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Revelation of organic matter sources and sedimentary environment characteristics for shale gas formation by petrographic analysis of middle Jurassic Dameigou formation, northern Qaidam Basin, China

Jing Qin[a,b,*], Shuangqing Wang[b], Hamed Sanei[d], Chunqing Jiang[c], Zhuoheng Chen[c], Shoumai Ren[e,**], Xuemin Xu[b], Jiajia Yang[b], Ningning Zhong[b]

[a] State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China
[b] National Research Center for Geoanalysis, 24 Baiwanzhuang Road, Xicheng, Beijing 100037, China
[c] Geological Survey of Canada (Calgary), 3303-33rd Street N.W., Calgary, Alberta T2L 2A7, Canada
[d] Aarhus University, Høegh-Guldbergs gade 2, DK-8000 Aarhus C, Denmark
[e] China Geological Survey, 45 Fuwai Road, Xicheng, Beijing 100037, China

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ABSTRACT

The 7th member of Middle Jurassic Dameigou Formation (J_2d^7) in northern Qaidam Basin, China was proposed to have good hydrocarbon generating potential in previous studies. Here we apply an integrated petrographic and geochemical analysis to investigate the depositional environment, real thermal maturity and shale gas potential of organic-matter (OM)-rich assemblage. The relatively high content of C_{29} regular sterane (56.8%–62.8%) and vitrinite predominance in maceral composition suggesting plenty of higher-plant input, combined with the high pristane/phytane ratio (Pr/Ph)(2.8–8.2) and low gammacerane index (0.2–0.4) reveals oxic water column with in-situ depositional condition of carbonaceous-mudstone when the lower J_2d^7 was deposited. The maceral composition of oil shale at the upper part of J_2d^7 is mainly amorphous OM with small proportion of reworked vitrinite and inertinite, consistent with a mainly algea and small amount of exogenous OM input. When associated with low Pr/Ph (0.8) and high gammacerane index (4.3), the oil shale was deposited in an anoxic saline water column with mainly zooplankton OM source. The geochemical and petrographic result implies a transitional environment ranging from suboxic semi-saline to oxic fresh water environment with varying proportion of higher-plant and algae input by in-situ deposition and distant transportation for the mudstone at the middle part of J_2d^7. By use of random reflectance (Ro) distribution, two sedimentary environment microcycles which are confirmed by maceral composition, from the depth of 1983 m to 1962 m and 1954 m to 1931.9 m, are differentiated within the homogenous mudstone section. The variation of OM input condition and alternation of depositional environment led to accumulation and deposition of various kinds of abundant OM when J_2d^7 was deposited. Although the OM has actually low maturity at oil window with vitrinite reflectance around 0.6% according to the petrographic results, the liptinite inherited from higher-plants especially suberinite is the main maceral to generate gaseous hydrocarbons at the low maturity, which implies that the Dameigou formation (J_2d^7) of Qaidam Basin is of gas potential.

1. Introduction

In recent years, shale gas has been accepted as a prolific fossil fuel energy source, globally especially in North America (Soeder, 2018). Shale gas is characterized by self-source and self-reservoir within an assemblage of thick shale. The shale gas reservoirs explored in North America are typically marine shales with sufficient OM and enough maturity to generate thermogenic gas (Jarvie et al., 2001; Kuuskraa, 2007; Pollastro et al., 2007; Loucks et al., 2009). Shale gas resource exploration has been focused on the widespread marine shales in southern China in the past years, which led to exploration of major gas fields such as Fuling, Changning and Weiyuan (Yang et al., 2017; Luo et al., 2016a, 2017; Feng et al., 2018). However, only some researches have been conducted on the marine-continental transitional facies and lacustrine facies shale that widely distributed in northern China (Liu et al., 2007a, 2007b; Li et al., 2014a, 2014b; Guo et al., 2018). When

* Corresponding author at: State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China.
** Corresponding author.
E-mail addresses: qinjing1985@hotmail.com (J. Qin), realshaw@vip.sina.com (S. Ren).

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comparing to the marine shale in the south China, the OM assemblages in continental sediment in the north are characterized by high diversity of lithology, type of OM and relatively low thermal maturity (Ma et al., 2013; Li et al., 2014a, 2014b).

Qaidam Basin is a petroliferous onshore basin in Northwest China. The 7th member of the Middle Jurassic Dameigou Formation (J_2d^7) which distributed along the northern margin of Qaidam Basin is a set of lacustrine sedimentary sequence with vertically thick OM rich assemblage (50-200 m) and laterally continuous distribution (Yang et al., 2007; Yue et al., 2011; Sun et al., 2013; Shao et al., 2014). There are three kinds of OM rich assemblages in the J^2d^7, including oil shale, mudstone and carbonaceous-mudstone. The conventional oil field and coal mine in the research area have proved that the J^2d^7 has high organic abundance and good potential to generate oil (Fu et al., 2014). Previous studies have indicated that the lithology, TOC, OM type and vitrinite reflectance of J^2d^7 varies within 150 m depth, as the TOC ranging from 2% to 10%, vitrinite reflectance ranging from 0.4% to 1.5%, and OM types including type l, II and lll (Liu et al., 2007a, 2007b; Fu et al., 2014; Li et al., 2016; Ren et al., 2016).

CY1 well in the Yuqia area of the northern Qaidam basin was drilled by the China Geological Survey in 2013. Presence of shale gas in the J_2d^7 have been identified by logging data of CY1 well, and the gas content by desorption has been reported (Up to 8 m^3/t) (Li et al., 2016; Guo et al., 2018). However, the differences between the excellent gas content of rocks and the relatively low maturity of the OM content, was difficult to explain, led to the uncertainties for shale gas exploration of the J_2d^7. Therefore, the present research was designed to investigate the relationship between the OM and gas generation.

2. Geological setting

Qaidam Basin (Fig. 1) is located at the northeast margin of the Qinghai–Tibet Plateau, and is surrounded by the Altyn Mountains to the northwest, the South Qilian Mountains to the northeast, and the East Kunlun Mountains to the south (Fig. 1). The northern fault block zone (Northern Qaidam), the western downwarped region (Western Qaidam), and the eastern downwarped region are the main first–order tectonic units divided by basement structures, sedimentary formations, and fault development features (Guo et al., 2018).

The Middle Jurassic carbonaceous deposits of the Dameigou Formation (Fm.) at the northern margin of Qaidam Basin have long been the subject of studies for their hydrocarbon potential (Yue et al., 2011; Pan et al., 2012; Li et al., 2014a, 2014b; Shao et al., 2014; Li et al., 2014a, 2014b; Ren et al., 2016;). The Dameigou Formation is divided into seven members by lithological characteristics and deposition periods (Yang et al., 2011; Yue et al., 2011). Three members were formed during early Jurassic, with carbonaceous-mudstone and oil shale in the first member, mudstone and sandstone with lean OM in the second and third members. During middle Jurassic, the other four members of Dameigou Formation were deposited, including a set of sandstone deposits from the forth to sixth member and thick OM–rich mudstones in the seventh member (J_2d^7) which has good hydrocarbon potential (Fu et al., 2014). The upper part of the J_2d^7 is lacustrine sediments with a set of OM rich assemblage dominated by black mudstone and oil shale. The lower part of the J_2d^7 is mainly lacustrine-swamp facies with interlaid mudstone, sandy-mudstone and thin layers of carbonaceous-mudstone (Fig. 2).

3. Samples and experiments

Total number of 99 core samples from the 7th member of Dameigou Formation of Middle Jurassic strata (J_2d^7) were collected from the CY1 well from the depths of 1905 to 2035 m. The lithology of the samples includes sandstone, sandy-mudstone, carbonaceous-mudstone and mudstone. Geochemical and petrographic analyses were conducted for the samples (Fig. 2) in the Laboratories of the National Research center for Geoanalysis, China and the Geological Survey of Canada (GSC) in Calgary.

3.1. Geochemical analysis

Rock-Eval pyrolysis of 99 crushed samples (70 mg, grain size < 0.15 mm) were conducted using a Rock-Eval VI device (Lafargue et al., 1998 and Behar et al., 2001). TOC (wt%) was quantified as the sum of the organic carbon released during pyrolysis and oxidation steps (Pyrolysable Carbon, PC % + Residual Carbon, RC %). The hydrogen index (HI, mg HC/g TOC) is calculated by normalizing the quantity of the hydrocarbons thermally converted from kerogen (S_2; mg HC/ g rock) to TOC ($HI = S_2/TOC \times 100$). The Oxygen Index (OI) is the ratio of oxygen- containing OM released during the pyrolysis stage (S_3; mg CO_2/g rock) to TOC ($OI = S_3/TOC \times 100$). The production index (PI) is the ratio of S_1 (mg HC/g rock) to the total hydrocarbons ($S_1/(S_1 + S_2)$) (Behar et al., 2001).

Biomarker analysis was performed for eight samples (Fig. 2). After processing soxhlet extraction for 72 h using dichloromethane. Removal of sulphur with colloidal copper, removal of solvent by rotary evaporation, and weighing out the mass of soluble OM (SOM) (Jiang et al., 1998), the extracts were separated into saturated hydrocarbon, aromatic hydrocarbon, resin, and asphaltene fractions by open column liquid chromatography fractionation (Fowler et al., 1995; Jiang et al., 2001). The saturated and aromatic fractions were analyzed by gas chromatography–mass spectrometry (GC–MS) and gas chromatography-flame ionization detection (GC-FID). The GC–MS analyses were performed on an Agilent 6890 GC coupled to a 5973 Mass Selective Detector (MSD) operated in select ion mode. A 30 m × 0.32 mm × 0.25 μm DB-5 capillary column was employed with helium as the carrier gas at a constant flow rate of 1.2 mL/min. The column temperature was programed at 4 °C/min from 40 °C to 325 °C and held for 15 min. Ions monitored were *m/z* 217 for steranes and m/z 191 for terpanes.

3.2. Petrographic analysis

Organic petrology was performed on 15 selected samples (Fig. 2). Maceral observation and reflectance measurements were conducted with a Zeiss Axioimager II microscope system equipped with an ultraviolet light source and Diskus-Fossil system. Reflectance measurements were carried out under oil immersion, by use of an ultra-fine pixel size (0.1 μm) probe. Fluorescence microscopy was carried out using ultraviolet G 365 nm excitation with a 420 nm barrier filter.

Standard procedure of ASTM D7708–14 methodology was generally followed. The main classification of dispersed OM is according to the TSOP / ICCP official classification. The random reflectance (Ro) measurements were conducted on four kinds of macerals, including i) huminite/vitrinite, ii) bituminite (degraded liptinite), iii) inertinitic matter (fusinite and semifusinite) and iv) reworked vitrinite. The %Ro analysis provided a wide range of reflection data on the macerals, which minimized the operator bias in distinguishing vitrinite. Minimum of one hundred Ro measurements were made for each sample except OM lean samples.

4. Results

4.1. Rock-Eval parameters

Rock-Eval analysis shows that the sediment in the section (J_2d^7) has high OM, Low OM maturity and variety of OM types (Table 1). The TOC value ranges widely from 0.1 to 49.0 wt%, and has diverse value within different lithological unit, such as 0.34 ± 0.14 wt%, $n = 37$ for sandstone and sandy-mudstones, 3.64 ± 1.90 wt%, $n = 52$ for mudstones, 7.28 ± 2.99 wt%, $n = 6$ for oil shales and 31.69 ± 12.91 wt%, $n = 4$ for carbonaceous mudstones. In general, the oil shale and