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Perspective

Characteristics, current exploration practices, and prospects of continental shale oil in China

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Abstract:
Oil generation in the continental shale has laid the resource foundation for the originality and development of China's petroleum industry; continental shale oil production is blazing a new trail in this field. In this paper, based on the geological conditions of continental shale oil in China, it is found that the main types of shale oil generally have four basic geological characteristics, which are large-scale continuous distribution, the domination of inorganic pores, the enrichment of "sweet areas", and initial production that is controlled by relatively high organic maturity and high yield that is governed by relatively high formation pressure. Then, as examples for the geological characteristics and development practice of continental shale oil, four key areas of Longdong, Gulong, Jimsar, and Jiyang are systematically summarized. Finally, the future prospects of continental shale oil in China are put forward. Middle-high maturity shale oil is currently the main force of development, and middle-low maturity shale oil also has a considerable development prospect after technological improvement. Meanwhile, "sweet area/spot sections" assessment and technological innovation are still research areas to be improved.

1. Introduction

During the history of China's petroleum industry exploration practices during the last 100 years, it has been proved that the onshore stratum is always the main body of resources and the principal base of exploration and development (Zou et al., 2019). With the recent trend from conventional to unconventional oil, and from outside to inside sources during exploration (Yang et al., 2015; Yu et al., 2022), continental shale oil is becoming a strategic replacement for the petroleum industry, which has been on the agenda for exploration and development. Based on the research level and the frequency of exploration activities, in light of the full investigation of exploration and development of continental shale oil, as well as the latest advances (Jin et al., 2021), this paper takes the Yanchang Formation in Ordos Basin, Qingshankou Formation in Songliao Basin, Lucaogou Formation in Junggar Basin, and Shahejie Formation in Bohai Bay Basin (Fig. 1) as the main study subjects to systematically analyze and summarize the basic geological features of continental shale oil as a hydrocarbon source. Moreover, we aim to elucidate the details of the distribution area, reservoir space, enrichment of "sweet spots" and control factors of production. Solutions to existing problems are also proposed, and the future development of continental shale oil is forecasted (Zhao et al., 2020).

2. Characteristics

2.1 Concept

According to the geological evaluation methods for shale oil (GB/T 38718-2020), issued by the Standardization Administration of the People's Republic of China, shale oil is a kind of oil that accumulates in organic-rich shale source rock strata whose single-layer thickness of siltstone, fine sandstone, and carbonate rocks is less than 5 m, and their cumulative thickness accounts for less than 30% of the total formation. Despite its potential, it can neither produce oil naturally, nor meet the lower limit of industrial production, and the latter requires special technical measures to accomplish.

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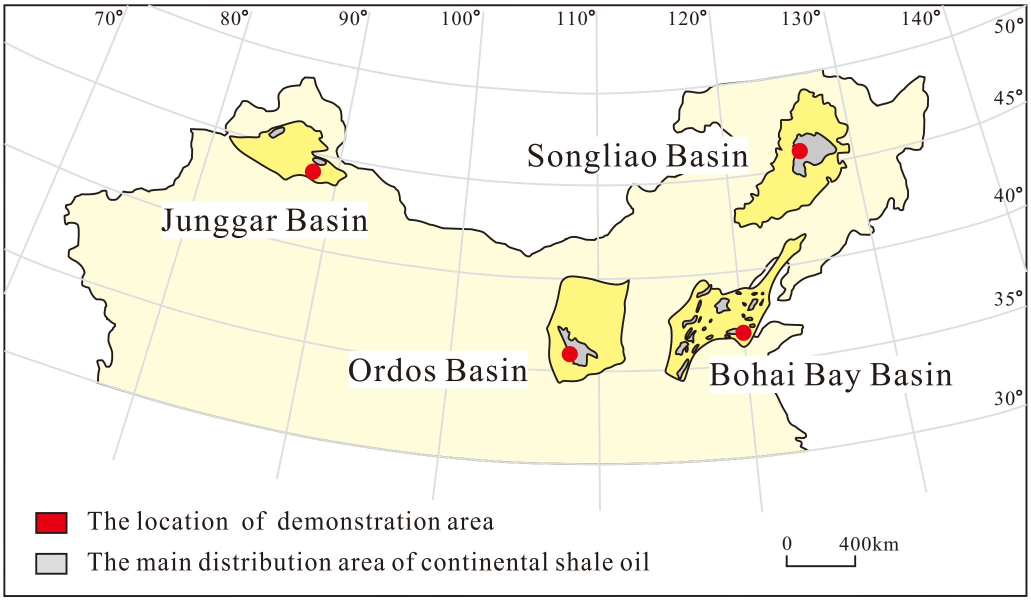

Fig. 1. Plane distribution map of continental shale oil in four basins (modified from Jiao et al., 2020).

2.2 Main types

Depending on the maturity level, continental shale oil can be divided into middle-low maturity shale oil and middle-high maturity shale oil (Zhao et al., 2020). The latter is currently the main object of exploration and development, which is characterized by lighter crude and higher steam-oil ratio, better fluidity, and higher ratio of movable oil. Furthermore, it can allow for industrial production by hydraulic fracturing (Du et al., 2019; Jiao et al., 2020). According to the source-reservoir assemblage, middle-high maturity shale oil has three main types: self-sourced type, separate source-reservoir type, and pure shale type. Meanwhile, based on the “sweet areas” of continental shale reservoirs, it can be divided into interlayer type, diamictite type, and shale type (Table 1).

2.3 Basic characteristics

Continental shale oil has certain limiting features due to many factors such as complex sedimentary environment, severe tectonic movements, frequent changes of facies, multiple organic matter types, lower organic maturity, more crude weight, lower steam-oil ratio, poor fluidity, abundant lithology, higher clay content, smaller “sweet areas”, and poorer continuity of distribution. Taking into account these special geological conditions, as well as the existing technologies, there are four essential characteristics of continental shale oil that provide the key and direction for its effective development on a massive scale, such as:

1) Large-area continuous distribution of continental shale oil resources. Their depositions of these resources consistently occurred in the lacustrine basin, which has a wide range as a result of the lacustrine transgressive process. Member 7 of the Yanchang Formation (Chang 7 Member), Qingcheng, Ordos basin, was at its maximum flooding stage during the late Triassic. The Chang 7 Member has an area of 6.5×10^4 km^2 from semi-deep lake to deep lake, black shale covers an area of 4.3×10^4 km^2 and the area of dark mudstone is 6.2×10^4 km^2. Besides, the area of profitable exploration is 3.6×10^4 km^2 (Fu et al., 2020). Member 1 of the Qingshankou Formation (Qing 1 Member), Songliao Basin, which was also deposited in the transgressive environment, covers an area of 5×10^4 km^2 from semi-deep lake to deep lake, and the area of middle-high maturity continental shale oil is 1.37×10^4 km^2 (Jin et al., 2022). The Jimsar Sag in the eastern Junggar Basin with an area of 1278 km^2 is nearly covered by the Lucaogou Formation, which is a set of sediments from semi-deep lake to deep lake deposited in saline lacustrine environments, and has a reservoir with good lateral continuity. The area of beneficial exploration is almost 1,000 km^2 (Jin et al., 2022). The Shahejie Formation in the Jiyang Depression, whose sedimentary circumstances are similar to the Lucaogou Formation, covers an area of 7,300 km^2 of the advantageous source rock in the Paleogene layer (Liu et al., 2022).
2) A high abundance of micro-scale and nano-scale inorganic pores in felsic and dolomitic minerals, and the general scarcity of organic-matter pores. The shale stratum of Chang 7 Member largely consists of mud shale and silty shale, and its storage space is dominated by intergranular pores of felsic minerals and intercrystalline pores of clay minerals. The pore throat diameter of its black shale is 60~220 nm, while that of its dark mudstone is 20~100 nm (Zheng et al., 2022). Dolomitic siltstone, silty dolomite, and shale are prevailing in the Lucaogou Formation, whose storage area consists mainly of dissolved pores, intergranular pores, intercrystalline pores, and microcracks. Micro-scale and nano-scale dissolved pores comprise a distinct majority, with more than 80% in the reservoir (Hou et al., 2021). The Shahejie Formation

Table 1. Types of middle-high maturity continental shale oil in China.

Source-reservoir assemblage	Example	"Sweet spot" type	
Self-sourced type	Lucaogou Fm., Jimsar Sag, Junggar Basin	Sandy dolomitic	Diamictite
	Kong 2 Mem., Kongdian Fm., Cangdong Sag, Bohai Bay Basin	Dolomitic	
	Da'anzhai Fm., Sichuan Basin	Limy type	
Separate source-reservoir type	Chang 7_{1+2} Mem., Yanchang Fm., Ordos Basin	Sandstone	Interlayer
	Qing 1 and Qing 2 Mem., Qingshankou Fm., Songliao Basin		
Pure shale type	Chang 7_3 Mem., Yanchang Fm., Ordos Basin	Foliage	Shale
	Qing 2 Mem., Qingshankou Fm., Songliao Basin	Lamination	

Notes: Fm, Formation; Mem, Member.

Table 2. Characteristics of typical continental shale oil cases in China.

Name	Depth (m)	Thickness (m)	TOC (%)	R_o (%)	Type of organic matter	Steam oil ratio (m^3/m^3)	Possible reserves (10^8 t)
Chang 7 Mem., Yanchang Fm., Ordos Basin	1,600~2,200	Back shale: 16 m Duck mud: 17 m	6~16 2~6	0.9~1.2	I and II_1 II_1 and II_2	0.80~0.86	10.52
Qingshankou Fm., Songliao Basin	1,750~2,600	30~70	0.5~10	1.0~2.0	I and II_1	0.79~0.83	12.68
Lucaogou Fm., Jimsar Sag, Junggar Basin	800~4,500	$P_2l_1 > 100$ m $P_2l_2 > 50$ m	> 4	0.6~1.1	I and II_1	0.88~0.93	1.53
Shahejie Fm., Jiyang Depression, Bohai Bay Basin	3,000~5,300	Upper E_2s_4: 250~300 m Lower E_2s_3: 150~450 m	2~6	0.6~1.8	I and II_1	0.73~0.94	10

Notes: P_2l_1 is Member 1 of Lucaogou Formation, P_2l_2 is Member 2 of Lucaogou Formation (Permian); E_2s_4 is Member 4 of Shahejie Formation, E_2s_3 is Member 3 of Shahejie Formation (Paleogene).

is mostly composed of sparry/cryptocrystalline marl and lime mudstone, and the reservoir space always consists of nano-scale intergranular pores, dissolved pores, intercrystalline pores, and occasionally organic-matter pores. The average pore throat diameter is 28~560 nm (Hu et al., 2021). The Qing 1 Member, which is mostly shale, siltstone, dolomite, and lime, has a reservoir featuring not only intergranular pores, intercrystalline pores, and dissolved pores, but also organic-matter pores and organic-matter fractures (Liu et al., 2020).

3) The enrichment of "sweet areas/sections" in those regions, which are assembled from both shales with higher maturity and reservoirs with higher porosity (Table 2). The Chang 7 Member is a set of thick shale layers with some thin fine siltstone interlayers. Its vitrinite reflectance (R_o) is 0.9%~1.2%, while the average T_{max} is 447 °C, and these parameters show that the source rocks reach the oil generation peak. In addition, the "sweet area" of shale reservoirs, namely self-sourced type, and pure shale type, can be found in the lower part of Chang 7 Member (Fu et al., 2020). The lithology of the Lucaogou Formation varies frequently in the vertical dimension, and the black-gray mudstone is interbedded with fine-grained dolomite. Its R_o value is 0.6%~1.1%. The upper "sweet area" is composed of feldspar-debris fine siltstone with a porosity of 14%~16%, and the lower area is dolomitic siltstone with 13%~15% porosity (Zhang et al., 2021).

4) Initial production depends on high free hydrocarbon content and steam-oil ratio, and the high yield is controlled by natural fractures and abnormal pressure. The free hydrocarbon content of Qing 1 Member appears pretty high, and the S_1 value of the layered shale is up to 8 mg/g, which is 6 mg/g for the laminate one; it is up to 2 mg/g as a whole, and the area with S_1 higher than 4 mg/g is about 6,700 km^2. The steam-oil ratio of Qing 1 Member is 70~400 m^3/m^3, and the highest value is 500 m^3/m^3. The lamellation fracture in the stratum is excellent, with nearly 780~3,000 fractures within 1 meter. These easily extend and break in the foliation and bedding plane, where the hydraulic fractures can create branches and construct an intricate network of fractures. In this district, the formation pressure coefficient is gen-

erally more than 1.2 (covering an area of about 4,550 km^2), with its extreme at 1.58 (Bi et al., 2021; Jin et al., 2022). The Guye 1 well, for instance, has much higher free hydrocarbon content (about 6∼12 mg/g), and testing oil production can be up to 30.5 m^3, while that of gas is 13,032 m^3 per day. At present, this well is still in the stage of self-injection trial production. The steam-oil ratio varies greatly between different subsags in the Jiyang Depression, and the highest ones are in Bonan Subsag at around 606∼1,063 m^3/m^3. The free hydrocarbon content of Bonan Subsag is generally within 2∼4 mg/g, and sometimes the highest value can exceed 4 mg/g. Multi-scale faults ranging from level 3 to level 5 are very common in the Bonan Subsag, and the fault area of the lower Member 3 of Shahejie Formation accounts for about 3/5 of these. The Jiyang Depression has sufficient formation energy, and the formation pressure coefficient of Bonan Subsag is 1.2∼1.8. The Yiyeping 1 well in Bonan Subsag has achieved a great breakthrough in technology and productivity of shale oil within the Jiyang Depression, with a peak daily oil production of 103 t and cumulative oil production of 5,203 t.

3. practice of key zones

It can be easily found that, in the last 10 years, the areas that have been frequently explored are those with the active application of new technologies, such as volume fracturing. This is to obtain more oil resources from the enriched organic polyporous shale reservoirs, which has led to important breakthroughs in a multiple-shale stratum (Jiao et al., 2020; Li et al., 2021; Wang et al., 2022). Moreover, it assists with the successful transformation from oil shale and fractured shale reservoir to a mature matrix-type (Zhao et al., 2020). For this process, there are many great large-scale reserves in the Ordos Basin (Fu et al., 2021; Li et al., 2022), Songliao Basin (Jin et al., 2022), Sichuan Basin, and Junggar Basin (Jin et al., 2022), as well as some national shale oil demonstration areas that are being built in Longdong, Gulong, Jimsar, and Jiyang (Qiao et al., 2022).

3.1 Longdong, Ordos Basin

It was in 2011 when the first exploration took place in Longdong. In the beginning, the premier target was the excellent sandstone in the shale stratum of the central lake basin, and the key aim was the assessment of research based on geological targets and the increase of output per well. The area has experienced exploration, testing, and demonstration periods, during which 3 remarkable pilot sites, X 233, Zh 183, and N 89 were established in Qingcheng, Gansu Province. The 25 horizontal wells had an average daily oil production of 12.5 t per well in the earlier period, which is currently 5.4 t, showing the true capacity of stable production. Since 2018, by integrating and innovating crucial technologies of exploration and development, these wells have achieved large-scale exploration and cost-effective production. In 2021, the accumulative proved reserve was 10.52×10^8 t, and the annual output was 123×10^4 t. Besides, a giant shale oilfield of 1 billion tons was discovered in Qingcheng (Fu et al., 2021).

3.2 Gulong, Songliao Basin

Gulong Sag has seen 40 years of exploration with an extensive history of discoveries, studies, and breakthroughs. In 2011, the research object of shale oil changed, expanding from shale fractured reservoir to interbed type and interlayer type. In 2018, oil testing achieved great advances. By choosing 18 vertical wells, including Guye 1, Ying X57, and Chao 21, an abundance of oil was discovered from the lower part of Qing 2 Member to the whole Qing 1 Member. What is intriguing is that the Qing 1 Member was exactly a light crude type. In "sweet areas", some horizontal wells achieved a brilliant output of 30.5 t oil as well as 13,032 m^3 gas per day, which is regarded as outstanding performance for a pure shale reservoir. The new potential reserves of Qing 1 Member are expected to increase by 12.68×10^8 t (Jin et al., 2022).

3.3 Jimsar, Junggar Basin

The exploration of the Lucaogou Formation began in 2010. In the early days, it was easy to notice good hydrocarbon shows, but oil production was unsatisfactory by conventional means. Until 2011, owing to separate-layer fracturing, a profitable oil flow could be seen in the Ji 25 well, hence the movements of Lucaogou Formation exploration were fully active. Based on systematic studies and tests on the upper and lower "sweet areas" featured by silicic and dolomitic minerals, the shale stratum in the Lucaogou Formation is individualized for the self-sourced reservoir, features superposed thin reservoirs and massive thickness, is filled with oil entirely, and is continuously distributed. The resource controlled by the exploratory well is 11.12×10^8 t. Since 2017, it has gradually formed a production procedure defined by small well space, long-distance horizontal well, and enormous fragments. In January 2020, a permission was granted to establish the Jimsar national continental shale oil demonstration area, whose confirmed reserve reaches 1.53×10^8 t, while the oil output was 42×10^4 t in 2021 (Hou et al., 2021).

3.4 Jiyang, Bohai bay Basin

In 2006, shale oil was explored in the Paleogene stratum of the Jiyang Depression, and it subsequently experienced encountering explorations, positive tests, and key experimental periods. The pace of research and explorations of shale oil have accelerated since 2016, and it was recognized that shale oil in the Jiyang Depression has many attributes, such as continuous accumulation and local enrichment, which also prove its great resource potential. Based on the optimal geological conditions, such as thick source rock, great resource abundance, massive natural fractures, super reservoir pressure, and easy fracturing, a new sequence of basic geological research and technological pilot tests were formulated for this area. In more than 20 straight deviated wells located at enriched organic shale layers, by using a set of fracturing technologies, almost 90% of wells enabled more than 1,000 t of oil production, which can be seen as a triumph for shale exploration in the Jiyang Depression. Since 2019, the explored targets have transformed from fractured reservoir to matrix-type, and from $R_o > 0.9\%$ to $R_o < 0.9\%$. In the shale layers of the lower Member 3 and upper Member 4 of Shahejie Formation, in Boxing Subsag and Niuzhuang Subsag (Dongying Sag), and Bonan Subsag (Zhanhua Sag), 5 horizontal exclusive explored wells have been drilled, which provided a peak output of more than 100 t per day, showing the excellent prospect of the enriched organic laminated limestone-dominated shale with different maturities in the Jiyang Depression (Liu et al., 2022).

4. Prospects

Continental shale oil is a crucial alternative resource for China's oil security. In 2021, the country's oil dependency was about 73%. There will be no better time either at present or in the near future to attempt to realize the remote possibility of the remaining 2×10^8 t oil output. Therefore, the exploration and development of shale oil are extremely urgent. China as a country with a major continental shale oil resource possesses 90% of the total land oil resource. It is also a major oil-producing country, with 93% of total oil production only in 2021. It is easy to see that continental shale oil is the major hope to exploit the remaining oil resources in China; it is not sustainable to copy the strategy of the U.S., and large-scale exploration and profitable development can only be realized by China.

Organic maturity plays a critical role in controlling the accumulation and distribution of shale oil. Based on this factor, shale oil can be divided into middle-high maturity shale oil ($R_o > 1.0\%$) and middle-low maturity shale oil ($R_o < 1.0\%$). The geological characteristics of these two types are quite different, so it is necessary to fully consider and study the influence and weight of source rock properties and reservoir properties on shale oil. Middle-high maturity shale oil, which has massive liquid hydrocarbon maintained in the shale, is featured by lighter crude, higher steam-oil ratio, and optimal reservoir pressure. Some of the reservoirs that are located in the central lacustrine basin are felsic and dolomitic reservoirs with good reservoir properties and great oil-holding ability, and they can produce most oil remaining in the shale layer by hydraulic fracturing, such as Gulong shale oil. Middle-low maturity shale oil, whose remaining hydrocarbon is up to 25% and the ratio of unconverted organic materials is 40%~90%, presents certain characteristics of higher-weight crude, smaller steam-oil ratio, and inferior reservoir pressure. The in-situ conversion processing of shale oil underground may be the best technique for its development at a large scale. As for the "sweet area" assessment of continental shale stratum liquid hydrocarbon, there should be a deep understanding of the diverse tectonic evolution cycles, varied lithology, and strong heterogeneity (Yang et al., 2019). Besides, it is essential to perform some enhanced evaluations of the fine-grained sedimentary model and profitable sedimentary microfacies, the reservoir multi-scale characterization and effective storage space, the occurrence of liquid hydrocarbon and oil-bearing properties, the petrophysical response mechanism and geophysical prediction, the simulation of fracture extension in horizontal wells, the fusion quality assessment of "geology-engineering-economic sweet areas", and so on. Beyond these fields of advanced research, it is also crucial to improve technologies of in-situ conversion processing and gas injection, as well as to develop new technologies using multiple perspectives for further evaluation.

5. Conclusions

In general, continental shale oil in China has four basic characteristics: large-area continuous distribution, inorganic pores as the main pore type, enrichment of "sweet spot sections", and high-pressure control of initial production and high yield. In addition, there are some recently developed national demonstration plots in Longdong, Gulong, Jimsar, and Jiyang, where masses of oil resources were found. Given this background, the appropriate utilization of hydrocarbon source rock properties and reservoir properties of onshore shale formations, as well as the continuous development of applicable theoretical technologies are conducive to promoting onshore shale oil as a strategic field of advanced oil exploration.

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Conflict of interest

The authors declare no competing interest.

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