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Research paper

Heterogeneity of organic-rich lacustrine marlstone succession and their controls to petroleum expulsion, retention, and migration: A case study in the Shulu Sag, Bohai Bay Basin, China

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ABSTRACT

We documented a new type of self-sourced unconventional reservoir consisting of interbedded organic-rich marlstone and calcareous conglomerates developed in lacustrine carbonate successions in the Eogene Shahejie formation (Es_3^3) of Shulu Sag, Bohai Bay Basin. The Es_3^3 interval used to be regarded as a set of homogeneous source rock for oil plays in the upper strata due to their high abundance of organic-matter. However, the Es_3^3 interval actually has very strong heterogeneity in their organic richness and hydrocarbon generation ability among different stratigraphic sequences (the Es_3^3 interval can be divided into sequence SQ1 to SQ5 from bottom to up). To better understand the heterogeneity in the unconventional reservoir and its effect on the hydrocarbon retention and migration, thin sections and scanning electronic microscopes were used to characterize the pore system in the reservoir, together with a amount of collected well database including wireline logging, gas logging, and physical property data (e.g. porosity and permeability). Intensive sampling from the Es_3^3 interval of Well ST1H was performed and samples were measured with Rock-Eval and TOC analysis. The rock extracts were analyzed with SARA and gas chromatography - Mass spectrum (GC-MS) analysis to examine the fluid geochemical characteristics and molecular biomarkers composition. The results show that although the whole Es_3^3 are characterized by low and ultra-low porosity and permeability, but the pore types in different lithology are different. The organic-rich marlstones develop large amount of organic matter pore and dissolved mineral pores, while the conglomerates developed inter-partical or inter-crystalline mineral pores dominantly. The sequence SQ2 has high quality of source rock for hydrocarbon generation, possessing moderate to high content of organic matter (TOC range 2–5 wt %) with Type I-II kerogen predominantly, basically in the thermal maturity stage of the peak oil window. OM and lithology play significant roles in controlling hydrocarbon expulsion and retention. Oil retained in the organic-rich marlstone was observed to absorb on the surface of OM and clay-rich matrix, which is also supported by the positive correlation between retained oil (represented by Rock-Eval S1) and TOC. Organic-lean conglomerates in the sequence SQ3 obtain abnormal high content of low mature oil determined by biomarker composition, which suggests the oil were derived from oil migration and mixture. Thermal maturity profile based on hydrocarbon biomarkers composition of rock extract provides a method to determine the effect of the hydrocarbon migration or retention within source rock. The organic-lean intervals adjacent or close to organic-rich source rock can be favorable targets for oil exploration.

1. Introduction

Shale oil or tight oil accumulations presently become an emergently important unconventional hydrocarbon resource worldwide (Angulo and Buatois, 2012; Hammes et al., 2013; Kuhn et al., 2012; Pollastro et al., 2008b; Zou et al., 2013). Most of tight reservoirs in North America are developed in the marine strata, and many are in carbonate-rich successions, such as the Bakken Formation in the Williston Basin (Flannery and Kraus, 2006; Pollastro et al., 2008a, 2013), Eagle Ford Formation in the western gulf basin and south Texas (Ko et al., 2017;

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Surles, 1987), and Niobrara Formation in the Denver-Julesburg basin (Campbell and Saint, 1991; Stright and Robertson, 1995). However, the unconventional petroleum system developed in the lacustrine carbonate successions have not been reported widely (Burton et al., 2014; Malvic et al., 2014; Pitman et al., 1982). Most tight-oil reservoirs in China are developed in lacustrine depositional environments, as represented by the Permian Lucaogou Formation in the Jungar Basin (Kuang et al., 2012; Cao et al., 2016), the lower-middle Jurassic Daanzhai Formation in the central Sichuan Basin (Chen et al., 2015), the upper Triassic Yanchang Formation in the Ordos Basin (Yao et al., 2013), the Mesozoic Qingshankou Formation in the Songliao Basin (Huang et al., 2013), and the Eocene Shahejie Formation in the Bohai Bay Basin (Pu et al., 2011, 2014). Compared with the marine carbonates, the lacustrine carbonates are characterized by restricted horizontal distribution, and higher heterogeneity due to more frequent change in depositional environments than marine carbonate (Lin et al., 2013; Jia et al., 2012; Zou et al., 2012). The heterogeneity in the source rock would significantly affect the petroleum expulsion and migration.

Over-centimeter migration within the source rock might also bring about hydrocarbon fractionation, especially for the n-alkane (Jarvie, 2014; Leythaeuser et al., 1984). Bitumen, the intermediate product between kerogen and oil, also has different geochemical signatures even at the sub-micrometer scale after migration had occurred (Bernard and Horsfield, 2014). The total organic carbon (TOC) content, lithology and physical property, such as porosity and permeability, vary with different facies and associated depositional environments, consequently affect the petroleum generation, expulsion and retention (Han et al., 2015, 2017; Jarvie, 2014; Tang et al., 2015).

The lacustrine carbonates were widely distributed in the Bohai Bay Basin and possess pronounced potential for Petroleum Exploration & Development (Xie, 1989; Du, 1990; Wang and Fan, 1998; Xia et al., 2003; Wang et al., 2007; Pu et al., 2011). Of them, the Shulu Sag developed huge thickness of lacustrine calcareous conglomerate-marlstone assemblages, which was considered as major source rock for hydrocarbon accumulations in the conventional petroleum plays in the upper strata (Zhao et al., 2014b; Lei et al., 1997). In the Shulu sag, the calcilutite is estimated to have 2.7 billion barrels of recoverable oil according to PetroChina Huabei Oil field estimate (Zhao et al., 2014b), and a proven reserve of 0.185×10^9 bbl according to the latest China National Hydrocarbon Resource Assessment report (The Ministry of Land and Resources of Oil and Gas resources Strategic Research Center, 2009). Several wells were drilled and encountered good hydrocarbon shows in the fractured zones of conglomerate-marlstone assemblage in the 1990s but no commercial production was achieved (Li et al., 2012). With horizontal drilling and multi-stage fracturing technology, recent successful commercial production in the Shahejie formation amounts to 345 bbl/day of oil and 814,390 scf of gas during the period of well testing (Song et al., 2013). However, the mechanism of petroleum generation, expulsion and retention is still unclear. Considering the strong heterogeneity of lacustrine carbonates, the source rock needs to be studied in detail. Combining detailed lithological and geophysical characterization of strata, geochemical analysis of the core samples and their extracts were conducted, we aimed to reveal the heterogeneity of source rock and their controlling upon the petroleum migration and retention mechanism. This paper provides a method based on the thermal maturity profiled to determine whether petroleum migration happening within source rock and the impact of hydrocarbon migration.

2. Geologic setting

2.1. Tectonics and structures

The Shulu Sag, located in the southern part of the Jizhong Depression, Bohai Bay Basin (Fig. 1), is a north-north-eastern trending wedge-shaped graben, bounded by the Xinhe Fault to the east and the Ningjin Uplift to the west (Figs. 1B and 2), encompassing an area of approximately 700 km^2 (Zhao et al., 2014a). The Shulu Sag is subdivided into three closed or semi-open sub-sags by the Jinqiu and Taijiazhuang faults.

2.2. Sequence stratigraphy and depositional environment

Since Eocene, the sag began rifting accompanied by intensive faulting and base tilting (Qiu et al., 2006). The Cenozoic strata, developed on the lower Paleozoic Cambrian-Ordovician carbonate in the western slope and on the upper Paleozoic Carboniferous-Permian coal-bearing rocks on the eastern slope, consist of the Shahejie Formation (Es), Dongying Formation (Ed) and Neogene strata (Zheng et al., 2015) (Fig. 3). The Shahejie Formation is the main source rock and oil-bearing strata, consist of three members: Es_1, Es_2 to Es_3 from top to bottom. The Es_3 member has a thickness of 7216 ft (0–2200 m) and consists of three units: from the basal Es_3^3 to the top Es_3^1. The Es_3^3 is the focus of this study. The Es_3^3 can be further subdivided into Interval I to IV from top to bottom according to lithology. During the deposition of the Es_3^3 interval, the Shulu Sag was surrounded by carbonate highlands to the east, south and west (Qiu et al., 2006). Previous study defined the Es_3^3 interval as a third-order sequence (Jiang et al., 2007; Kuang et al., 2007; Jin et al., 2008). The latest research further sub-divided the Es_3^3 interval into five sequences from sequence SQ1 bottom upward to sequence SQ5 (Fig. 4) (Zheng et al., 2015). Every sequence deposits coarse grain sediment at the bottom and fines upward to marl or calcareous mudstone.

During the period of sequence SQ1 deposition, the sag was experienced rapid rift and the lake range enlarges, and flooding brought a huge amount of coarse-grain sediments eroded from Paleozoic carbonates into lake and formed a thick layer of conglomerates. The sequence SQ1 was only encountered by well ST3 until now, consisting of huge thickness of conglomerates with thin layers of mudstone and calcareous sandstone on the top.

The extent of the lake was widest and the sag rifted to its most during the deposition of sequence SQ2 with thickness of conglomerates developed at the bottom and covered by a thick layer of organic-rich fine-grain sediments including grey-black massive marlstone and varve-like marlstone.

During the period of sequence SQ3 deposition, the boundary faults (e.g. Xinhe fault) reactivated and the earthquake induced a slump depositing as conglomerate-rich turbidite fan (Zheng et al., 2015). Conglomerate deposited alternatively with mudstone.

During the deposition of sequence SQ4 and SQ5, the tectonics came into stable and lithology are mainly marlstones with thin-layer siltstone and breccia-bearing marlstone.

2.3. Samples and methods

The Well ST1H has two boreholes, one is vertical borehole (terminate at the bottom of sequence SQ2) and the other is horizontal borehole which was deflected and went through along the equivalent layer of the basal conglomerates in the sequence SQ2. Intensive sampling from the cores of vertical borehole of Es_3^3 interval in the Well ST1H (locations can be seen in Fig. 1B) ranges between the depths from 3702 m to 4365 m. Oil and gas were produced in the sequence SQ2 from the ST1H horizontal borehole by fracturing. For this study, sampling and the Well data files associated with vertical borehole of ST1H were collected including routine well-loggings, geochemical datasets (e.g. TOC and Rock-Eval parameters) and physical property datasets (e.g. X-Ray diffraction (XRD), porosity and permeability) from the research institute of Petroleum Exploration and Development of PetroChina Huabei Oilfield Company. Additional cores observations were operated from the well ST3, ST2, and J100 in the Es_3^3 for reservoir characterization.

26 marlstone and 15 conglomerate core plugs samples were