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Research paper

Geochemistry and sedimentology of the Lower Silurian Longmaxi mudstone in southwestern China: Implications for depositional controls on organic matter accumulation

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A B S T R A C T

Spatial and temporal changes of lithofacies and abundance of organic matter in mudstones control distribution of prospective unconventional petroleum reservoirs in a sedimentary basin. Lithofacies characterization is an essential prerequisite to understanding of organic matter accumulation, depositional processes and water column chemistry. This research combines geochemical analyses and detailed sedimentologic observations in order to investigate the depositional controls on organic matter abundance in the prolific black mudstone of the Long-1 Member of the Lower Silurian Longmaxi Formation in southwestern China.

Six primary lithofacies deposited at variable marine water depths and under differing water column chemistry were identified from an 83 m long core based on microscopic observations of sediment texture and structure, and biota, and analyses of total organic carbon (TOC) content, mineralogy, and trace element abundances. Our results show that TOC content is well correlated to biogenic quartz content and the non-detrital components of V, U, Mo, Ni and Cu, suggesting the accumulation of organic matter in the studied mudstone was controlled by high paleoproductivity and anoxic water conditions. The good correlations also suggest that the abundant organic matter was produced by algal blooms, which are typically associated with radiolarian thrive because of the symbiotic relationship between algal and radiolarian. The low Mo/TOC ratios of the three lithofacies formed in deep, anoxic environments were similar to the ratios of modern sediments deposited in anoxic-euxinic environments, suggesting moderate basin restriction during deposition. The mudstone in the lower Longmaxi Formation may be part of the globally abundant organic-rich mudstones of Early Silurian age, whose depositional mechanism have yet to be fully explored.

The distribution of lithofacies in the studied interval shows an overall trend from deep water to shallow water depositional environments. We developed a detailed depositional model to interpret the evolution of depositional environments of the lower Longmaxi Formation. This study provides an example to how better characterize unconventional hydrocarbon systems through coupling of rigorous geochemical and sedimentological analysis.

1. Introduction

Mudstones with high TOC (>1.0 wt%) and high hydrocarbon yield upon pyrolysis are good source rocks (e.g., Bissada, 1982; Katz, 2005). Although such source rocks have very low porosity and

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permeability, they are in certain cases prolific unconventional reservoirs because hydraulic fracturing and horizontal drilling have made commercial hydrocarbon production from such rocks feasible (e.g., Hao et al., 2013; Tan et al., 2014; Camp et al., 2016). Rock texture, composition, organic carbon type and amount are often heterogeneously distributed throughout each mudstone unit, making geologic characterization of unconventional reservoirs a requirement that has to be part of each evaluation of gas capacity, optimization of well designs, and stimulation strategy (Bowker, 2007; Hickey and Henk, 2007; Ross and Bustin, 2008; Chen et al., 2011; Guo, 2013; Hart et al., 2013; Romero-Sarmiento et al., 2013; Sondergeld et al., 2013; Tan et al., 2014).

Depositional processes, productivity, and bottom water redox conditions have a profound control on the basin-wide distribution of lithofacies as well as the amount and quality of organic matter (e.g., Pedersen, 1985; Wignall, 1989; Macquaker, 1994; Macquaker et al., 2010; Bowker, 2007; Hickey and Henk, 2007; Loucks and Ruppel, 2007; Schieber et al., 2007; Könitzer et al., 2014). Recent advances using microscopic techniques have allowed significant progress in understanding mudstone heterogeneity and the underlying depositional processes that form fine-grained sedimentary rocks. For example, studies about major gas shale plays in North America, including the Barnett Shale in the Fort Worth Basin and the Marcellus Shale in the Appalachian Basin, have demonstrated that mudstone lithofacies can be well characterized based on mineralogy composition, rock texture, and organic matter content, and are crucial for effective placement of lateral wells and choice of proppant material (e.g., Jarvie et al., 2007; Hickey and Henk, 2007; Loucks and Ruppel, 2007; Abouelresh and Slatt, 2012; Wang and Carr, 2013). The combination of geochemical and sedimentologic approaches not only brings understanding to paleoproductivity and water chemistry conditions, but also unravels the relationships among organic matter accumulation, depositional processes and water column chemistry (e.g., Jiang et al., 2013; Könitzer et al., 2014).

The Lower Silurian black mudstone of the Longmaxi Formation is encountered throughout the upper Yangtze craton in southwestern China (Fig. 1). The Longmaxi Formation has long been known to be the principal source rock for conventional carbonate petroleum reservoirs of the Carboniferous Huanglong Formation and the Early Permian Qixia and Maokou formations (Zhang et al., 2011). The formation has recently become a target for exploration and development of unconventional shale gas. In the Sichuan Basin, the formation is 229–673 m thick (Chen et al., 2011), and the formation is thermally mature with a measured vitrinite reflectance (R_0%) varying from 1.5% in most parts of the basin to 3.5% in the Fulin-Shizhu area, the eastern Sichuan Basin and the Dazhou-Wanxian area in the northeastern Sichuan Basin (Wang et al., 2009; Liu et al., 2013; Wu et al., 2013). The lower Longmaxi Formation is the most prolific shale interval with a stable gas production rate greater than 60,000 m^3 per day in some wells in Fulin County. Previous studies of the Longmaxi Formation focused mainly on understanding the mechanisms of gas maturation and accumulation by characterizing the regional structure, sedimentation patterns, and the micro-pore structures, with the aim of making quantitative gas content predictions (e.g., Su et al., 2007; Yan et al., 2008; Zhang et al., 2011; Guo, 2013; Guo and Liu, 2013; Jiang et al., 2013; Liu et al., 2013; Chen, 2014; Guo et al., 2014; Guo and Zhang, 2014; Yan et al., 2014). A paleoenvironmental description and lithologic framework of the Lower Silurian strata within the Sichuan Basin has been presented elsewhere (e.g., Zhao, 1984; Chen et al., 1998; Wen et al., 2002; Wan and Xu, 2003; Guo et al., 2004; Wang et al., 2008; Jiang et al., 2013). A recent study of the Longmaxi Formation in the southeastern Sichuan Basin has documented sequence stratigraphic control on mudstone heterogeneity (Chen et al., 2015). However, as one of the most important source rocks and unconventional reservoirs in China and a prime example for a Lower Paleozoic deep shelf succession deposited during a worldwide marine transgression after the Early Silurian melting of Gondwana glaciation (Mu et al., 1981; Wang and Mo, 1995; Chen et al., 2004; Guo, 2013; Guo and Zhang, 2014; Yan et al., 2015; Yang et al., 2016), a detailed depositional model that explains the influences of depositional processes and water column conditions on organic matter accumulation in the prolific lower Longmaxi Formation is still lacking.

In this study, we characterize the mudstone-dominated lower Longmaxi Formation in an 83 m long, continuous vertical core from the JY1 Well in Fulin County, which is located in the center of the upper Yangtze craton (Fig. 1). We combine geochemical and sedimentological data collected from closely-spaced shale samples. Our geochemical analyses include TOC weight percentage, mineralogy compositions based on X-ray diffraction (XRD) analysis, and trace element index. Our sedimentologic study is based on microscopic observations of mineralogy, rock texture and structure, biota, and degree of bioturbation. The new data and lithofacies interpretation are used to develop a depositional evolution model of the lower Longmaxi Formation and understand the depositional controls on organic matter abundance.

2. Geologic setting and stratigraphy

The Sichuan Basin developed on the Precambrian metamorphic basement of the upper Yangtze craton (Zhang et al., 2012) (Fig. 1A). The accumulation of basinal, Lower Paleozoic strata was significantly influenced by several important tectonic events during the Sinian to Silurian, including the late Sinian Tongwan movements, the Early Cambrian Xingkai movements, the Late Cambrian Yunan movements, and the Late Ordovician to Late Silurian Kwangsian movements (Tong, 1985; Chen et al., 2013). By the Early Silurian, tectonics had formed several Kwangsian paleohighs surrounding the Sichuan Basin, including the Chuanzhong uplift in the west, the Xuefeng uplift in the east, and the Qianzhong uplift in the south of the basin (Wang and Mo, 1995; Chen et al., 2006) (Fig. 1A).

The Lower Silurian Longmaxi Formation is widespread in the Sichuan Basin, and pinches out toward the Chuanzhong uplift (Guo, 2013; Guo and Zhang, 2014). The formation is dominantly composed of mudstones that were deposited during a major marine transgression after the Early Silurian global glacial ablation (e.g., Mu et al., 1981; Wang and Mo, 1995; Chen et al., 2004). In Fulin County, the Longmaxi Formation is conformably overlain by the Silurian Xiaoheba Formation and is underlain by the Ordovician Wufeng Formation (Guo and Liu, 2013) (Fig. 1B). The Longmaxi Formation is divided into three members which are, from bottom to top, including the Long-1 Member, which is composed of black mudstone and argillaceous siltstone; the Long-2 Member, which consists of light gray argillaceous siltstone and fine-grained sandstone; and the Long-3 Member dominated by gray mudstone (Chen, 2014). The Long-1 Member is the major gas-bearing interval in the Longmaxi Formation and the focus of this study (Fig. 1).

3. Methods

This study integrates the observations of sedimentary structure and texture, and chemical and biogenic features in core and thin sections of an 83 m long drill core from the JY1 Well, which was drilled by China Petroleum and Chemical Corporation in November 2012 (Guo and Zhang, 2014). XRD analysis of 80 samples, TOC analysis of 93 samples, and trace element analysis of 88 samples were included to characterize the mudstone lithofacies and assist with the interpretations of depositional environments. Samples