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Characteristics of Jurassic Source Rocks and Evaluation of Hydrocarbon Resources in Tarim Basin, western China

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ABSTRACT

Jurassic strata in Tarim are significant for their hydrocarbon-rich content. However, the distribution of hydrocarbon source rocks in this region is uneven, and the conditions for hydrocarbon accumulation vary significantly among the different structural elements. Therefore, it is essential to investigate the distribution of Jurassic source rocks, the evolution history of hydrocarbon generation, and the mechanisms influencing hydrocarbon accumulation for effective hydrocarbon exploration and development. To achieve this, seismic, geologic, drilling, logging, and testing data were integrated to analyze the distribution and quality of hydrocarbon source rocks, the evolution of hydrocarbon generation, and the factors influencing hydrocarbon accumulation in Jurassic hydrocarbon source rocks in Tarim Basin. The study revealed that the Jurassic effective hydrocarbon source rock centers are mainly located in the piedmont areas of Kuqa depression, southwest depression, and southeast depression, as well as Yingjisu sag and Manjiaer sag in the eastern Tarim area. Based on a comprehensive evaluation and comparison of the potential of Jurassic hydrocarbon potential in each secondary structural unit, it is concluded that Kuqa Depression has the most favorable exploration zone due to its excellent hydrocarbon accumulation conditions and abundant hydrocarbon resources. Although the overall exploration potential of the southwest depression is lower than that of the Kuqa depression, the hydrocarbon resources potential of the piedmont thrust belt and the associated depression is very high. Similarly, the eastern part of the Manjiaer sag and the Altun piedmont zone of the southeastern depression still have promising exploration prospects, although the overall exploration potential of the eastern Tarim area and the southeastern depression is not as good as the former two.

KEYWORDS

Tarim Basin; Jurassic; Hydrocarbon source rocks; Hydrocarbon accumulation.

1. INTRODUCTION

Many hydrocarbon-rich basins are developed in the western China, including Tarim, Junggar, Qaidam and Tuha basins. Tarim Basin, the largest basin in China, contains coal-bearing strata in the Jurassic period that are rich in oil and gas resources and are a key target for hydrocarbon exploration and development[1]. Many hydrocarbon fields related to Jurassic hydrocarbon source rocks have already been discovered in Tarim Basin[2-6].

The enrichment of hydrocarbon resources is closely related to hydrocarbon source conditions, and the distribution of Jurassic source rocks in Tarim Basin is uneven, with thick deposits mainly found in depression areas surrounding the basin. The Kuqa and Southwest Depressions are particularly promising areas for hydrocarbon exploration and development, with extensive research focusing on the distribution of source rocks, geochemical characteristics, hydrocarbon accumulation evolution, and resource evaluation. In contrast, the Southeast Depression and Eastern Tarim area have received less attention and have relatively low exploration degrees and slower research progress[7-9].

Combined with previous studies, in addition to the national hydrocarbon resource evaluation, it is believed that the relevant research in the Tarim Basin is mostly focused on a single structural unit. There are relatively few studies on the evaluation of hydrocarbon source rocks and hydrocarbon enrichment and accumulation at the whole basin scale, which leads to the unclear understanding of the difference of hydrocarbon source conditions among the Jurassic structural units in the Tarim Basin, and the lack of comprehensive analysis of hydrocarbon generation and expulsion and thermal evolution process of source rocks in each depression and intuitive comparison of hydrocarbon enrichment in each region. The guidance of hydrocarbon exploration strategy selection in the Tarim Basin is limited. Therefore, this study aims to explore the quality, distribution, thermal evolution, and hydrocarbon generation history of Jurassic hydrocarbon source rocks in various hydrocarbon-generating depressions in Tarim Basin using drilling, logging, seismic, and geochemical test data. By visually showing differences in hydrocarbon source conditions among different tectonic units, the study also evaluates hydrocarbon resources using genetic methods and clarifies the factors influencing hydrocarbon enrichment. Ultimately, this research aims to establish the dominant sequence of favorable exploration zones in Tarim Basin, providing theoretical support for the development and exploration of hydrocarbon resources.

2. GEOLOGICAL SETTING

The Tarim Basin, situated in the Xinjiang Uygur Autonomous Region, is the largest inland intermountain basin in China[10]. It is surrounded by the Kunlun Mountains, Tianshan Mountains, and Altun Mountains (Fig.1) and covers a total area of 56×104km2 [11] . The basin comprises 7 first-order tectonic units and 22 second-order tectonic units, with Fig.1 depicting only the second-order units relevant to this study. The Jurassic residual strata in the Kelasu thrust belt of the Kuqa depression are the thickest, reaching up to 2500 m, and gradually thinning towards the piedmont of the southern Tianshan Mountains[12]. The southeast depression and the eastern Tarim area are about 1500 m thick, while the northern Tarim uplift is thin[13].

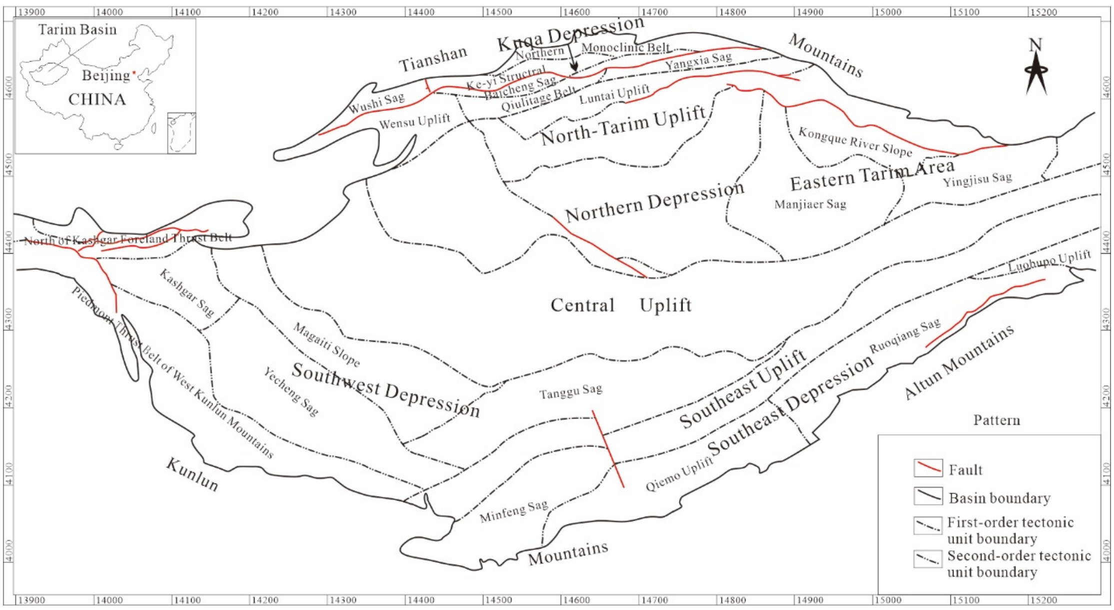

Figure 1. Geographical location and tectonic division map of Tarim Basin

The Jurassic-Paleogene is the development and demise stage of the Neo-Tethys Ocean.In the early-Middle Jurassic, the South Tianshan fold-up belt began to suffer strong denudation. Under the background of regional weak extension, with the possible thermal subsidence and stress relaxation after the orogenic period and the influence of gravity balance, the joint part of Tarim Basin and orogenic belt is in the structural weak zone, which forms many faulted lacustrine basins, including Kuqa, southwestern and southeastern Tarim fault basins and eastern Tarim depression. In the late Jurassic, due to the dry and hot climate, the basin gradually narrowed and these faulted depressions gradually evolved into depressions. The main Jurassic strata in the basin are mostly distributed in these depression areas.

The Jurassic strata in the Tarim Basin are unevenly distributed[14,15]. The strata in the Kuqa Depression are extremely thick, generally showing the characteristics of thick in the south and thin in the north. It is a lacustrine bog facies coal-bearing clastic rock deposit. The Jurassic strata in the depression overlap above the Triassic strata, and each set of strata in the Jurassic system overlap upwards. From bottom to top, they are the Lower Jurassic Ahe Formation and Yangxia Formation, the Middle Jurassic Kezilenur Formation and Qiakemake Formation, and the Upper Jurassic Qigu Formation and Kalazha Formation[16]. The Jurassic strata in the southwestern Tarim Basin are mainly distributed in the piedmont areas of the South Tianshan Mountains and the West Kunlun Mountains. From bottom to top, the Lower Jurassic Shalitashi Formation and Kangsu Formation are developed, the Middle Jurassic, Yangye Formation and Taerga Formation and the Upper Jurassic Kuzigongsu are developed. The Jurassic strata in the southwest depression can be divided into two parts. The Lower Jurassic-Lower Middle Jurassic is mainly dark gray coal-bearing strata, while the Upper Middle Jurassic-Upper Jurassic develops dark red and variegated strata. The Jurassic strata in the southeastern depression are derived from the East Kunlun Mountains, mainly distributed in the eastern Ruoqiang sag and the western Minfeng sag. Because of the limitation of boundary structure, the stratigraphic distribution of Minfeng sag is small. The Jurassic strata are widely developed in the Ruoqiang Sag, which develop two sedimentary center in the southern piedmont and is distributed like a NEE-trending belt. The overall thickness of the Jurassic strata is gradually thinning and pinching out to the interior of the basin. The thickness gradually increases in the Altun piedmont area, only missing in the western part of the Qiemo uplift. The Jurassic in the eastern Tarim area is a set of fluvial-lacustrine facies coal-bearing clastic deposits. There are two sedimentary thickness centers in the eastern margin of Manjiaer Depression and Yingjisu Depression. The Jurassic strata are not completely covered, and the strata gradually overlap and pinch out from north to south. The strata from bottom to top are the Lower Jurassic Kangsu Formation and the Middle Jurassic Yangye Formation and Taerga. Lack of upper Jurassic strata[17].

3. RESULT

3.1. Hydrocarbon geochemistry characteristics

3.1.1. Organic matter abundance

Based on the geochemical analysis presented in Table 1, it appears that the Kuqa Depression contains a generally good abundance of organic matter in its source rocks, with the highest concentration found in the Kuche Depression. While some of the dark mudstones meet the general standards for hydrocarbon source rocks, others only meet the standard for organic carbon content but have lower hydrocarbon-generating potential. Carbonaceous mudstones mostly meet the standards for good hydrocarbon source rocks in terms of organic carbon content, but only reach the general hydrocarbon source rock standards for generating potential. Coal in the area meets the standards for good to high-quality hydrocarbon source rocks. In the southwestern depression, most hydrocarbon source rocks meet the general standards, with only a small portion meeting the standards for good hydrocarbon source rocks. In the southeastern depression, while the organic matter content is relatively high, the hydrocarbon-generating potential and hydrogen index are lower. Most of these rocks meet the general standards, with a few able to meet the standards for good hydrocarbon source rocks. In the Tadong area, the dark mudstones mostly meet the general standards, while the carbonaceous mudstones and coal mostly meet the standards for good hydrocarbon source rocks, with very few reaching the high-quality hydrocarbon source rock standards.

Table 1. Main pyrolysis parameters of organic matter of source rocks with different lithology in some areas of Tarim Basin.

Area	lithology	layer	TOC%	S1+S2（mg/g）	IH (mg/g)
Kuqa depression	dark mudstone	J_2q,J_2kz,J_1y	0.04~9.39 / 2.84	0.01~27.48 / 3.74	4.17~408.10 / 94.47
	carbon mudstone	J_2kz, J_1y	3.13~21.45 / 14.71	2.21~62.83 / 22.53	18.37~539.96 / 140.93
	coal		12.61~95.07 / 47.1	8.1~187.3 / 65.58	18.40~853.46 / 165.96
southwest depression	dark mudstone	J_1K, J_2y	0.03~6.0 / 1.88	0.02~23.21 / 1.42	0.8~213.0 / 47.51
	carbon mudstone		2.07~20.76 / 9.66	0.09~28.42 / 6.98	4.0~258.1 / 28.6
	coal	J_1K	0.1~12.6 / 2.12	0.2~23.2 / 4.89	41.1~296.0 / 48.0
southeast depression	dark mudstone	J_1k, J_2y	0.41~5.23 / 2.92	0.06~6.90 / 3.02	9.79~170.02 / 81.74
	carbon mudstone		0.62~39.66 / 18.18	0.07~52.30 / 18.08	57.56~175.94 / 104.36
	coal	J_2y	16.43~70.21 / 45.80	4.77~108.12 / 54.39	67.84~310.68 / 164.85
Eastern Tarim area	dark mudstone	J_2kz, J_1y	0.03~6.01 / 1.88	0.1~9.15 / 1.92	100.1~200.0 / 109.5
	carbon mudstone		2.23~56.48 / 14.04	5.3~75.4 / 32.08	144.0~543.1 / 187.9
	coal		29.32~114.72 / 50.95	14.62~191.5 / 72.82	156.3~743.1 / 365.7

Note : The numerical expression in the table is $\frac{\text{min}\sim\text{max}}{\text{average}}$

3.1.2. Organic matter type

The type of organic matter present in source rocks is crucial to the amount and types of hydrocarbons generated. Biomarker characteristics can be used to explore oil and gas sources as well as sedimentary environments, indicating the type of organic matter. In the Jurassic source rocks of the Kuqa Depression, tricyclic terpanes with low carbon numbers are dominant, particularly C19 tricyclic terpane, which shows a decreasing trend in C19, C20, and C21. The relative content of C24 tetracyclic terpane is high, while the hopane content is much higher than the sterane, and the relative content of gammacerane is very low. The sterane distribution is dominated by C29 sterane, indicating a terrigenous hydrocarbon source. In the Southwest depression, the relative percentages of C27 sterane and C29 sterane in the source rock are not significantly different, suggesting a mixed origin of low-grade aquatic and high-grade terrestrial organic matter. In the Southeast depression, the relative content of regular C29 sterane is high, indicating a hydrocarbon source primarily derived from higher terrestrial plants, with humus-type organic matter being the main type. In the Tarim Basin, the coal-bearing dark shale is mainly of type II2-III organic matter, biased towards a gas-prone type, while the lacustrine shale has more characteristics of type II2 source, with a strong oil-generating ability. The coal-bearing mudstone is mostly type III organic matter, biased towards a gas-prone type, but with some oil-generating ability. Coal generally has type III organic matter and is a good source of gas but has a poor oil-generating ability. Based on the HI-Tmax diagram, the source rocks in the main hydrocarbon-generating areas are mainly of type II2-III organic matter. These biomarker characteristics provide important information for exploring oil and gas sources and sedimentary environments in these areas.

3.1.3. Maturity of organic matter

Based on the Ro distribution analysis of Jurassic strata in the Tarim Basin, it can be observed that most of the Kuche Depression in the basin has high maturity, with a vitrinite reflectance of around 1.5~2.7% in the Baicheng Depression and the northern tectonic belt. This suggests that the area is in the mature-overmature stage. However, most of the other areas are in the low-maturity-maturity stage. In the southwestern depression, the vitrinite reflectance is 1.0~2.5%, and the source rocks have reached maturity stage in the Kunlun Mountain foreland and the northwestern piedmont thrust belt. In areas with higher burial depths, the source rocks have reached the over maturity stage. The central parts of the Kashgar Depression and the Yecheng Depression can reach the high-maturity-overmaturity stage. The distribution of source rock thickness and high maturity value areas in the depression are mainly associated with the nearby piedmont thrust belt. The mudstone and coal-bearing source rock belts with high maturity and thickness are mainly distributed in the Kuzigongsu fault depression, the southwestern part of the Qimugen arcuate uplift in the Kunlun Mountain foreland thrust belt, and the Kekeya area. These areas have enormous oil and gas generating capacities and are important oil and gas resources for the region. Overall, the Ro value in the eastern part of the eastern Tarim area ranges from 0.3~0.6%, with the maximum vitrinite reflectance in the buried deeper part of the Manjiaer Depression reaching the low maturity stage.

4. DISCUSSION

4.1. Favorable area evaluation of prospective resources

After conducting a zoning evaluation of the Tarim Basin, three favorable zones for hydrocarbon generation were identified and sorted by geological scores.

The Kuqa Depression was found to have high-quality mature source rocks with a high organic matter abundance and large thickness, making it the most enriched area for oil and gas resources in the Tarim Basin. As a result, it is comprehensively evaluated as a Class I favorable zone. The Southwest Depression has limited distribution of Jurassic source rocks, but the piedmont thrust belt in the West Kunlun Mountains has a relatively large thickness, and most of the source rocks are generally of good quality. The amount of oil and gas resources is second only to the Kuqa Depression, making it a Class II favorable zone.

The exploration potential of the eastern Tarim area and the southeast depression is not as good as that of the Kuqa Depression and the Southwest Depression, and is comprehensively evaluated as a Class III favorable zone. The Tadong area has high organic matter abundance but generally low maturity, resulting in poor hydrocarbon generation capacity. However, the eastern part of the Manjiaer sag has a large buried depth, making it a favorable oil and gas accumulation zone in the area with high potential for hydrocarbon generation.

The Jurassic Yangye-Kangsu Formation in the southeastern depression has hydrocarbon source rocks that are generally of good quality, but most of them are shallowly buried and are still in the immature-low mature stage, which means they cannot generate oil and gas at this point. However, the source rocks of the Yangye Formation in the piedmont area of the Altun Mountain in the Qiang Sag have the potential to generate oil and gas if they are deeply buried, and this area is considered a favorable zone for oil and gas accumulation in the southeastern depression.

5. CONCLUSIONS

(1) The primary thickness centers of the Jurassic effective source rocks in the Kuqa, Southwest, and Southeast Depressions are located mainly in the piedmont zone of the basin margin. In the Tadong area, two sedimentary centers have developed in the Manjiaer and Yingjisu Depressions. The source rocks in the Kuqa and Southwest Depressions have attained a relatively high level of maturity, with the majority having reached the mature stage. Conversely, most of the source rocks in the Southeast Depression and Tadong area are in the immature stage, and only those located in areas with deep burial have reached the low mature stage.

(2) In the Tarim Basin, the development of Jurassic source rocks is primarily controlled by the sedimentary environment and tectonic framework, with lacustrine environments being the primary location of development. Stable subsidence conditions play a crucial role in controlling the hydrocarbon generation and thermal evolution of the source rocks in these areas, making them the primary source rocks of the Jurassic in the Tarim Basin. The generation of oil and gas resources is strongly influenced by the hydrocarbon source conditions of the basin, while the quality of the reservoir-cap assemblage is a key factor in determining the enrichment horizon of oil and gas resources. Additionally, faults, serving as source channels, play a significant role in the migration, accumulation, and preservation of oil and gas.

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