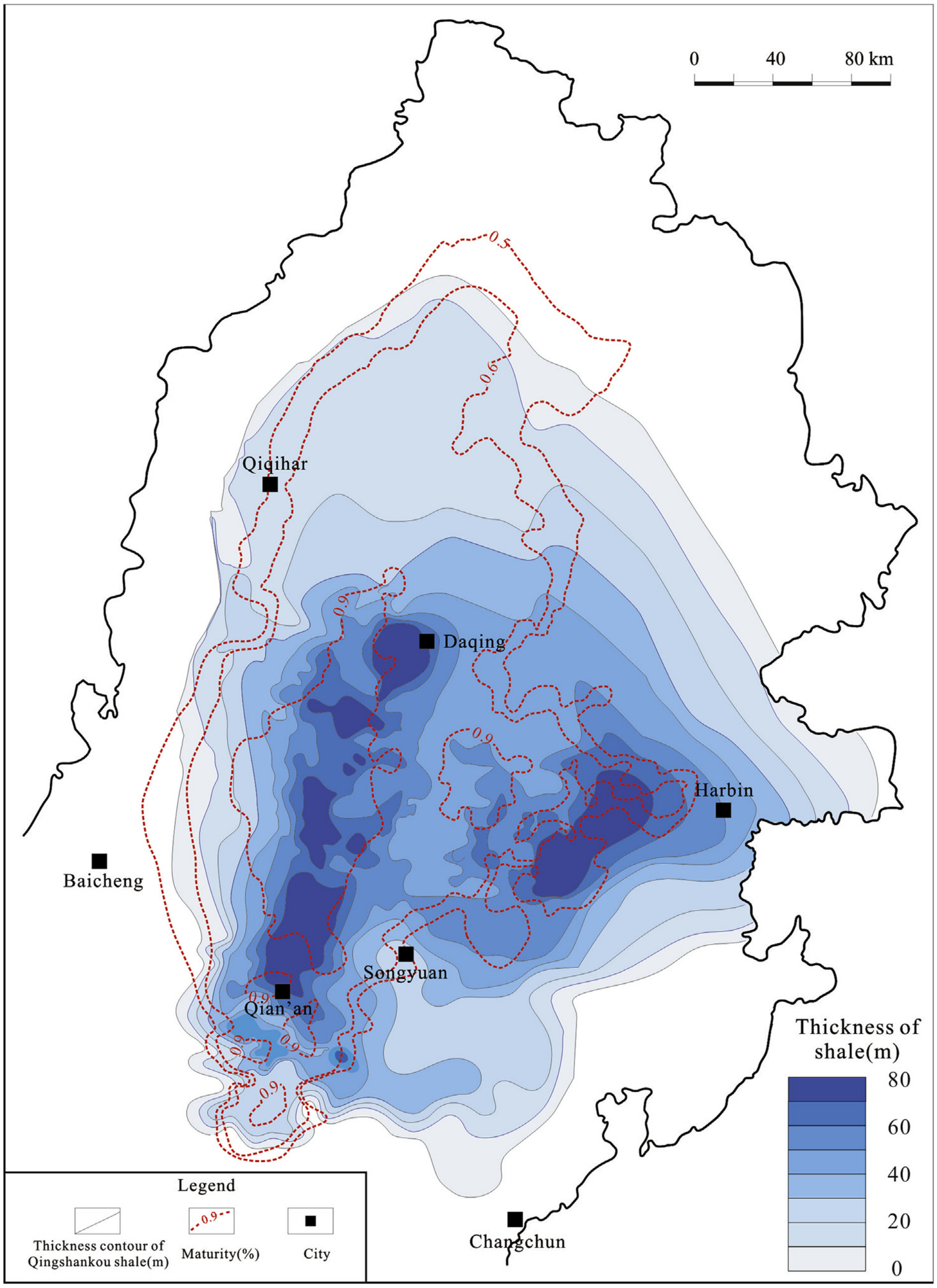

Fig. 8. Overlay of the shale thickness and vitrinite reflectance of the Cretaceous Qingshankou Formation in the Songliao basin, China.

Theoretically, through large-scale in situ volumetric heating conversion and efficient coverage of the shale system, heavy oil, bitumen and various organics in organic-rich shale formations can be converted into light oil and condensate oil on a large scale. During this process, a new underground natural fracture system, overpressure and gas would create a new, effective, artificial displacement system, and ultimately high-quality oil products can be obtained. Through in situ heating and conversion of shale oil, the "above-ground refinery" model with high energy consumption and high pollution can be transformed to the "underground refinery" model with high quality and cleanliness. Since 2015, in situ conversion technology and field pilot tests have been conducted in the Qingshankou Formation in the Songliao Basin. Through international cooperation, core analysis and field tests, the lower limit for in situ conversion tests has been demonstrated. Using combustion fracturing, retorting and critical water, etc., a small amount of artificial shale oil has been obtained in the field tests. Recently, in the Seventh Member of Triassic Yanchang Formation shale in the Ordos Basin, the Research Institute of Petroleum Exploration and Development (RIPED) conducted a comprehensive analysis of sealed coring to carry out a feasibility study of in situ conversion. RIPED proposed an efficient conversion technology of using underground "electric heating in horizontal wells" to achieve the development and utilization of shale oil resources. According to the preliminary evaluation, the potential for in situ conversion of shale oil in China is very large, and the amount of technically recoverable oil is about (400–500) $\times 10^8$ tons.

Based on basic geological conditions applicable for electric heating technology in horizontal wells and in situ conversion process (ICP), key geological parameters that include the thickness, organic matter abundance, thermal evolution level and buried depth of the Seventh Member of Triassic Yanchang Formation shale in the Ordos Basin were comprehensively considered. The scale, maximum burial depth and

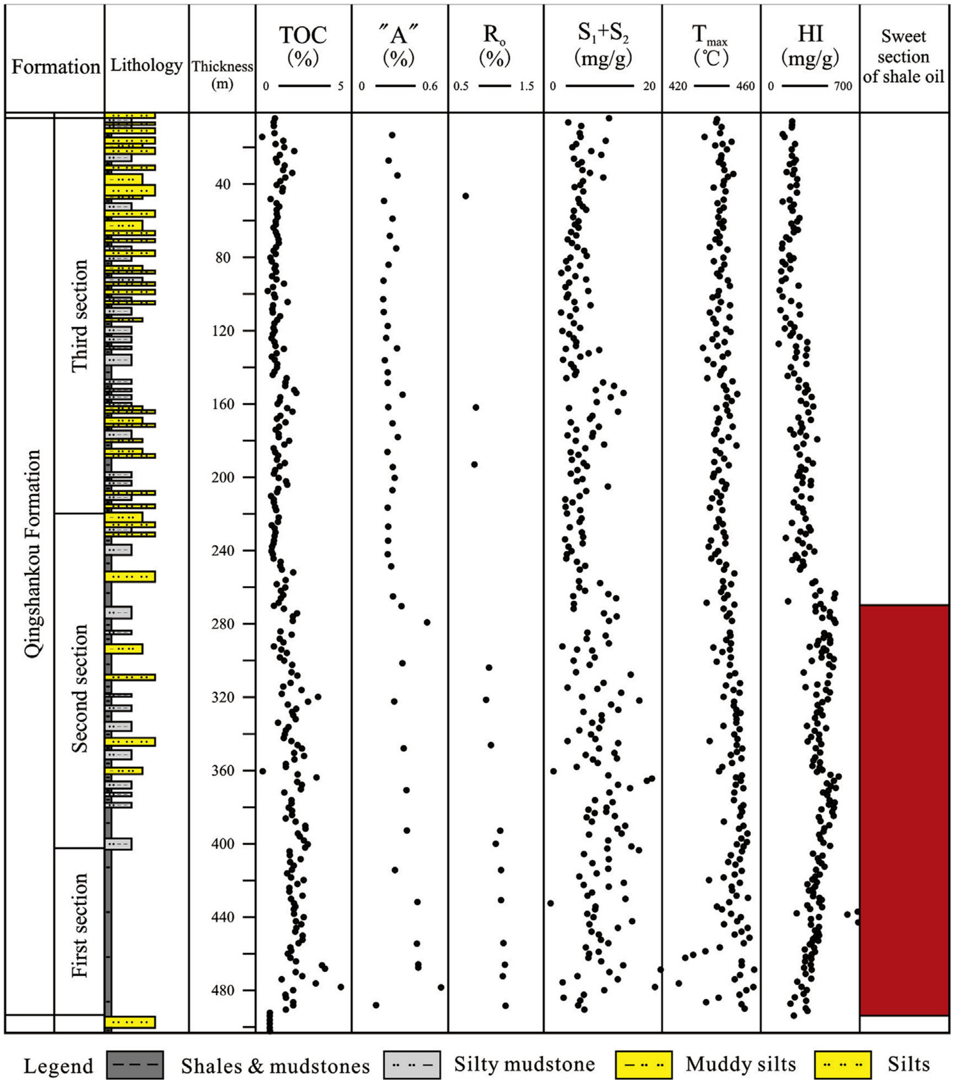

Fig. 9. Geochemical depth profile of Cretaceous Qingshankou Formation lacustrine shale in the Songliao basin, China.

present depth of the organic-rich shale are the three key parameters proposed for the selection of favorable pilot zones. The favorable pilot zones are mainly distributed in the southeast of the basin, which is structurally located in the southern part of the Yishan slope and the northern part of the Weihe graben (Fig. 12). The distribution area is approximately 1.2×10^4 km^2 (more than 50% of the area has a buried depth of less than 1500 m) (Fig. 12). In the favorable pilot zones, the maximum buried depth of the Seventh Member of the Triassic Yanchang Formation shale is generally shallower than 2600 m (with a corresponding R_o of less than 0.8%), the thickness × TOC of shale is greater than 100 m × %, and the current depth of the shale bottom is mainly from 700 to 1700 m. In addition, the zones have convenient infrastructures such as drilling, ground facilities, traffic communication, and transportation pipeline network.

Artificial technical intervention is needed to achieve effective development and utilization of shale oil resources for medium to high mature shale or medium to low mature shale. Therefore, the notation of "man-made reservoir" for shale formations is proposed in this paper, wherein the overall industrial output of "sweet areas (sections)" is set up by using technologies such as an artificial horizontal well, volume fracturing and in situ heating conversion and an underground fracture network with "man-made permeability" is constructed (Fig. 13). At present, the research and exploration of continental shale oil has just started all over the world. There is no consensus on whether oil existing in continental shale or mudstone can be produced on a large scale.

How to quickly overcome the technical difficulties in continental shale oil exploitation and convert shale oil resources with great potential into production is a long-term goal for oil exploration and development. Continental shale oil is the oil resource that has the greatest developmental technological challenges. Adhering to the persistent exploration of "man-made reservoir", continental shale oil may be another revolution of unconventional oil and is expected to be the first successful unconventional oil that is developed in China.

5. Conclusions

(1) Based on a systematic study of the geological characteristics of shale oil in major continental basins in China, the geological notation of "sweet areas (sections)" in shale oil is proposed in this paper. The formation conditions and distribution characteristics of continental shale oil in China are analyzed, and with a focus on geological properties, the "sweet areas" of shale oil with medium to high maturation are determined to be mainly at thick shale zones with Ro greater than 0.9%, and the "sweet sections" are mainly in the middle and lower parts of the shale formation. The geological resources of continental shale oil in the major continental basins in China are estimated to be approximately 3700×10^8 tons.

(2) In situ conversion process (ICP) may be a key technology for the

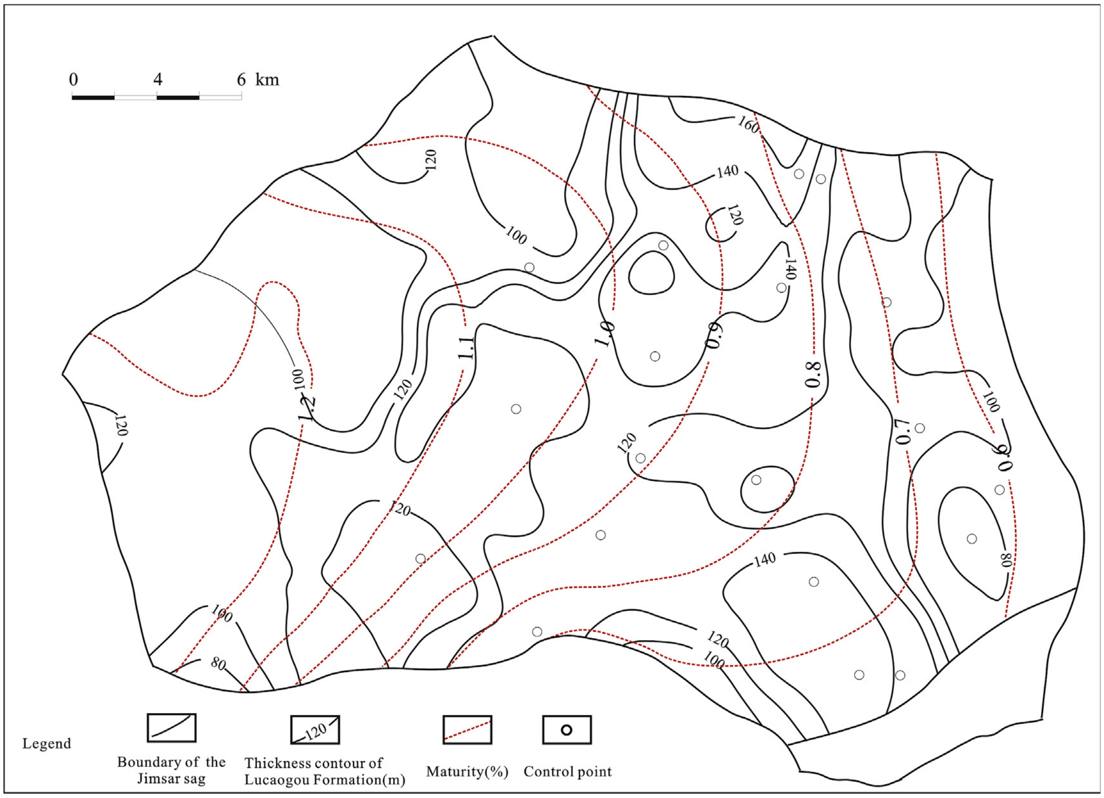

Fig. 10. Overlay of the shale thickness and vitrinite reflectance of the Permian Lucaogou Formation in the Jimsar Sag, Junggar basin, China.

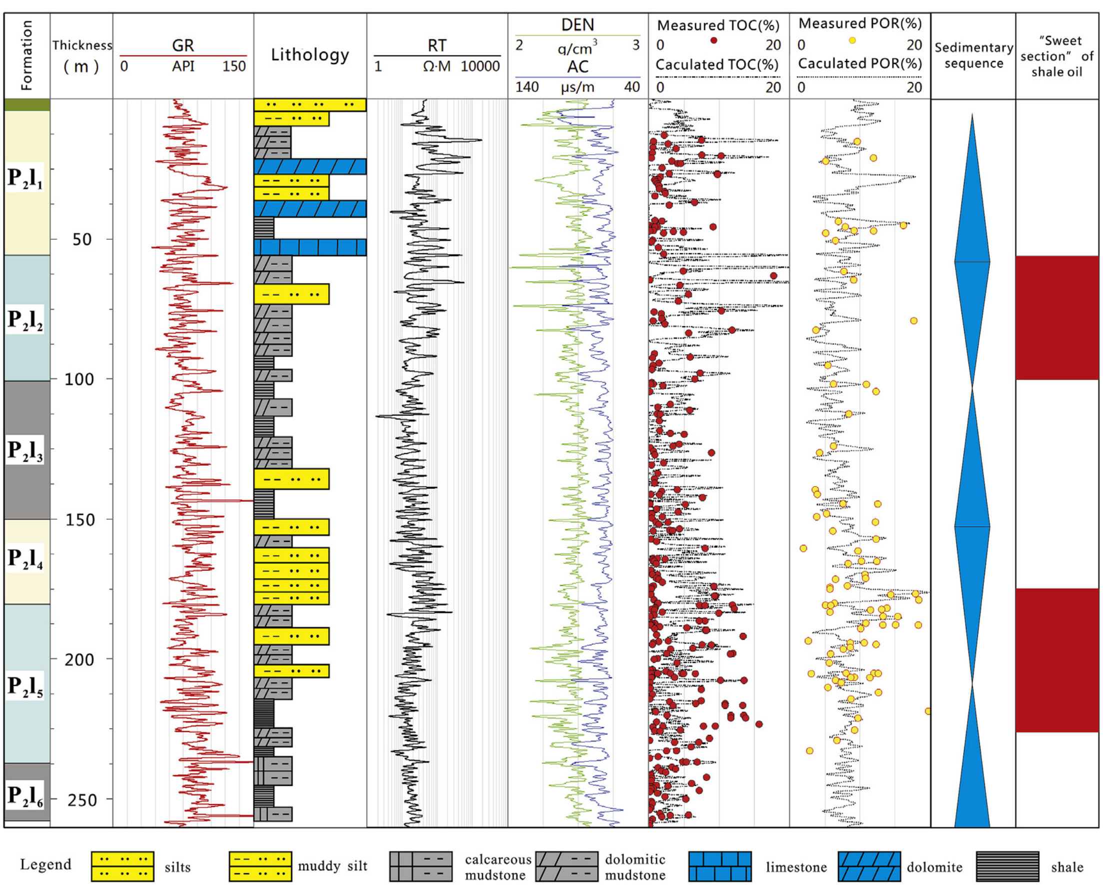

Fig. 11. Stratigraphic histogram of the Permian Lucaogou Formation lacustrine shale in the Junggar basin, China.

Table 2
Lacustrine shale oil resource potential evaluation of the main basins in China.

Basin	Formation	Oil generation	Oil expulsion	Oil detention	Shale oil recoverable (10^8 t)		
		(10^8t)	(10^8t)	(10^8t)	2%	5%	10%
Songliao	Cretaceous	1100	400	700	14	35	70
Bohai Bay	Paleogene	1400	500	900	18	45	90
Ordos	Triassic	1300	450	750	15	38	75
Junggar	Permian	800	250	550	11	28	55
Sichuan	Jurassic	300	100	200	4	10	20
Qaidam	Paleogene, Neogene	300	100	200	4	10	20
Erlian	Cretaceous	200	50	150	3	8	15
Santanghu	Permian	45	15	30	1	2	3
Jiuquan	Cretaceous	50	15	35	1	2	4
Nanxiang	Paleogene	30	12	18	0	1	2
Subei	Paleogene	115	17	98	2	5	10
Jianghan	Paleogene	82	11	71	1	4	7
Total		5722	1920	3702	74	185	370

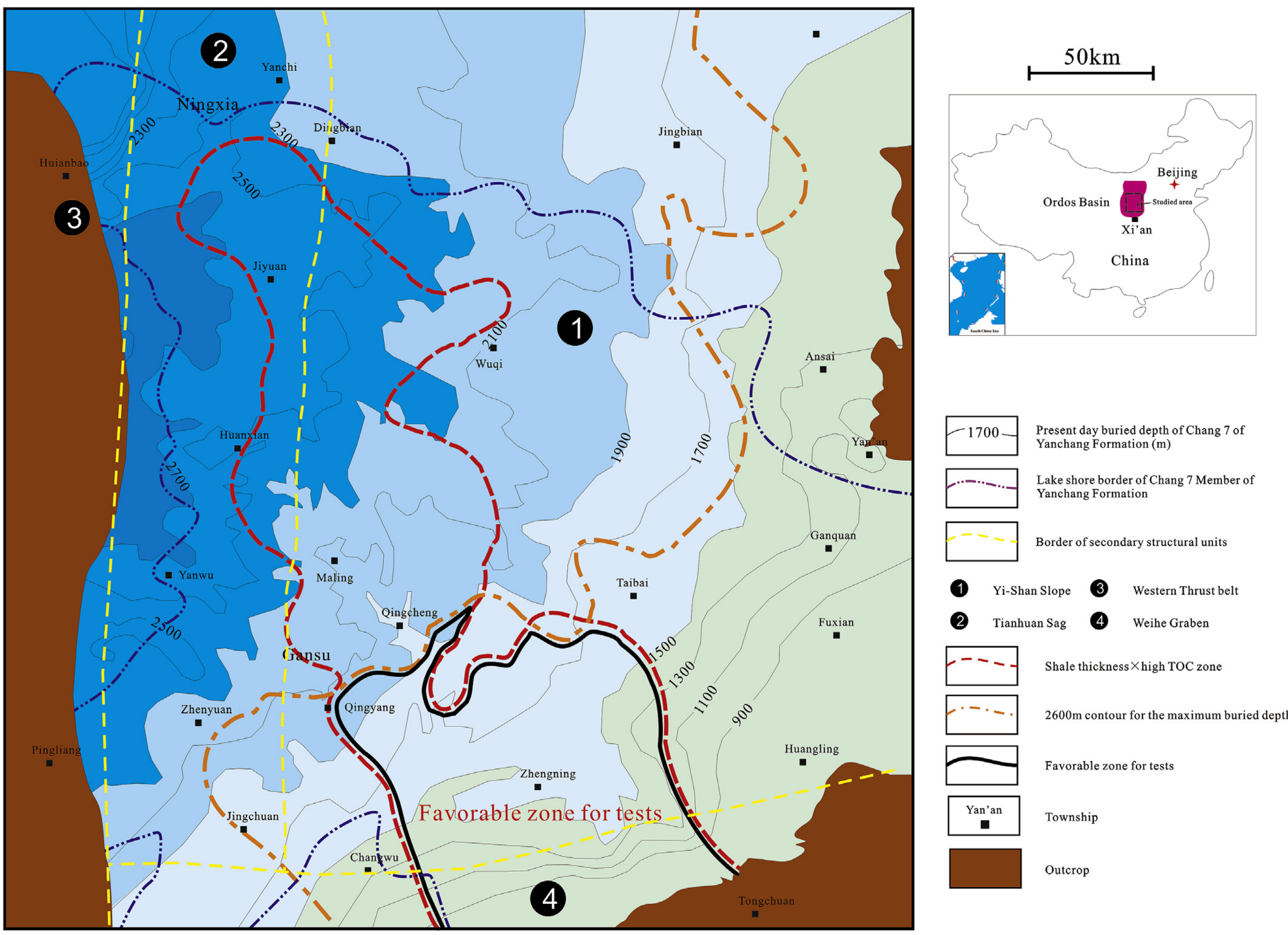

Fig. 12. Comprehensive evaluation of the favorable pilot area for the Triassic Yanchang Formation shale in Ordos basin in China using ICP technology.

effective development of medium-to- low-mature shale oil. The scale, maximum burial depth and present depth of organic-rich shale are the three key parameters proposed for the selection of pilot zones by taking the Triassic Yanchang Formation in the Ordos Basin as an example. It is expected that the recoverable resources of China's continental shale oil using ICP will be approximately (400–500) × 10^8 tons. The notation of "man-made reservoir" is proposed in this paper, wherein the overall industrial output of "sweet areas (sections)" will be produced by artificial intervention and the construction of underground fracture networks with "man-made permeability".

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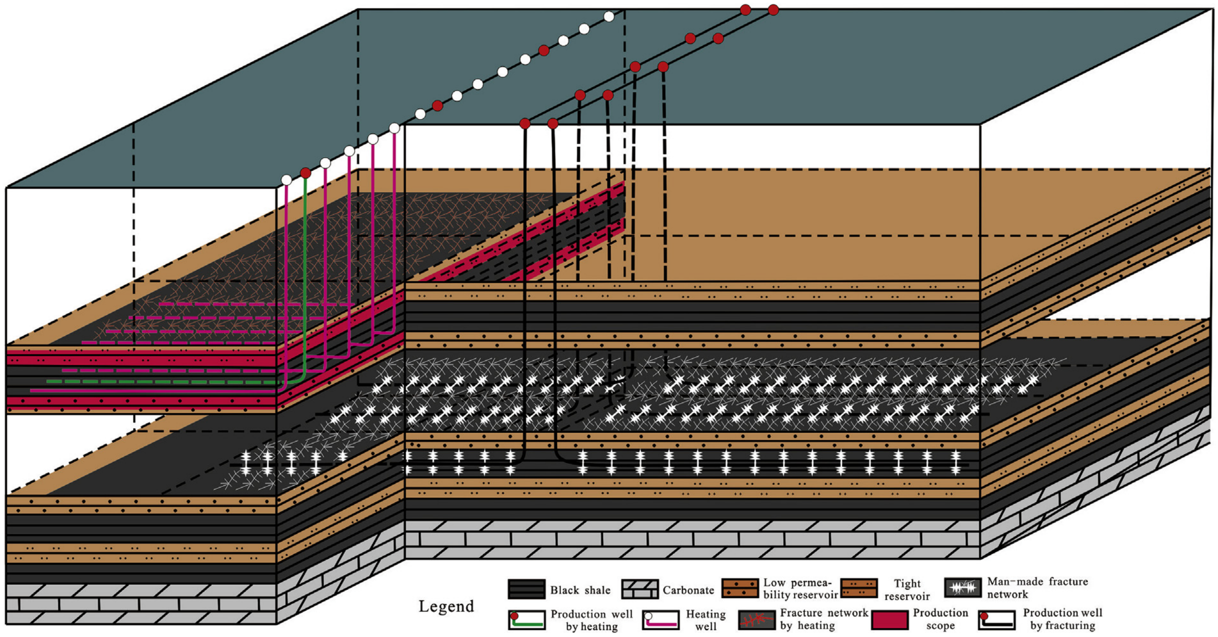

Fig. 13. “Man-made shale oil reservoir” exploitation model.

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