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Thermal maturity of the Permian Lucaogou Formation organic-rich shale at the northern foot of Bogda Mountains, Junggar Basin (NW China): Effective assessments from organic geochemistry

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ABSTRACT

The northern foot of Bogda Mountains in Junggar Basin, Northwest China hosts thick organic-rich shale deposits in the Permian Lucaogou Formation. The Lucaogou Formation consists of the lower member and upper member. To assess the thermal maturity of Lucaogou Formation organic-rich shale in this area, the maturity parameters from organic geochemistry of twenty-four samples selected from JZK well are analyzed. The analytical results from hopanoids (Ts/(Ts + Tm), 29Ts/(29Ts + norhopane), C_{31}–C_{32} 22S/(22S + 22R) homohopanes, C_{29}–C_{30} αβ/(αβ + βα) hopanes) and steroids (C_{27} diasterane/ααα sterane, C_{29} αββ/(αββ + ααα) sterane and C_{29}ααα20S/(20S + 20R) sterane) indicate that the Lucaogou Formation has reached the oil window. But these parameters can not distinguish the maturity differences between the lower and upper members of Lucaogou Formation. The aromatic hydrocarbons such as alkylnaphthalene ratios (methylnaphthalene ratio (MNR), trimethylnaphthalene ratio-2 (TNR-2), dimethylnaphthalene ratio-1 (DNR-1), trimethylnaphthalene ratio (TMNr), tetramethylnaphthalene ratio (TeMNr), tetramethylnaphthalene-1 ratio (TeMNr-1)), alkylphenanthrene ratios (methylphenanthrene index (MPI), methylphenanthrene distribution fraction (MPDF), methylphenanthrene ratio (MPR)) and alkylbiphenyl ratios (methylbiphenyl ratio (MBpR), dimethylbiphenyl ratio-x (DMBpR-x), dimethylbiphenyl ratio-y (DMBpR-y)) are also used to assess the thermal maturity of Lucaogou Formation organic-rich shale. These aromatic indicators show that the lower member is mainly in the early mature stage (early oil window), which is consistent with the results from Rock-Eval pyrolysis and R_o. But the evaluation effects of alkylphenanthrene ratios (MPI, MPDF, MPR) and alkylbiphenyl ratios (MBpR, DMBpR-x, DMBpR-y) are not as clear and therefore not as useful as alkylnaphthalene ratios (TMNr, TeMNr, TeMNr-1). Above analytical results suggest that the alkylnaphthalene ratios (TMNr, TeMNr and TeMNr-1) can act as effective maturity indicators to assess the Lucaogou Formation organic-rich shale in Junggar Basin. Additionally, with the evidences of thermal maturity from organic geochemistry and shale energy phenomena observed in the JZK well, it can be concluded that the organic-rich shale is immature in the upper member and has generated oil in lower member (early oil window). However, shale gas is not a producible resource in the Lucaogou Formation, because the maturity hasn't reached the gas generation stage.

1. Introduction

The Junggar Basin is one of the most important hydrocarbon-bearing basins in Northwest China. The Permian Lucaogou Formation is the most important source rock at the northern foot of Bogda Mountains, Junggar Basin [1–4]. Some scholars have studied the sedimentary facies, sequence stratigraphy and paleontology of Lucaogou Formation. The sedimentary, organic geochemistry and elemental geochemistry methods are used to reconstruct the sedimentary environments such as paleocalimate, paleosalinity, preservation environments and primary productivity. The analytical results show that Lucaogou Formation organic-rich shale is mainly formed under the sedimentary environments with warm-humid climate, high salinity, anoxic conditions and high productivity [5–7].

The oil shale, shale oil and shale gas potential of Lucaogou Formation in the study areas have been widely reported. Among of

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them, the abundant oil shale is found in Yaomoshan and Dahuangshan areas [1,4,8]. Shale oil is discovered in the deep strata of Shichanggou areas. Based on the analysis of oil-source rock correlation, some researchers have proved that the shale oil is sourced from Lucaogou Formation, not migrating from the other layers. It is a kind of self-sourced reservoir [9]. While the shale gas investigation mainly focuses on theoretical speculations [10]. Therefore, the understanding on the organic-rich shale characteristics of Lucaogou Formation is becoming more and more important. Some studies show that the organic matter abundance of Lucaogou Formation is very high (TOC ranging from 0.3% to 20%) [11,12], indicating that Lucaogou Formation is excellent source rock. But the thermal maturity assessment of Lucaogou Formation should be further investigated.

Numerous researchers have done much work on the thermal maturity of organic-rich rocks [13–15]. Vitrinite reflectance (%) and T_{max} (°C) are widely used to assess the thermal maturity of organic matter [16,17]. Some scholars use T_{max} to evaluate the thermal maturity of Lucaogou Formation as immature stage in the shallow stratum of some areas. But recent study shows that shale oil are obviously discovered in the Lucaogou Formation [9], implying a higher maturity. This means that there are still some disagreements on the thermal maturity of Lucaogou Formation at the northern foot of Bogda Mountains. Various effective maturity proxies used for Lucaogou Formation are necessary to be further probed. Some analytical results have proved that the maturity evaluation parameters from molecular organic geochemistry are more sensitive than T_{max} [15,18]. This study aims to find and utilize effective maturity indicators from saturated hydrocarbons and aromatic hydrocarbons to reveal the thermal maturity of Lucaogou Formation organic-rich shale at the northern foot of Bogda Mountains in Junggar Basin. In addition, Rock-Eval pyrolysis (S_1, S_2, S_1+S_2, HI, OI and T_{max}) and R_o will be analyzed to verify and prove the conclusions from molecular organic geochemistry.

2. Geological setting

Northwest China is one of the most important oil and gas zones (Fig. 1a). The Junggar Basin is a large and organic-rich foreland basin in Northwest China [19]. Nowadays, two subordinate sedimentary basins, namely the Santanghu Basin and Turpan-Hami Basin, are situated next adjacent to its eastern and southern margins, respectively (Fig. 1b). The northern foot of Bogda Mountain is in the Eastern Tianshan Mountain Range and is located on the southern margin of the Junggar Basin. Due to the Mesozoic and Cenozoic strong tectonic activities, large numbers of multiple anticlines and multistage thrust faults are well developed here. Among of them, the Bogda Mountain fault, Keli Mountain fault and Fukang fault are the main faults in this area. Thus, the study area is divided into the first slip wedge, second slip wedge and subduction shell by these great faults (Fig. 1c). Various ages of sedimentary stratum including the Carboniferous, Permian, Triassic, Jurassic, Neogene and Quaternary are widely developed and exposed on the surface of the joint areas between Junggar Basin and Bogda Mountains [20]. This study will be carried out in this area (Fig. 1d).

The northern foot of Bogda Mountains was a sedimentary depression during the Permian Lucaogou Formation sedimentary period. Numerous aquatic organisms were well developed at this time [8]. Thus, the organic-rich lacustrine shales covering an area of 153 km^2 approximately 33 km long from east to west were formed [4,21]. The main sedimentary facies of Lucaogou Formation are lake facies and fan delta facies. The extensive development of deep lake subfacies may provide the good deposition environments for the formation of organic-rich shale [2]. The rock types of Lucaogou Formation are oil shale, shale, mudstone, calcareous mudstone, dolomite, calcareous siltstone, siltstone, fine-grained sandstone and medium-grained sandstone. In addition, some scholars have reported that the Lucaogou Formation can be divided into two well-completed 3rd order cycles, sequence 1 and sequence 2. Each sequence consist of four systems tracts: lowstand systems tract (LST), transgressive systems tract (TST), highstand systems tract (HST) and regressive systems tract (RST) from bottom to top. The sedimentary facies distributions in each systems tract are different from each other [11].

3. Materials and methods

3.1. Study well and sampling

JZK well is located at the southwest area of Santai city (Fig. 1d), which consists of the lower member of Lucagou Formation and the upper member of Lucaogou Formation (Fig. 2a, b). The main rock types

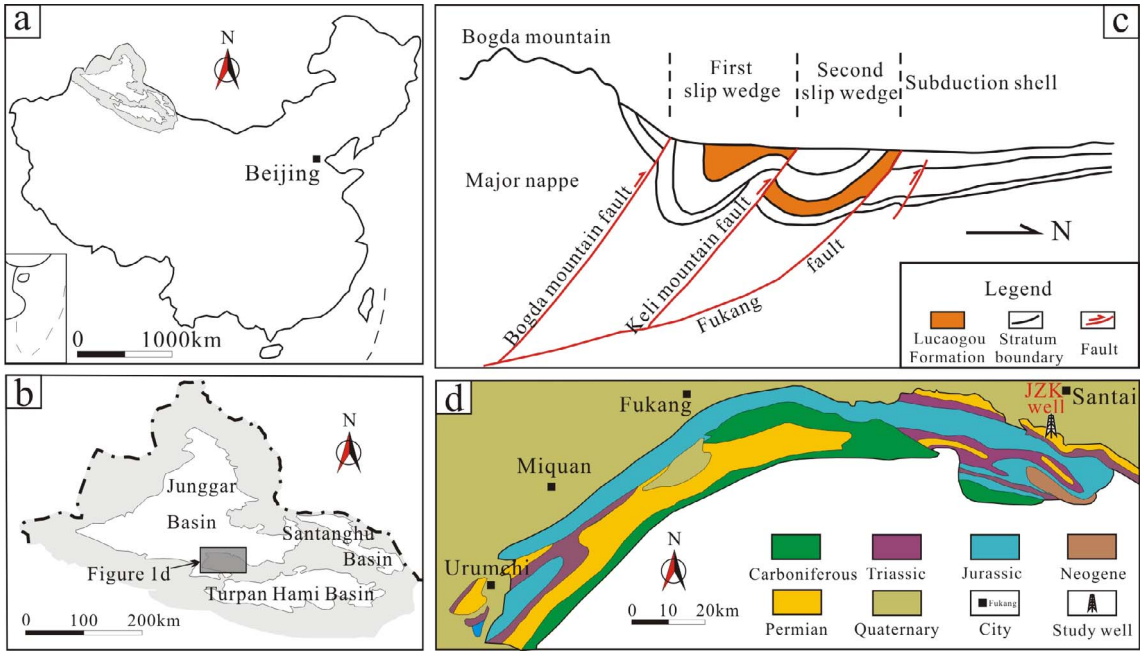

Fig. 1. Geological sketch of the study areas. (a): Location of Northwest China; (b): Location of the northern foot of Bogda Mountains (modified from [12]); (c): Structural features of the northern foot of Bogda Mountains; (d): Stratum distribution map of the northern foot of Bogda Mountains (modified from [11]).