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Oil content evaluation of lacustrine organic-rich shale with strong heterogeneity: A case study of the Middle Permian Lucaogou Formation in Jimusaer Sag, Junggar Basin, NW China

Tao Hu[a,b,c], Xiongqi Pang[a,b,*], Shu Jiang[c,*], Qifeng Wang[a,b,c], Xiaowei Zheng[a,b], Xuguang Ding[a,b], Yi Zhao[a,b], Chenxi Zhu[a,b], Hui Li[a,b]

[a] State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Changping District, Beijing 102249, PR China
[b] College of Geoscience, China University of Petroleum, Changping District, Beijing 102249, PR China
[c] Energy & Geoscience Institute, University of Utah, Salt Lake City, UT 84108, USA

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ABSTRACT

Large shale oil resources were recently been found in lacustrine organic-rich shale with strong heterogeneity, however, few studies have been conducted to examine their oil contents, resulting in considerable risks in lacustrine shale oil exploration. The Middle Permian Lucaogou Formation (P_2l) shale in Jimusaer Sag is a typical lacustrine deposit with strong heterogeneity, and its shale oil resource shows great potential. Integrated geochemical characterization of 265 core samples were conducted and results show that the P_2l shale developed in an anoxic lacustrine with stratified salty water and the organic matter in the upper sub-member shale of the P_2l is more oil-prone than that in the lower sub-member shale of the P_2l. The hydrocarbon generation potential of the P_2l shale decreases with the kerogen types changing from Type I to Type III, however, the residual hydrocarbon contents of the P_2l shale increases from Type I to II_1 kerogen, and then decreases from Type II_1 to III kerogen, this is mainly due to differentiated hydrocarbon expulsion efficiencies among different kerogen types. Based on S_1 and TOC values and the S_1/TOC ratios, considering the oil enrichment degree, this study classified the shale oil resources in the P_2l shale into four categories: enriched, moderately enriched, less efficient, and invalid resources. The enriched and moderately enriched resources are mainly shales with Type II_1 kerogen, followed by Type II_2 kerogen, and the middle interval of the Lower P_2l shale is the most favourable target for further shale oil exploration. The improved evaluation criteria are applicable for evaluating shale oil plays with strong heterogeneity qualitatively and quantitatively in terrestrial lacustrine basins in other parts of the world.

1. Introduction

Large shale oil resources were recently been found in lacustrine organic-rich shale in China, which is characterized by variable total organic content (TOC) and strong heterogeneity, such as the Paleogene shale oil plays in Dongying Depression [1–3], Bonan Sag [4], and Zhanhua Sag in the Bohai Bay Basin [5–7], the Qingshankou Formation shale oil plays in the Songliao Basin [1,8], the Triassic shale oil plays in the Ordos Basin [9–12], the Eocene shale oil plays in the Pearl River Mouth Basin [13,14], and the Middle Permian Lucaogou Formation (P_2l) shale oil plays in the Jimusaer Sag of Junggar Basin [15–17]. However, existing studies of the lacustrine organic-rich shale with strong heterogeneity are mainly focused on shale distribution [6,8,9], basic geochemical characteristics [2,4,5,12,17], petroleum generation and expulsion capability [1,3,6,8,13–16], and pore structure characteristics [7,9–11]. Little work has evaluated the shale oil content, which is a fundamental factor in evaluating shale oil potential [18–21], resulting in considerable risks associated with lacustrine shale oil exploration.

Several scholars have conducted systematic evaluations of the oil content of “shale oil plays” in North America [18,19], yielding remarkable results. However, the shale oil plays found in North America generally involve petroleum in marine fine-grained sediments that mostly are not shale. Some examples are the Bakken shale oil in the Williston Basin, which is mainly hosted in silty dolomite and calcareous fine sandstone [22]; similarly, the Eagle Ford shale oil in the South Texas Basin, the Green River shale oil in the Piceance Creek Basin, and the Niobrara shale oil in the Denver Basin are all mainly hosted in carbonatite [23,24]. Li et al. examined the oil content of terrestrial shale oil play in Jianghan Basin of China and established the grading

* Corresponding authors at: College of Geoscience, China University of Petroleum, Changping District, Beijing 102249, PR China (X. Pang).
E-mail addresses: pangxq@cup.edu.cn (X. Pang), sjiang@egi.utah.edu (S. Jiang).

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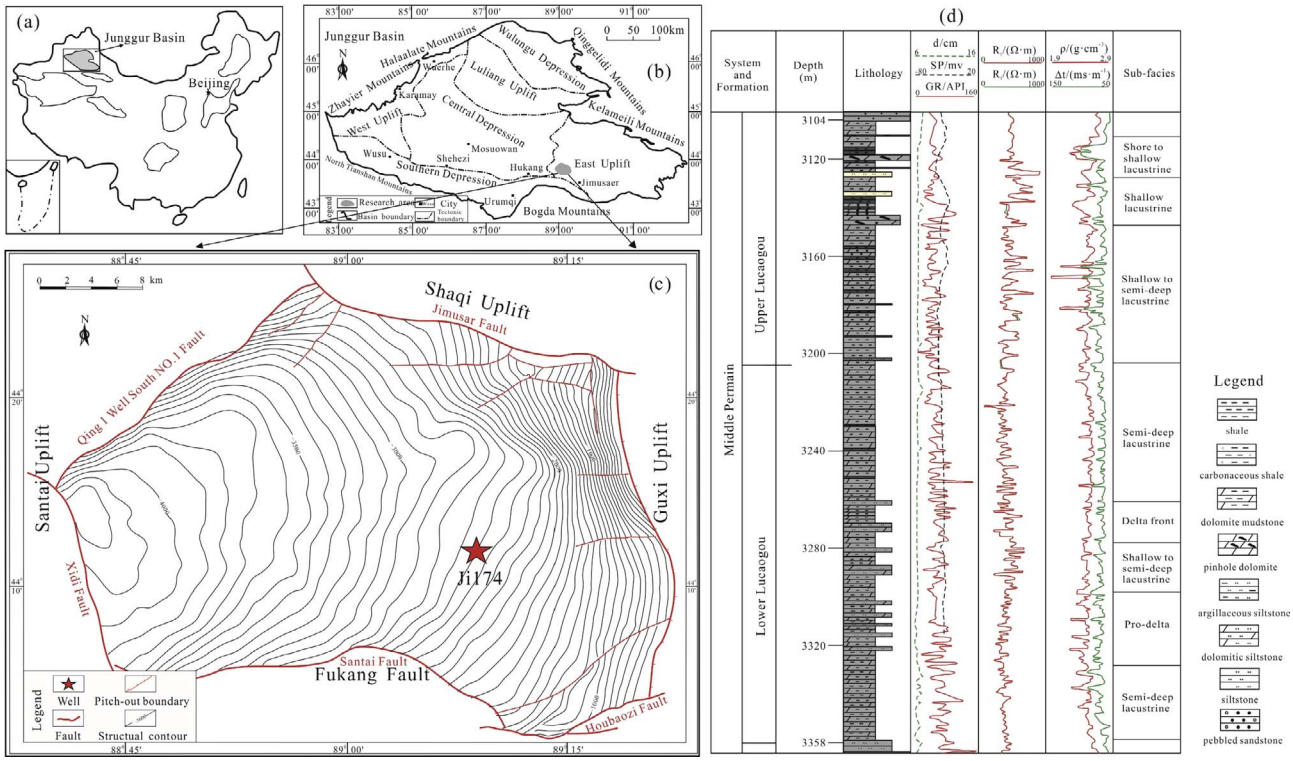

Fig. 1. Regional geologic maps of the Middle Permain Lucaogou Formation (P_2l), Jimusar Sag (JS), Junggar Basin. (a) the location of Junggar Basin; (b) the location of the Jimusaer (JS); the location of the Well Ji174 and structure contour map of the P_2l (below sea level); (d) Stratigraphic column of the P_2l. The P_2l are divided into two intervals: Upper sub-member and Lower sub-member.

evaluation criteria [21]. However, the evaluation criteria are not applicable to the shale oil plays in the other basins, which involves petroleum stored in argillaceous dolomite instead of shale. In addition, because of a lack of continuous core samples from the well, the TOC and pyrolysis data used to evaluate the shale oil play were from logging data calculations; no systematic measurements of TOC or pyrolysis data was conducted to validate the accuracy of this method. The marine carbonates and fine sandstones of North America and the lacustrine argillaceous dolomite in China differ significantly from the organic-rich shales of the Junggar Basin with regard to geology, hydrocarbon generation, expulsion and preservation. Thus, previously established evaluation criteria are not appropriate for oil content evaluation of the lacustrine organic-rich shale with strong heterogeneity.

Pang et al. proposed a method for calculating the retained oil-gas content in the shale based on the different retention forms of the oil and gas [25]. This model considers the adsorbed hydrocarbons, free hydrocarbons, oil-soluble hydrocarbons, and water-soluble hydrocarbons. Jiang et al. calculated the retained hydrocarbon content of source rocks in the North Harbin area of the Songliao Basin using this method and achieved good results. However, the method involves many parameters and is difficult to apply [8]. Jarvie proposed that a shale layer could be identified as a favourable shale oil exploration target with potentially sufficient producible petroleum when the oil saturation index (S_1/TOC × 100) > 100 mg HC/g TOC; the phenomenon is called the "oil crossover effect" [19]. A higher oil saturation index means a higher quantity of potentially producible petroleum. This phenomenon is supported by evidence from shale oil exploration in the United States [18,19]. However, unlike the features of high total organic content (TOC) and weak heterogeneity of the marine shale, the lacustrine shale is characterized by variable TOC and strong heterogeneity [2,4,5,12,17], thus a problem associated with using the oil saturation index to evaluate the oil content of strong heterogeneous lacustrine shale is as follows: when the absolute values of S_1 and TOC are low, the oil saturation index (S_1/TOC × 100) may still be high (exceeding 100 mg HC/g TOC), which could lead to significant uncertainty in evaluating the shale oil potential. To solve this problem, Lu et al. proposed the grading evaluation method that segregated shale oil resources into the following three categories: enriched resources (immediate exploration targets based on the current development capabilities), less efficient resources (with a potential for future exploitation when technologically and economically viable), and invalid resources (with no potential for effective exploitation) [20]. This method avoids the uncertainty associated with using the oil saturation index to evaluate shale oil potential. Jiang et al. proposed that the residual oil quantity of shale could be calculated quantitatively based on features of petroleum generation and expulsion of shale, in combination with "S_1/TOC" parameters, thickness, area, density, and organic matter abundance [1]. However, this method only provides a resource value and does not evaluate the favourability of the shale oil as an exploration target. Li et al. argued that the presence of petroleum expulsion was an indicator of the shale oil potential and proposed a new hydrocarbon index (the PG amount minus the pyrolysis value, S_1) [26]. However, the above methods do not consider shale oil recoverability, which is a significant index in evaluating oil potential of extremely low permeability and low porosity shale. Li et al. proposed an improved grading evaluation method to evaluate shale oil potential that associates the oil saturation index with the grading evaluation method [15,16,40], and the argillaceous dolomite oil resources in the Jianghan Basin were evaluated and the evaluation criteria were established [21].

Following the previous oil content evaluation methods, this study assessed the free oil (pyrolysis S_1), oil content (oil saturation index), and oil recoverability of 265 successive lacustrine shale core samples in the P_2l shale oil play of the Jimusar sag, and the oil content-based evaluation criteria were established. This is the first attempt to establish oil content-based evaluation criteria for lacustrine organic-rich shale with strong heterogeneity. Our results will be important for further lacustrine shale oil exploration in Junggar Basin as well as lacustrine basins in other parts of the world.