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Comparison of marine, transitional, and lacustrine shales: A case study from the Sichuan Basin in China

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ABSTRACT

Shale reservoirs have different properties and production performance depending on their geologic nature. Study of Precambrian to Jurassic shales in the Sichuan Basin in China indicates that the marine, transitional environment and lacustrine shales have tremendous shale gas and oil potential. Regional shale property mapping, recent drilling and production data, lab tests of 187 samples for geochemistry, mineralogy and petrophysics, and comparison of properties between shales reveal the distinctive reservoir characteristics between different type of shales: the shale of marine origin exampled by widespread Precambrian to Silurian shales has high to over maturity, high TOC, highest brittle mineral content, lowest clay content (< 40%), and high gas content; The shale of coal-associated transitional origin exampled by Upper Permian shale has the highest clay content (usually > 50%) and high to over maturity; The shale of lacustrine origin exampled by Triassic to Jurassic shales is relatively clay-rich compared to the marine shale but is less clay-rich compared to transitional shale. The maturity of Triassic lacustrine shale is high, while the Jurassic shale is mature in the oil to wet gas window. All of the shales in the Sichuan Basin have porosity less than 9% and the marine shale has more micron-scale to nano-scale organic pores than the transitional and lacustrine shales. The marine shale has the lowest permeability, dominated by nanodarcy range permeability, while the lacustrine shale has the highest permeability, ranging from microdarcy to millidarcy. The marine shale in the Sichuan Basin has the best reservoir and completion quality.

1. Introduction

China is estimated to have the largest shale gas potential in the world, with the Sichuan Basin alone holding 626 TCF of technically recoverable shale gas resources (EIA, 2013). Most offered blocks for shale gas exploration are located in the Sichuan Basin and its neighboring areas, and nearly 800 shale gas wells have been drilled there in the last five years (Fig. 1).

The Sichuan Basin is the most important shale gas basin in the Yangtze Platform's major shale exploration and development areas, with shales ranging in age and depositional setting from Precambrian Sinian to Middle Permian marine shales, Upper Permian transitional setting (coastal swamp setting associated with coal measures) shales, to Triassic and Jurassic lacustrine shales, which are thought to have the greatest shale gas potential in China (Pu, 2008; Zhang et al., 2008; Cheng et al., 2009; Wang et al., 2009; Zou et al., 2010, 2011a; Huang et al., 2012; Stevens et al., 2013; Jiang, 2014; Jiang et al., 2016). So far, industry and academics have been focused on the quartz-rich marine shales through analog to successful U.S. marine shale plays, while the lacustrine and transitional shales have been considered less prospective due to clay-rich nature comparing to marine shale (De Silva et al., 2015; Jiang et al., 2016).

Petroleum exploration has taken place in the Sichuan Basin for more than 50 years, and approximately 300 natural gas accumulations

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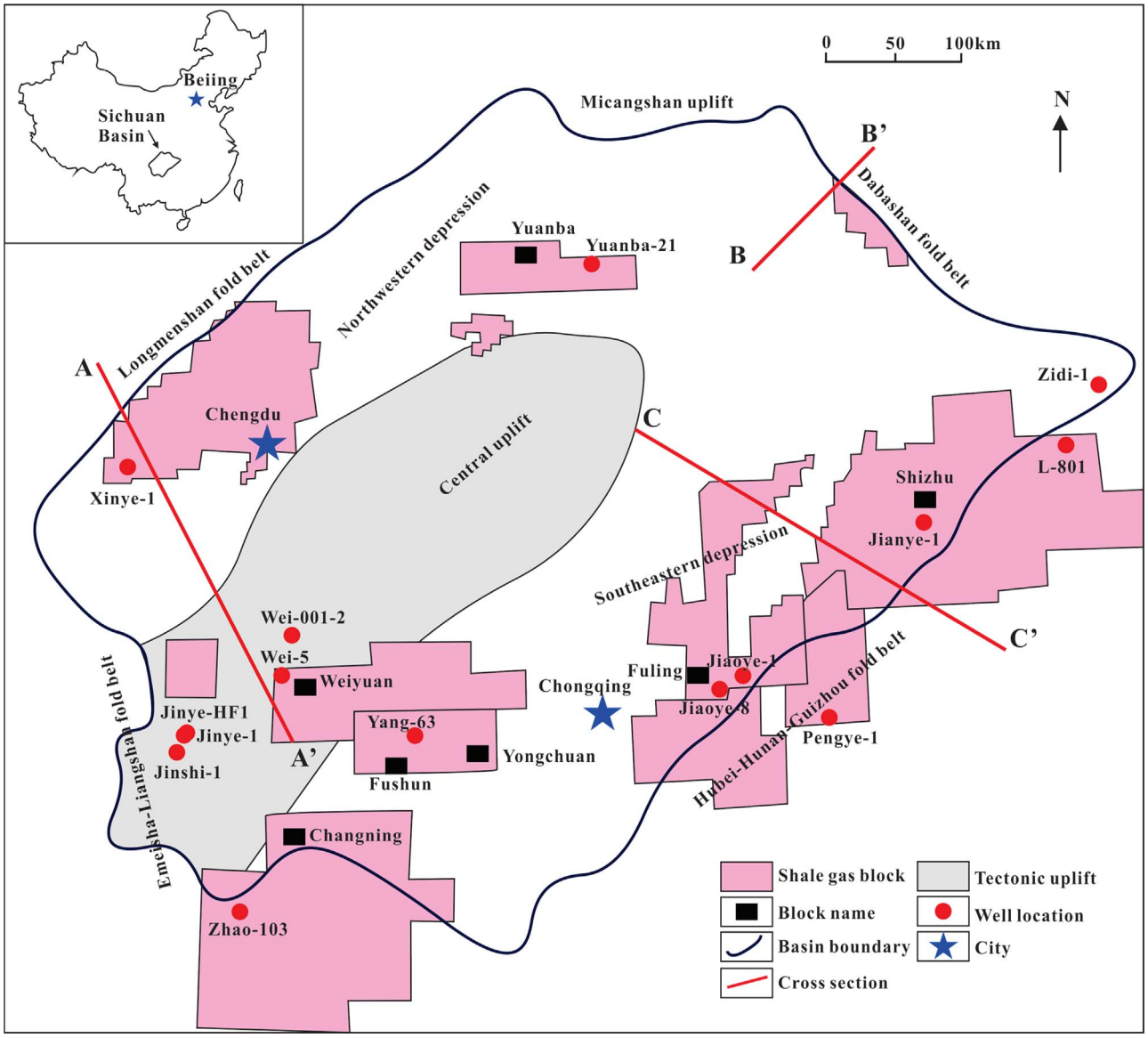

Fig. 1. Regional map of the Sichuan Basin. Most offered blocks for shale gas exploration are located in the Sichuan Basin and its neighboring areas. The locations of geologic cross-sections in Fig. 2 are shown in red lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

have been discovered (Ma et al., 2008). Conventional producing horizons range from Precambrian marine strata to Jurassic lacustrine strata, and the produced gas is mainly sourced from Precambrian Sinian, Lower Cambrian, Upper Ordovician, Lower Silurian, Permian, Upper Triassic, and Lower Jurassic shales (Ma et al., 2007, 2008). Historically, some gas shows have been recorded from shale source-rock intervals. In 1966, well Wei-5 in the Weiyuan area (shown in Fig. 1) of the southwest Sichuan Basin encountered a 15–22 m high well-kick as it drilled into the Cambrian Qiongzhusi marine shale at a depth of 2797 m. Daily output of 24,600 m^3 from this well was measured at a formation pressure of 29.17 MPa (Li et al., 2007; Zou, 2012; Guo and Zeng, 2015). Reports indicate gas shows have been observed in the Cambrian Qiongzhusi Formation in 68 intervals in 41 wells (Wei et al., 2012). In 1981, well Yang-63 (Fig. 1) was reported a low-yield gas flow during a formation test in the Silurian Longmaxi marine shale (Chen et al., 2014) and gas shows from Longmaxi shale have been reported in 32 intervals from 15 wells (Li et al., 2007; Hackbarth et al., 2011).

Sinopec announced the discovery of the Fuling Shale Gas Field (Fig. 1) in the southeastern Sichuan Basin with production from the Lower Silurian Longmaxi marine shale in 2014, making China the only country outside of North America to report commercial shale gas production. The Fuling area, including the Jiaoshiba Shale Gas Field, has shale gas resources of approximately 2×10^{12} m^3 (74 TCF). Sinopec and the China Ministry of Land and Resources (MLR) reported a 106-km^2 portion of this field to have geological reserves in excess of 107 billion m^3 (3.8 TCF) and technically recoverable reserves of 26.7 billion m^3 (0.96 TCF) in the Lower Silurian Longmaxi marine shale.

Many shale gas blocks in the Sichuan Basin were reported to have good production test results after hydraulic fracturing (Dong et al., 2015), e.g., Triassic lacustrine shale in western Sichuan Basin; Jurassic lacustrine shale in the Yuanba area (Fig. 1) in the north and NE Sichuan; Jurassic lacustrine shale in the Shizhu area (Fig. 1) in eastern Sichuan; and Cambrian to Silurian marine shales in the Weiyuan, Fushun-Yongchuan, and Changning blocks (Fig. 1) in southern and SW Sichuan Basin. But only marine shale in the Fuling area in the southeastern Sichuan Basin and Weiyuan and Changning blocks in the southern Sichuan Basin has produced at commercial scale so far. The U.S. shale gas development paradigm, such as slick water hydraulic fracturing, does not apply to lacustrine shale and transitional shale since the water will cause the swelling of clay-rich lacustrine and transitional shales (Jiang, 2014; Jiang et al., 2016).