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Lithofacies characteristics and its effect on gas storage of the Silurian Longmaxi marine shale in the southeast Sichuan Basin, China

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ABSTRACT

Based on a detailed description and analysis of outcrops and drilling cores, onsite gas desorption, and laboratory testing data, shale lithofacies characteristics and its effect on gas storage of the Silurian Longmaxi Formation marine shale in the southeast Sichuan Basin have been studied. Twelve types of shale lithofacies are classified based on the organic matter content and mineral composition, of which 9 types were identified in the study area based on their dramatically differences in color, grain size, lamination, organic matter content, mineralogy, density, and other physical properties. The bottom of the Longmaxi shale Formation is primarily organic-rich siliceous shale with stable distribution of thickness and good continuity. The upper section has characteristics of rapid vertical and lateral change in lithofacies, exhibiting a strong spatial heterogeneity. Organic-rich siliceous shale in the lower section, showing the highest content of gas desorption in situ, has a high content of organic matter, a high brittleness index and good permeability, which is conducive to shale gas storage, hydraulic fracturing, and exploitation. Organic-rich argillaceous shale was also observed to have the highest methane adsorption capacity. The interval with lithofacies association of organic-rich siliceous shale with organic-rich argillaceous shale interlayer is the pay zone for shale gas generation and accumulation.

1. Introduction

In recent years, the exploration of shale gas has been conducted in an orderly fashion in China. The exploration practice shows that the reservoir characteristics are important for shale gas accumulation. However, the key to the study of reservoir characteristics is to identify favorable lithofacies for commercial development (Jacobi et al., 2008; Sahoo et al., 2014). Due to the strong heterogeneity of shale reservoirs from the macro-scale to micro-scale, it is difficult to predict effective shale gas reservoirs (Chen et al., 2015; Jiang et al., 2015). Thus, a new method should be used to comprehensively evaluate shale gas reservoirs to accurately characterize their geochemistry, mineralogy, petrology, petrophysics and gas storage potential. Elucidating these features is important for predicting productive shale lithofacies. The lithofacies is the basic unit that constitutes a shale reservoir, reflecting geochemical, geological and petrophysicsal information. Every typical lithofacies reflects the characteristics of one type of shale reservoir with a relatively high level of homogeneity (Slatt and Rodriguez, 2012). Thus, studying lithofacies is one effective method of evaluating a shale reservoir and studying the main controlling factors of shale gas accumulation. Systemic investigation on the characteristics of lithofacies, such as the distribution of mineral composition, content of organic matter, gas storage potential, and the relationship between lithofacies and gas content, would benefit shale gas exploration and development (Abouelresh and Slatt, 2012; Rivard et al., 2014).

Eberzin (1940) first used the term “lithofacies” in geology to describe the lithological characteristics of sedimentary rock. The lithofacies characteristics could be described by partially qualitative and partially quantitative parameters, including mineral composition, texture, structure, bedding, color, size distribution, roundness and sorting (Dill et al., 2005). Before the successful development of

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shale gas, studies of lithofacies focused on conventional sandstone and carbonate reservoirs, which reflect their sedimentary setting and process. However, the understanding of shale lithofacies remains poor (Wang and Carr, 2012; Slatt et al., 2014).

At present, many studies on the lithofacies of shale reservoirs have been carried out, mainly focusing on the Barnett Shale and Marcellus shale (Loucks and Ruppel, 2007; Singh, 2008; Wang and Carr, 2012). In China, the studies of shale lithofacies have just begun, and much important information has been accumulated, mainly focusing on a qualitative description of the outcrops and drilling cores. For instance, shale was classified into categories including carbonaceous shale, siliceous shale, silty shale, and calcareous shale and described extensively (Du et al., 2014; Tan et al., 2014; Chen et al., 2015). These studies are of great significance for understanding the sedimentary process and setting of shale and characterizing shale reservoirs. As shale is a fine-grained sediment and poorly exposed on surface, it is very difficult to describe outcrops, resulting in an ineffective classification of shale lithofacies (Hughes and Thomas, 2011). In addition, some shales comprise a high content of expandable clay minerals, which would be easily reactive to water, resulting in swelling and deformation and a difficulty of making thin section as well as great difficulty of microscopic description. Due to different research objectives and laboratory methods, different definitions and classification criteria for shale lithofacies, there have been too many complex classifications of shale lithofacies (Schieber and Zimmerle, 1998). Thus, it is necessary to choose an appropriate, simple and practical approach to scientifically classify shale lithofacies to reflect their mineral composition, texture, structure, content of organic matter, gas storage potential and geomechanical properties.

The purpose of this paper is to scientifically classify shale lithofacies based on sample description and analysis of sample tests of rock properties and gas content, and then to investigate the characteristics of each shale lithofacies of the Silurian Longmaxi Formation in the southeastern Sichuan Basin and their control of its gas storage potential. All samples of the Silurian Longmaxi Shale were from outcrops and drill cores from CY 1 to CY 6 wells in the southeast Sichuan Basin, China (Fig. 1).

2. Theory

2.1. Selection of lithofacies parameters

Shale gas exploration and development in North America shows that the analysis of shale lithofacies is the key to evaluating shale gas reservoir volume, fracturing, and gas productivity (Hickey and Henk, 2007). It is an effective technology to recognize favorable targets at the regional or basin scale (Loucks and Ruppel, 2007). Thus, the classification of shale lithofacies should be capable of reflecting gas storage capacity, horizontal fracturing effect and gas flow capacity in shale (Wang and Carr, 2012).

The shale gas storage capacity has a good positive correlation with the organic matter richness. Shale reservoirs with high total organic carbon (TOC) content have relatively high gas adsorption capacity, representing high gas storage potential (Chalmers and Bustin, 2008). Exploration in the southeastern Sichuan Basin shows that shale samples with a TOC content greater than 2 wt. % have a gas storage content greater than 1 m^3/t, as demonstrated by onsite shale gas desorption experiment to get gas content close to in situ condition. Hence, organic matter is regarded as an important parameter for the classification of shale lithofacies.

The effectiveness of hydraulic fracturing is mainly controlled by geomechanical properties, which are closely related to mineral composition (Jarvie et al., 2007). Compared to clay minerals, the high content of quartz and carbonate would improve the fracability of shale, resulting in the easier generation and propagation of a widespread complex fracture network (Rickman et al., 2008; Sondergeld et al., 2010). Thus, mineral composition should be considered in the classification of shale lithofacies to reflect the geomechanical properties.

The shale gas flow capacity is mainly determined by the development situation and the connectivity of the pores in shale (Slatt and O'Brien, 2011). However, these parameters are closely related to the mineral composition and content of organic matter of the shale (Jiang et al., 2015). Organic matter tends to contribute the development of many nanoscale pores, while minerals mainly develop microscale and nanoscale pores (Tang et al., 2015). For shale with the same maturity, the shale gas storage potential and the ratio of free gas to absorbed gas are related to the content of organic matter and mineral composition (Wang and Carr, 2012). Thus, shale lithofacies can reflect the gas flow capacity through considering organic matter and the mineral composition.

Therefore, the critical criteria for defining shale lithofacies should include organic matter and inorganic mineral composition instead of texture, bedding, structure, and particle size distribution. Shale lithofacies divided based on the organic matter richness and mineral composition could effectively reflect the quality of shale reservoirs. Furthermore, the content of organic matter and mineral composition could be easily and accurately obtained through consistent experiments using same instruments in the same labs.

2.2. Definition of lithofacies parameters

The threshold of hydrocarbon generation in shale remains controversial. Schmoker (1981) and Peters and Cassa (1994) suggested that shale with a TOC greater than 2 wt. % has good hydrocarbon generation potential. Jarvie (1991) noted that shale with a TOC >1 wt. % could be of sufficient hydrocarbon generation potential to be regarded as an effective source rock. Bowker (2007) argued that a TOC of at least 2.5 wt. %–3.0 wt. % was necessary in commercial shale gas fields. Burnaman et al. (2009) showed that a shale reservoir should have a TOC of at least 2 wt. %. The Longmaxi Formation marine shale in southern China consists mainly of type I kerogen, which is at the over-mature stage, leading to obvious differences between the contents of original organic matter and remnant organic matter, presenting an effective shale reservoir with a remnant organic matter of approximately 1 wt. % (Chen et al., 2011). In the southeastern Sichuan Basin, samples with TOC>1 wt. % are generally gas-bearing proven by onsite gas desorption experiments, and those with TOC>2 wt. % are generally measured to have gas desorption contents of greater than 1 m^3/t (Guo and Zhang., 2014). Furthermore, with a TOC>2 wt. %, the shale porosity is mainly contributed by organic pores rather than inorganic pores, and the shale gas exists mainly as absorbed gas state (Tang et al., 2015). Therefore, taking the TOC contents of 1 wt. % and 2 wt. % as demarcations for lithofacies classification is reasonable.

When the content of clay minerals is greater than 40%, the shale generally shows plasticity (Jarvie et al., 2007). Although a high content of clay minerals could favor shale gas adsorption, it is disadvantageous for shale fracturing. Shale consisting mainly of clay minerals also presents relatively strong homogeneity (Wang and Carr, 2012). Thus, shale of a clay mineral content of greater than 40% is considered argillaceous shale.

With a clay mineral content of less than 40%, shale is brittle, which is favorable for hydraulic fracturing. The influences of calcareous and siliceous minerals on the shale properties also become significant. The shale properties are actually the composite results of different types of minerals (Jiang et al., 2015). When Ca/Si > 2, calcareous minerals prevail, indicating a warm and shallow water sedimentary setting, which is disadvantageous for the