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Effect of lithofacies on gas storage capacity of marine and continental shales in the Sichuan Basin, China

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ABSTRACT

Lithofacies types of the marine shale of the Lower Cambrian Qiongzhusi Formation in the southwestern Sichuan Basin and the continental shale of the fifth member of Upper Triassic Xujiahe Formation in the western Sichuan Basin were classified based on a modified three-end diagram concerning the contents of siliceous minerals, carbonate minerals and clay minerals. Various experiments including X-ray diffraction, low pressure nitrogen adsorption, high pressure methane adsorption, and gas content measurement were designed for comparative analyses among different lithofacies in terms of core, pore structure, methane adsorption and gas-bearing characteristics. Then, the discrepancies between marine and continental shales lithofacies were analyzed, and the effects of lithofacies on gas adsorption and storage capacities were investigated. It is demonstrated that there are mainly five types of lithofacies developed in the marine shale of the study area, namely siliceous shale lithofacies (S), mixed siliceous shale lithofacies (S-2), clay-rich siliceous shale lithofacies (S-3), silica-rich argillaceous shale lithofacies (CM-1), and argillaceous/siliceous mixed shale lithofacies (M-2), while there are also mainly five types of lithofacies developed in the continental shale of the study area, which are carbonate-rich siliceous shale lithofacies (S-1), mixed siliceous shale lithofacies (S-2), clay-rich siliceous shale lithofacies (S-3), silica-rich argillaceous shale lithofacies (CM-1), and argillaceous/siliceous mixed shale lithofacies (M-2). Geological characteristics significantly vary among different lithofacies in terms of core, pore structure, methane adsorption and gas-bearing characteristics. Compared to the continental shale lithofacies, the marine shale lithofacies was characterized by a higher proportion of siliceous shale lithofacies group and a lower proportion of argillaceous shale lithofacies group, which could be attributed to different sedimentary environments and sediment provenances. On the condition that the organic matter content keeps constant, the silica-rich argillaceous shale lithofacies (CM-1) is favorable for adsorbed gas storage due to its strong methane adsorption capacity resulting from the highest clay minerals content, while the siliceous shale lithofacies group is favorable for gas storage due to its well-preserved primary and organic pores resulting from the highest siliceous mineral content.

1. Introduction

Shale gas has become a new prospect of global unconventional oil and gas exploration and development, and China has conducted a series of regional basic researches on shale gas enrichment mechanism, which implicates tremendous resource potential (Chen et al., 2011, 2014; Du et al., 2015a,b; Tan et al., 2014a,b). The discovery of Fuling shale gas field in the Sichuan Basin has greatly promoted the development of shale gas industry in China (Chen et al., 2015; Guo and Zhang, 2014; Yang et al., 2016).

Although commercial shale gas production has recently begun at a few shale gas fields in China, there has been significant

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controversy on the classification of lithofacies which is regarded as the basis of shale and shale gas. The concept of “facies” originated from Amnaz Gressly, a Switzerland geologist, who referred facies as the overall characterization of lithological and biological characteristics of sedimentary rocks (Cross and Homewood, 1997; Teichert, 1958). “Lithofacies” was first used by Russian geologist Eberzin in 1940, and its essence is the extension of “facies” as it highlights the characterization of lithological characteristics of sedimentary rocks (Krumbein, 1948). To be specific, lithofacies is the overall reflection of mineral composition, texture, bedding, structure, color, size distribution, sorting and roundness (Borer and Harris, 1991; Khalifa, 2005; Qi and Carr, 2006; Qing and Nimegeers, 2008; Tang et al., 2016a).

Rapid development has been experienced in shale lithofacies, and the criterion has also been changing. When it refers to shale lithofacies classification standards, single mineral content now is highlighted rather than the combination of mineral composition, paleontology, texture and structure (Chen et al., 2015; Jarvie et al., 2007; Wang and Carr, 2012, 2013). In terms of research methods, more attention has been paid to geophysical method based on well logging and seismic rather than petrological and geochemical methods (Doyle and Sweet, 1995; Yao and Chopra, 2000). As for the classification of shale lithofacies types, results are more systematic and accurate rather than random (Mitra et al., 2010). Although it has been noted that there are significant differences among different shale lithofacies in mineral composition, organic matter content and gas content (Abouelresh and Slatt, 2012; Dong et al., 2015; Du et al., 2015a; Han et al., 2016; Jiang et al., 2013), there is still lack of unified standard about the classification of marine and continental shales lithofacies which formed in different sedimentary environments.

At present, different opinions and different methods have been suggested in terms of the shale lithofacies classification, which can be generally grouped into three types: (1) macroscopic sedimentary characteristics such as shale texture and structure characteristics (Hickey and Henk, 2007; Loucks and Ruppel, 2007); (2) mineral composition (Wang and Carr, 2012, 2013); and (3) paleontology such as graptolite shale microfacies and radiolarian shale microfacies (Li and Quan, 1992). Among them, the second type is an important way to identify favorable area for shale gas enrichment (Wang and Carr, 2012, 2013), which is applicable to both marine and continental shales. Therefore, a modified three-end diagram concerning the contents of siliceous minerals, carbonate minerals and clay minerals is introduced in this study to accurately classify and evaluate lithofacies types of the marine shale of Lower Cambrian Qiongzhusi Formation in the southwestern Sichuan Basin and the continental shale of the fifth member of Upper Triassic Xujiahe Formation in the western Sichuan Basin. Furthermore, the effects of lithofacies on gas adsorption and storage capacity are discussed based on the results of methane adsorption and gas content measurements. This study can be of great significance for shale gas exploration and development.

2. Samples and experiments

2.1. Geological setting and samples

The Sichuan Basin is located in the southwestern part of China (Fig. 1). It is a huge petroliferous basin characterized by the stable tectonic background and multiple structural evolution cycles, and it is bounded by the Micang Mountain (uplift) and Daba Mountain (fold belt) in the north, the Daxiangling and Dalou Mountains in the south, and the Longmen Mountain (fold belt) in the northwest (Ma et al., 2007). In terms of administrative regions, it covers a vast area of the eastern Sichuan province and most of the Chongqing metropolitan region, with an area of more than 180,000 km^2. Tectonically, the basin is composed of six structural districts: the west district, the north district, the east district, the south district, the southwest district and the central district.

There are mainly two periods in terms of tectonic evolution: an earlier cratonic depression forming stage during the period from the Paleozoic to the Early Triassic and a later foreland basin forming stage starting from the Late Triassic (Zhu et al., 2007). At the end of the Middle Triassic, the basin experienced a transition from marine to continental sedimentation. The Late Himalayan period since 25Ma was an important period of tectono-thermal evolution in the basin, during which the basin was in a compressed and uplifted tectonic dynamical environment. In this tectonic environment, the present structure of the Sichuan Basin was formed by folding. There are totally six tectonic cycles in the evolution history, which are Yangtze, Caledonian, Hercynian, Indosinian and Yanshanian and Himalayan orogenies (Li et al., 2015), all of which gave rise to the complex deformation and denudation in the Sichuan Basin.

In this study, a total of 128 samples are collected, including 8 marine shale samples of Qiongzhusi Formation from well JS1 (JS1-1~JS1-8), 82 marine shale samples of Qiongzhusi Formation from well JY1 (JY1-1~JY1-82), 23 continental shale samples of the fifth member of Xujiahe Formation from well XY1 (XY1-1~XY1-23), and 15 continental shale samples of the fifth member of Xujiahe Formation from well XY2 (XY2-1~XY2-15). All the shale samples were collected from fresh core materials, with the weight up to 100–200 g. Each of them was then crushed to 60 mesh particle size below and got sufficiently mixed.

2.2. Mineralogical composition determination by XRD

Quantitative X-ray diffraction (XRD) measurement of randomly oriented powders was used for the mineralogy analysis of the shale samples at Experimental Research Center of East China Branch, SINOPEC. All shale samples were conducted with mineral composition analysis and each sample (approximately 5 g) was crushed and sieved for a 300 mesh (0.75 mm) size fraction. The measurements were performed on Ultima IV diffractometer using Cu Kα-radiation ($\lambda = 0.15418$ nm) produced at a voltage of 40 kV and a current of 40 mA. A scan rate of 4° (2θ)/min was used in the range of 5°-45° for the recording of the XRD traces. The relative mineral percentages were estimated semi-quantitatively using the area under the curve for the major peaks of each mineral with correction for Lorentz Polarization (Chalmers and Bustin, 2008).

2.3. Low pressure N_2 adsorption

By using a Micromeritics® Tristar II 3020 surface area analyzer, low pressure (<0.127 MPa) N_2 adsorption analyses was performed at State Key Laboratory of Heavy Oil Processing in China University of Petroleum, Beijing. A total of 10 shale samples were selected, including 2 of Qiongzhusi Formation from well JS1, 3 of Qiongzhusi Formation from well JY1, and 5 of the fifth member of Xujiahe Formation from well XY1. Shale sample aliquots weighing 1–2 g were analyzed with N_2 to obtain information about microscopic pore structure. Samples were crushed into grains of 60–80 mesh size (250-180 μm) and automatically degassed at about 110 °C under vacuum for about 14 h to remove adsorbed moisture and volatile matter before analyzing with N_2. The sample was kept at the temperature of liquid nitrogen (77.35 K at 101.3 kPa) in order to quantify nitrogen gas adsorption. The relative pressure (P/P_0) for N_2 adsorption ranges from 0.001 to 0.995. The equilibrium interval (time over which the pressure must remain stable within a very small range) was set at 30 s, and the pressure tolerance was set at 0.6666 kPa (5 mmHg). Based on multiple adsorption theories, the