Source rock characteristics and sedimentary environment analysis of Lucaogou Formation in the eastern Jimusaer Sag, Junggar Basin

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Abstract. In recent years, shale oil has gradually become the focus of oil exploration. The source rocks of Lucaogou Formation in the east of Jimusaer Sag of the Junggar basin have great shale oil potential. However, there is still much controversy regarding the sedimentary environment of the source rocks which restrict shale oil exploration. In order to address this problem, 45 mudstone samples of Jx-1 well are selected for testing and analysis. The results show that the Permian Lucaogou Formation in the Jimusaer Sag is developed with high quality source rocks, and the organic matter type is mainly type II, and the source rocks are in mature stage. Both higher terrestrial plants and aquatic algae are important sources of organic matter in source rocks, but the source of organic matter is still dominated by lower aquatic organisms. The source rocks of Lucaogou Formation are mainly deposited in reducing environment, and the water salinity is high, which is conducive to the preservation of organic matter.

1. Introduction

In recent years, unconventional oil and gas such as shale oil have gradually become the focus of oil and gas exploration. The Permian Lucaogou Formation in the Jimusaer sag of the Junggar basin has obtained industrial oil flow in well J25, well J23, and well J171, showing a good prospect for shale oil exploration and development. Previous studies have shown that the source rocks of Lucaogou Formation are of high quality with total organic carbon (TOC) content as high as 10% (average > 3%), kerogen is mainly type II, vitrinite reflectance (R₀) is 0.76% - 0.96%[1-2]. However, due to the lack of a complete stratigraphic profile, there are still controversy about the sedimentary environment of the source rocks of Lucaogou Formation. Some scholars believe that the source rocks of Lucaogou Formation were deposited in the environment of weak reduction and relatively low salinity[2], while others believe that the source rocks of Lucaogou Formation were deposited in the conditions of weak oxidation -weak reduction and fresh water brackish water[3]or brine and reduction conditions[1]. Due to the lack of understanding of the sedimentary environment of Lucaogou Formation source rocks, the evaluation of the quality and distribution of source rocks in Jimusaer Sag is greatly restricted, and the exploration and development process of shale oil in Junggar basin is affected.

Therefore, through systematic core observation, rock pyrolysis, gas chromatography-mass spectrometry (GC-MS), gas chromatography (GC) and other experimental techniques, the organic matter characteristics and sedimentary environment background of Lucaogou Formation are also discussed in this paper. In addition, this study can enrich the understanding of the sedimentary background of Lucaogou Formation, and provide basis for further exploration and development of
shale oil and evaluation of oil and gas resources in the Jimusaer Sag of the Junggar Basin.

2. Geological setting

Jimusaer Sag is located in the eastern uplift of Junggar basin, with an area of about 1300km². It is a dustpan like depression with deep west and shallow East (Figure 1). From Permian, Junggar Basin mainly experienced rift-fault basin stage, followed by Triassic-Jurassic fault depression basin stage, Cretaceous-Paleogene intracontinental depression basin stage and Neogene-Quaternary regeneration foreland basin stage[1-3]. The Paleozoic (Carboniferous, Permian), Mesozoic (Triassic, Jurassic, Cretaceous), Cenozoic (Paleogene, Neogene, Quaternary) strata are relatively developed in the sag, and the thickness of the strata is also large (the maximum thickness can reach 5200m).

The Lucaogou Formation belongs to Permian strata, which is one of the important oil-bearing series in the Junggar Basin. The Lucaogou Formation covers an area of about 1278km²[1-3]. The Lucaogou Formation in the depression is mainly developed in the inland lake environment, mainly composed of semi deep sea and deep sea sediments, mainly developed mudstone, siltstone and dolomite, with the sediments thickness of 100-400m (average 280m).

3. Samples and methods

A total of 45 dark mudstone samples of well Jx-1 of the Lucaogou Formation in the Jimusaer depression were selected and analyzed, and the core wells penetrated the whole Lucaogou Formation. The experimental study includes total organic carbon (TOC) analysis, rock pyrolysis analysis, gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS) analysis, and the specific operation methods are as follows.

The TOC content of the samples was measured by a vario MICRO element analyzer (Elementar). To analyse the TOC content of the samples, they were first ground to 200 mesh and then reacted with 5% hydrochloric acid. After standing for 24 hours, the residues were neutralized using deionized water, and then dried at 60 °C for 72 h prior to analysis. Rock-Eval pyrolysis was carried out by using a Rock-Eval II instrument. The free hydrocarbon (S1) released at 300 °C and the cracking hydrocarbon (S2) produced during the gradual heating process from 300 °C to 600 °C, and the maximum pyrolysis peak temperature (Tmax) were measured.

The saturated hydrocarbons were analyzed by gas chromatographic (GC) using a PerkinElmer Clarus 500 chromatograph (HP-5MS fused silica column, 60 m × 0.25 mm × 0.25 µm) equipped with a flame ionisation detector (FID). The saturated hydrocarbons were analyzed by GC-MS on a PerkinElmer Clarus 500 gas chromatograph coupled with PerkinElmer Clarus 500 mass spectrometer, equipped with an Agilent HP-5MS fused silica column (60 m × 0.25 mm × 0.25 µm). The initial
temperature of the oven was 70 °C (constant temperature for 5 minutes), which was heated to 300 °C at 3 °C/min, and then a constant temperature for 30 minutes.

4. Results and discussion

4.1. Organic matter enrichment

The TOC content of the mudstone in the Lucaogou Formation ranges from 0.16% to 8.62%, with an average value of 2.2%. The distribution range is mainly 0.6% to 2%, accounting for 91%, which reflects that the source rocks in the study area have good hydrocarbon generation capacity, and the quality of source rocks is above medium (Figure 2). The average value of (S1 + S2) in the mudstone is 9.34%. Although the distribution range is mainly less than 2%, there are more than 50% samples with the range of (S1 + S2) greater than 2% (Figure 2). According to the TOC and (S1 + S2) diagram, most of the samples are medium and above source rocks. In conclusion, the Permian Lucaogou Formation in Jimusaer Sag is developed with high quality source rocks, high organic matter abundance and good hydrocarbon generation capacity (Figure 3).

4.2. Kerogen type and thermal maturity

The HI vs T_max diagram is generally used to divide the organic matter type. The kerogen types of the mudstone samples of Lucaogou Formation are mainly type I and type II, and the organic matter type is better (Figure 4). Vitrinite reflectance (R_o) is the most widely used maturity index at present. The R_o values of the source rocks of Lucaogou Formation range from 0.76% to 0.95%, indicating that the source rocks are in the mature stage[1-2]. In addition, C_29(20S/(20S + 20R)) and C_29ββ/(ββ + αα) are also commonly used to evaluate the maturity of source rocks. With the increase of thermal maturity, the ratio of C_29(20S/(20S + 20R)) increased from 0 to 0.50 (balanced between 0.52-0.55), and the ratio of C_29ββ/(ββ + αα) increased from close to 0.7, and reached a balance between 0.67 and 0.71. The distribution range of C_29(20S/(20S + 20R)) ratio ranges from 0.37 to 0.48, and that of C_29ββ/(ββ + αα) ranges from 0.39 to 0.59, indicating that the mudstone samples in the study area are in the mature stage (Figure 4).
4.3. Depositional conditions of source rocks

In order to study the source of organic matter and sedimentary environment of Lucaogou Formation source rocks, a series of biomarker parameters such as ($\sum(nC_{21}^-)/\sum(nC_{22}^+)$), $(C_{27} + C_{28})/C_{29}$ regular sterane, pristane / phytane (Pr/Ph), gammacerane and other biomarkers were analyzed.

4.3.1. Source of organic matter. The ratios of some n-alkanes are helpful to determine the relative abundance of terrestrial and aquatic hydrocarbons in source rocks. The distribution of n-alkanes with high carbon number (>23) indicates the input of terrestrial organic matter, while the n-alkanes with medium relative molecular weight (nC 15-nC 21) represent the input from aquatic organisms such as algae. The ($\sum(nC_{21}^-)/\sum(nC_{22}^-)$) ratios of the mudstone samples from Lucaogou Formation in the Jimusaer Sag are distributed in the range of 0.46-2.30, and mainly in the range of 0.73-1.98. The ($\sum(nC_{21}^-)/\sum(nC_{22}^-)$) ratios are basically above 1, indicating that low carbon number n-alkanes are dominant, and the source materials of hydrocarbon generation are mainly from lower aquatic organisms (Figure 5).

It is generally believed that aquatic organisms are rich in C 27 and C 28 steranes, and terrestrial higher plants contribute more to C 29 steranes. Therefore, the source of organic matter can be determined by the relative abundance of regular C 27, C 28 and C 29 steranes. It can be seen from the Figure 5 that C 29 sterane abundance is relatively high, while C 27 and C 28 steranes abundance is low. However, some previous studies have shown that C 29 steranes can also be extracted from green algae in addition to terrestrial plants[4], which can explain the abnormal advantage of C 29 sterane observed in this study. Therefore, the organic matter source rock of Lucaogou Formation in the Jimsa Sag is mainly from algae (lower aquatic organisms), and some terrestrial plants also contribute to it.
4.3.2. Salinity and redox conditions. Gammacerane can be used to investigate stratified water columns that are generally caused by highly reducing and hypersaline conditions in the source rocks sedimentary environments[5]. In this paper, the ratio of gammacerane to C31R-αβ hopane is defined as the gammacerane index. The ratio of gammacerane index in the source rocks of Lucaogou Formation ranges from 0.26 to 1.69, and mainly concentrates in the range of 0.6-1.4, which indicates that the water salinity is relatively high in the sedimentary period, and it was deposited in the saline water and super saline water condition (Figure 6.).

Generally, low Pr/Ph ratios (<0.5) indicates that the organic matter was deposited in a strong reducing environment[6]; Pr/Ph = 0.5-1.0 and Pr/Ph = 1.0-2.0 indicate that the organic matter was deposited in reducing environment and weak reduction-weak oxidation environment, respectively; and high Pr/Ph ratios (>2.0) have been reported to be related to oxidizing conditions. The Pr/Ph ratio of the mudstone samples in the Lucaogou Formation ranges from 0.40 to 2.26, and the Pr/Ph ratio is mainly distributed around 1, indicating that the source rocks of Lucaogou Formation are mainly deposited in a partial reduction environment (Figure 6.).

Figure 6. The figure on the left shows the variations of gammacerane index of samples; the figure on the right shows the variations of Pr/Ph of samples.

5. Conclusions
(1) The source rock samples of Lucaogou Formation of Permian in the Jimusaer Sag of the Junggar Basin have high organic matter abundance, good organic matter type (mainly type II), and organic matter is in the mature stage.

(2) The organic matter of source rock samples mainly comes from lower aquatic organisms and some from terrestrial higher plants; the source rocks are mainly deposited in partial reduction sedimentary environment, and the water salinity is higher in the deposition period.

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References
[1] Cao, Z., Liu, G., Xiang, B. (2017) Geochemical characteristics of crude oil from a tight oil reservoir in the Lucaogou Formation, Jimusar sag, Junggar Basin. AAPG Bulletin, 101: 39-72.
[2] Hu, T., Pang, X., Wang, X. (2017) Source rock characteristics of Permian Lucaogou Formation in the Jimusar Sag, Junggar Basin, northwest China, and its significance on tight oil source and occurrence. Geological Journal, 52: 624-645.
[3] Ding, X., Gao, C., Zha, M. (2017) Depositional environment and factors controlling β-carotane accumulation: A case study from the Jimsar Sag, Junggar Basin, northwestern China. Palaeogeography, Palaeoclimatology, Palaeocology, 485: 833-842.
[4] Meng, F., Zhou, C., Yan, K. (2006) Biological origin of early Palaeozoic and Precambrian hydrocarbon source rocks based on C_{27}/C_{29} sterane ratio and organic carbon isotope. Acta Micropalaeontologica Sinica (in Chinese with English abstract), 23: 51-56.
[5] Summons, R.E., Hope, J.M., Swart, R. (2008) Origin of Nama Basin bitumen seeps: petroleum derived from a Permian lacustrine source rock traversing southwestern Gondwana. Organic Geochemistry, 39: 589-607.
[6] Ten Haven, H.L., Leeuw, J.W., Rullkötter, J. (1987) Restricted utility of the pristane/phytane ratio as a palaeoenvironmental indicator. Nature, 330: 641-643.