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Characterization of the reservoir in Lower Silurian and Lower Cambrian shale of south Sichuan Basin, China

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A B S T R A C T

Natural gas has become an important source of energy. In China, external dependency on natural gas reached 32.2%. China is rich in shale gas resources, and both government and oil companies have promoted the development of shale gas. Lower Silurian Longmaxi Formation (LSLF) shales and Lower Cambrian Qiongzhusi Formation (LCQF) shales are believed to be favorable shale gas targets in the Sichuan Basin. Oil companies have extracted gas from LSLF shale but not from LCQF shale in and around the Sichuan Basin. The total organic carbon content (TOC) increases with buried depth in LSLF shales and LCQF shales, but the organic matter (OM) in the LCQF shales is more compacted than LSLF shales. The mineral brittleness index of these shales means that they are favorable for hydraulic fracturing to generate the complex fracture geometry in both shales. The OM is rich in the pores and the surface porosity of OM is from 7.18 to 9.52% in the LSLF shale and LCQF shales with low TOC (TOC <1.0%). The LCQF shales with high TOC are poor in the OM host pores and surface porosity of OM is less than 0.1%. The gas contents of LSLF shales increase with the TOC contents, but there is a poor correlation in LCQF shales, especially in LCQF shales with TOC of greater than 3.0%. There was a linear correlation between gas content and V_{TOC} in both shales, which was multiplied by the TOC and surface porosity. For the LCQF shales, the TOC and the surface porosity of OM are also important to the shale gas content and selection of favorable resource targets. The TOC of LCQF shales was less than 1.0% and greater than 3.0% in this paper, so the inflection point of surface porosity should be further examined in OM.

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1. Introduction

Natural gas has become a more prominent source of energy, with the total natural gas consumption being 180 billion cubic meters (BCM) in China in 2014 (Li and Zhai, 2015). Natural gas production could not meet the demands last year, so the external dependency of natural gas reached 32.2% in China (Li and Zhai, 2015). Because of the imbalance of energy supply and consumption, the Chinese government has expanded natural gas development projects in recent years, especially after the U.S. natural gas market was transformed by the shale gas “revolution.” Shale-gas production has become an important share of US energy supply, driven, to a large extent, by the advances in sweet spot selection, production technology and multistage hydraulic fracturing (Arora and Cai, 2014; Yuan et al., 2015). China's government and oil companies have been promoting shale gas development in recent years.

Shale gas resources are rich in China with an estimated 3.07×10^4 BCM in main basins and 1.35×10^4 BCM in and around Sichuan Basin (Liu et al., 2010). The Lower Silurian Longmaxi Formation (LSLF) and Lower Cambrian Qiongzhusi Formation (LCQF) shales within and around Sichuan Basin are believed to be the primary gas shale targets because of their widespread occurrence, high organic matter content, favorable mineral composition, and thickness as indicated from analysis of many outcrops and a few

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core samples (Han et al., 2013; Zhu et al., 2007; Guo et al., 2011; Liang et al., 2014). The total shale gas production in China was 1.3 BCM in 2014, all of which was produced from LSLF shale in and around Sichuan Basin (China Geological Survey, 2014). The Fulin shale gas reservoir, the first shale gas reservoir to be developed in China, was put into commercial development. The target formation of the Fulin shale gas reservoir was also LSLF shale. It is projected that 1.0 BCM will be produced from the Lower Silurian shales of this area in 2017 (Dong et al., 2014; Wang, 2015). However, the gas production has been very low and no commercial gas was obtained from LCQF shale. Therefore, the sweet spot selection should be further investigated on LSLF shales and LCQF shale to reveal the reasons for distinctly different production rates.

The sweet spot selection of shale gas reservoir should consider many parameters including depth, thickness, total organic carbon content (TOC), maturity, porosity, gas content, and brittleness of the mineral component (Zou et al., 2010; Curtis, 2002; Li et al., 2007; Huang et al., 2012). Pore space in the organic matter are generally present as irregular round to elliptical shapes in kerogen, and their sizes range between 5 and 750 nm, with an average pore size of approximately 100 nm (Boruah and Ganapathi, 2015; Loucks et al., 2009, 2012). Because of the organic matter (OM) hosted pore, the TOC of shale is always positively correlated to the porosity and gas content, especially the samples with TOC less than 5.5% (Wang et al., 2013a, 2013b; Tian et al., 2015; Tian et al., 2013). OM contributes to the amount of specific surface area. Higher TOC of shale also relates to stronger adsorption capacity and more absorbed gas content. Some researchers found a large number of clay mineral intercrystalline pores and fractures with a size range of 10 nm to 2 μm. These pores and fractures also contribute to the porosity and free gas content in shale gas reservoirs (Varma et al., 2014; Pan and Connell, 2015; Desbois et al., 2009; Xue et al., 2013; Milliken and Reed, 2010). Therefore, the TOC was considered as one of the most important parameters in the selection of a sweet spot in a shale resource. According to the TOC and other parameters obtained from outcrop and core samples, the LSLF shales and LCQF shales were preliminary selected as sweet spots, but the gas production from both stratums was inconsistent with the facts.

A well was designed and drilled to collect the whole core for study of shale gas content and gas production potential in LSLF shales and LCQF shales in the Sichuan Basin. Shales samples were selected and experiments were designed to characterize and compare the geochemistry, petrology, and gas content of LSLF shales and LCQF shales. The microstructure of shales was investigated to reveal the difference in shale gas content and production. Accurate interpretations of factors affecting shale gas production from the two stratums will be invaluable for evaluating resource potential of shale gas in LCQF shales in China.

2. Geological background

Several wells were previously drilled with the goal of discovering conventional hydrocarbon-bearing layers in the Silurian and Ordovician, but no wells were drilled with the specific aim of distinguishing between the properties of LSLF shales and LCQF shales. One of the wells designed for the evaluation of the LSLF shales and LCQF shales was located in Yibin city of the Changning region at the margin of the southern Sichuan Basin (Fig. 1). Sichuan Basin is located in southeast China, west of the Yangtze Metaplatform, and covered an area of more than 1.8×10^5 km^2. There are four different source rocks in the Paleozoic in this area, the Lower Cambrian (marine shale), Lower Silurian (marine shale), Lower Permian (marine carbonate) and Upper Permian (coal measures) (Ran, 2006; Zou et al., 2008; Zhang et al., 2008a). The LSLF shales and LCQF shales are formed in a neritic shelf with a biased, stagnant marine sedimentary environment. They are widely distributed and recognized as favorable target formations and can be explored for production in the Sichuan Basin (Fig. 2).

Total thickness of LSLF shales, currently the major production stratum in China, varies greatly from 60 to 700 m. The TOC in LSLF shales varies from 2.0 to 4.0%, whereas their vitrinite reflectance (R_o) values are in the range of 1.6–3.6% (Liang et al., 2014; Zou et al., 2010; Zhang et al., 2008a; Shi et al., 2015; Chen et al., 2011; Zhang et al., 2010, 2008b). The LCLF shale was also regarded as having the highest gas content and greatest potential for exploration and production. During the Early Cambrian, a thick succession was deposited and the total original thickness could have been up to 1200 m. The thickness of the LCQF shale within and around Sichuan Basin varies from 60 to 600 m and the TOC values vary from 0.55 to 25.7%, whereas their R_o values are more than 3.5% (Han et al., 2013; Huang et al., 2012).

Twenty-five LSLF shales and eight LCQF shales samples (chip from whole core) were respectively selected from the well in the interval 1201.9 m–1442.4 m and 3251.4 m–3435.1 m (as listed in Tables 1 and 2, Figs. 3 and 4).

3. Experimental methods and data acquisition

It is important to understand the geochemical, mineralogical, and petrophysical characteristics to evaluate the unconventional hydrocarbon system. TOC and gas content were quantified and the microstructural features of shale also were studied to interpret the differences of gas content between LSLF shales and LCQF shales.

3.1. Organic geochemistry and petrology

The TOC and organic thermal maturities of all samples were determined at the Key Lab of Unconventional Oil and Gas, Petrochina. After the samples were treated by hydrochloric acid to remove the carbonates, TOC was measured using a LECO carbon-sulfur analyzer. Because of the lack of vitrinite in the marine shales, bitumen reflectance measurements were carried out on polished blocks using a MPV-SP microscope photometer. Bitumen reflectance (R_B) was then converted to equivalent R_o using the equation of Jacob (1989), $R_o = 0.618R_B + 0.40$ (Jacob, 1989).

The mineral components were analyzed using a Rigaku TTRIII X-ray diffractometer at the National Energy Shale Gas Innovation and Experiment Center, China (NESGIEC). All samples were crushed and milled to a 200-mesh powder and were continuously scanned at an accelerating voltage of 40 kV and a current of 30 mA. The scanning speed of the instrument was 2°/min at 0.02°increments.

3.2. FE-SEM scan of microstructures

Field emission scanning electron microscope (FE-SEM) analysis produces a visual depiction of pore types in these core samples and it was used for precise characterization of pore structure (Loucks et al., 2009; Shi et al., 2015; Curtis et al., 2012). The samples were prepared using an argon-ion milling instrument (IM4000, Hitachi High-Tech) with an accelerating voltage of 3 kV and a milling time of 4 h, and then mounted with carbon tape. Carbon-coated thin sections were inspected using a FEI Helios 650 Workstation Focused Ion Beam SEM (FIB/SEM) at NESGIEC. Secondary electron (SE) and backscattered electron (BSE) images were acquired to document topographic variation and the accelerating voltages of 5 kV with working distances about 4.0 mm were typically used on these systems.

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