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Assessment of shale oil potential using a new free hydrocarbon index

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ABSTRACT

Shale oil is currently a highlight and frontier field in petroleum industry. However, the assessment and quantitative evaluation of oil content in the shale is challenging, which is one of the critical issues in understanding the resource potential. Here, we explore a new free hydrocarbon index based on a case study in the currently most successful shale oil play case in China, i.e., the Eocene Hetaoyuan Formation in the Biyang depression of the Nanxiang Basin, eastern China. This index ΔS_1 represents the difference between hydrocarbon generation quantity and pyrolysis free-hydrocarbon value S_1. It is new in that it considers not only the residual oil contents in the rocks like previous parameters but also the hydrocarbon expulsion and migration conditions that have rarely been focused before. When $\Delta S_1 < 0$, it is implied that there are migrated oils from external sequences within the shale system and thus the shale sequence has a good shale oil potential. When ΔS_1 is around 0, it is implied that the generated oil nearly has not expulsed and resided in the shale and thus there is also a good shale oil potential. In contrast, when $\Delta S_1 > 0$, it is implied that certain amounts of generated oils have migrated to external reservoirs and thus there is a poor shale oil potential. This method has potential general implications and the results in the Biyang can be used in the practical shale oil exploration.

1. Introduction

Shale oil is currently a frontier and highlight field in the petroleum industry and has received continued attention in recent years (Holditch, 2013; Chew, 2014; Davies et al., 2014; Song et al., 2015). However, the shale oil potential in a given set of shale has not been well constrained due to complex controlling factors, e.g., organic richness, oil content and reservoir properties (Liu et al., 2012; Zou et al., 2013; Hao et al., 2014; Wu et al., 2014; Jarvie, 2014; Katz and Lin, 2014; R.F. Yang et al., 2015). Of the many challenging issues, the assessment and quantitative evaluation of oil content is critical, which is one of the fundamental parameters for understanding the shale oil resource potential (Jarvie, 2012; Lee, 2012; Lu et al., 2012; Hakimi and Abdullah, 2013). Production of shale oil under current technological conditions targets free oil rather than adsorbed oil and is often equated to the pyrolysis free hydrocarbon S_1 yield, which represents the hydrocarbons released from the rock under temperature of 300 °C during Rock-Eval pyrolysis experiments, and has been widely used (Cooles et al., 1986; Behar et al., 2001).

However, the S_1 yield includes certain adsorbed hydrocarbons in addition to the free hydrocarbons because of the pyrolysis temperature. Hence, a high S_1 value does not exactly indicate a high amount of free hydrocarbons that can be easily produced (Peters, 1986; Jarvie et al., 2007), i.e., large portion of the oils may be adsorbed (Loucks et al., 2009). To compensate, Jarvie (2012) developed a methodology termed oil crossover. In this study, he plotted stratigraphically geochemical sections of TOC and S_1, and oil crossover refers to the zone where the S_1 curve crosses over the TOC curve. In addition, he used an index termed oil saturation index ($OSI = S_1 / TOC \times 100$) to determine the oil content in the shale, and an OSI value >100 is believed to imply potential shale oil reservoir. This eliminates the impact of the background organic matter adsorption, which is the problem present where only the S_1 value is used as outlined above. Thus, Jarvie's OSI method is good at evaluating the shale reservoir potential. However, when the TOC and S_1 values in the shale are both low, the OSI value may still be over 100 but the free oil content is not high. As such, the use of OSI alone is not necessarily accurate for assessing the oil content in shale and associated shale oil potential. In addition, the shale oil expulsion received little attention, which is important for evaluating the shale oil potential. Therefore, multiple parameters should be used in the geological context in the study of shale oil (e.g., TOC, S_1, oil crossover and OSI) and new parameters needs to be developed.

Here, we explore a new index based on a case study in the currently most successful shale oil play in China (the Eocene Hetaoyuan Formation in the Biyang depression of the Nanxiang Basin, eastern China) (Chen et al., 2011; Wang et al., 2013). This index ΔS_1 represents the difference between hydrocarbon generation quantity (HCGQ) and pyrolysis free-hydrocarbon value S_1. Compared with the previous parameters, we comprehensively considered the generation and expulsion of the source sequences and the migrated hydrocarbons from external sequences in the shale system. The migration here does not mean that the oil migrated from other shale systems,

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i.e., the secondary hydrocarbon migration in traditional terminology. It is the migration from one sub-unit to another sub-unit of a single shale system due to the difference of migration and accumulation conditions caused by heterogeneity of lithofacies, mineralogy and petrophysics. Thus, the migration is in situ and the oil is shale oil in definition. The method can have potential general implications and the results in the Biyang can be applied in the regional practical shale oil exploitation.

2. Conceptual theoretical foundation of the new method

For a shale system, more and more exploration and research results have implied that the shale system is complex and variable in terms of lithofacies and porosity/permeability (Bernard et al., 2010; Uffmann et al., 2012; Zhang et al., 2013; Chen et al., 2015). Thus, the system can be divided into sub-units based on the heterogeneity of lithofacies, mineralogy and petrophysics. Consequently, the shale oil in the system can be expected to migrate from one sub-unit to another sub-unit due to the difference of migration and accumulation conditions caused by heterogeneity of lithofacies, mineralogy and petrophysics. We term this "micro-migration from one shale unit to another adjacent sub-unit".

Thus, for this shale unit, the commonly-used free hydrocarbon index S_1 represents the HCGQ minus the expulsed hydrocarbons and plus migrated hydrocarbons, if any, from external sequences in the shale system. Therefore, to improve the understanding especially of the expulsion and migration conditions of the shale, which have rarely been focused before, we propose a new index ΔS_1 and it represents the difference between HCGQ and pyrolysis free-hydrocarbon value S_1, i.e., expelled hydrocarbons minus migrated hydrocarbons from external sequences within the shale system. This parameter is apparently indicative of the content of residual oils in shale like those previously suggested parameters including TOC, S_1, oil crossover and OSI. In addition, the hydrocarbon expulsion and migration are considered, which are new and different from previous indexes.

When $\Delta S_1 < 0$, it is implied that there are some migrated oils from external sequences within the shale system and thus the shale sequence has a good shale oil potential. When ΔS_1 is around 0, it is implied that the generated oil nearly has not expulsed and thus there is also a good shale oil potential; this is similar to the former condition. In contrast, when $\Delta S_1 > 0$, it is implied that much generated oil has migrated to external reservoirs and thus there is a relatively poor shale oil potential.

ΔS_1 can indicate the oil-bearing capacity of the shale. The more negative the ΔS_1 value, the more the migrated hydrocarbons from external sequences within the shale system and better oil-bearing capacity of the shale. This may be described as a type of lithofacies characterized by initially open but later healed fractures (type I interval). If the ΔS_1 is close to zero, it means that the amount of generated hydrocarbons and the currently residual hydrocarbons are nearly equal (type II interval). There are two possibilities. One is that both the amounts are large, and the other is that they are both small. The former suggests small expulsion and good oil-bearing capacity of the rock, which may be described as organic-rich shale without open fractures (type II_1 interval), while the latter indicates that the rock has poor oil-bearing capacity and may be described as organic-lean intervals without open fractures (type II_2 interval). If the ΔS_1 value is greater than zero, the greater the value, the poorer the oil-bearing capacity of the shale. This means that the generated hydrocarbons have mostly expulsed, and the rock may be described as organic-rich shale with open fractures (type III interval).

In this method, the pyrolysis free-hydrocarbon value S_1 was measured and the hydrocarbon generation quantity (HCGQ) was calculated based on the geochemical values including TOC, HI and Ro (Cheng et al., 1987; Riediger, 2002; Xu, 2008). Based on the results, the ΔS_1 value can be calculated as follows.

(1) Ro of all the samples was measured. Based on the results, a regression equation can be obtained (Fig. 1). Then, the Ro at any depth can be calculated by the equation
(2) The type of kerogen was identified based on hydrogen index (HI). As for different types of kerogen, we establish the equation to calculate the hydrocarbon generation rate (HCGR) based on the experimental analysis on the generation of kerogen accordingly (Fig. 2). Then, the HCGR at any depth can be calculated similar to the method above.
(3) The hydrocarbon generation quantity HCGQ was calculated by $HCGQ = HCGR \times TOC$.
(4) $\Delta S_1 = HCGQ - S_1$ as outlined above.

3. Geological setting of the Biyang depression in eastern China

The Biyang depression, Nanxiang Basin is located in eastern China between the south of the Henan Province and the northwest of the Hubei Province (Fig. 3). The depression, covering an area of about 1000 km^2, is located in the northeastern corner of the Nanxiang Basin at the junction between the Qinling fold belt and the block-faulted belt on the northern margin of the Yangtze Plate. It is a Mesozoic–Cenozoic (Cretaceous–Paleogene–Neogene) rift depression stacked on the suture between the North China Plate and the Yangtze Plate, showing a fan-shaped dustpan structure, deep in the south and shallow in the north (Chen and Philp, 1991; Chen and Summons, 2001; Qiu et al., 2002). The tectonic pattern of the depression can be divided into three zones: the northern slope, the central deep sag and the southern slope (Fig. 3).

In the depression, the thick Upper Cretaceous–Paleogene strata are unconformably overlain by the Neogene–Quaternary sediments (Fig. 4). The stratigraphic thickness of these strata varies in different areas and can reach about 8000 m in the deepest central sag (J. Yang et al., 2015). The Paleogene from bottom to top includes the Eocence–Paleocene Dacangfang and Yuhuangding formations and Oligocene Hetaoyuan and Liaozhuang formations (Fig. 4). There are three members in the Hetaoyuan Formation. In terms of lithology, the lower and

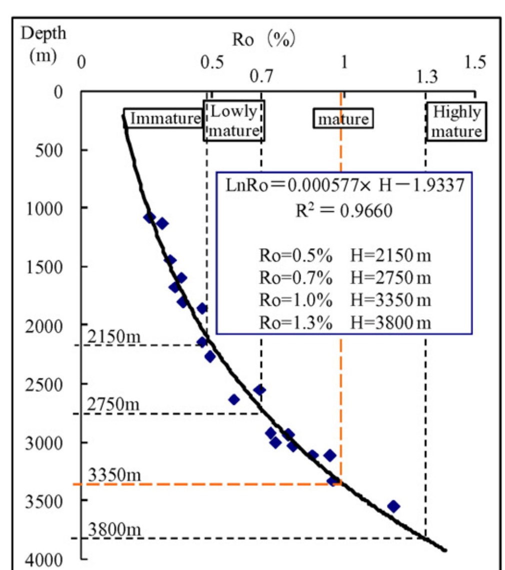

Fig. 1. Relationship between Ro and stratigraphic depth in the Biyang depression.