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Research paper

Differential fluid migration behaviour and tectonic movement in Lower Silurian and Lower Cambrian shale gas systems in China using isotope geochemistry

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ABSTRACT

Isotope geochemistry has been introduced as a means to trace origin of the hydrocarbon and characterize highly productive shale gas systems recently. To assess the impact of tectonic movement and the sealing of shale gas systems, isotope geochemistry, pressure coefficients and the distribution of bitumens are analysed. Many samples yield isotope geochemical data with typical carbon isotopic reversals ($\delta^{13}C_1 > \delta^{13}C_2$) and hydrogen isotopic reversals ($\delta^{13}D_{C2H6} > \delta^{13}D_{CH4}$) in the Lower Silurian shale gas. Isotopically reversed gases are considered to originate in sealed, self-contained petroleum systems. Besides, isotope “reversals order” degree of shale gas has positive correlation with gas production. Isotopically normal gases from the Lower Cambrian indicate that this formation was a continued relatively open petroleum system when oil and gas generated. The pressure coefficients of the Lower Silurian shale gas reservoir range from 1.45 to 2.03, indicating that the reservoir is overpressurized, whereas the Lower Cambrian shale gas reservoir possesses a normal pressure system. Overpressurization of the Lower Silurian shale gas reservoir also indicates that it is a well-sealed system. The distribution and isotope geochemistry of bitumens in the Sinian dolomite and Cambrian shale suggests that the source rock of the Sinian hydrocarbon is the Cambrian shale. An unconformity induced from tectonic movement during the Tongwan period is interpreted to be the fluid migration tunnel and the cause of the differential shale gas content and production. Finally, the isotopic reversals associated with maturity, pressure coefficients and tectonic evolution can both assess the preservation conditions of the reservoir and explain the differential fluid migration behaviour.

1. Introduction

China has experienced a significant breakthrough in shale gas production in recent years. Sinopec stated that China produced more than 4.47 billion m^3 of shale gas in 2015 and that it will reach 20 billion m^3 in 2020 (data from Dr. Ma in the 8th International Symposium on Tight Sandstone and Shale Plays Exploration and Development). Most of the productive shales are found in the Lower Silurian Wufeng-Longmaxi shale and Lower Cambrian Qiongzhusi shale, Sichuan Basin, southwest China (Guo, 2016). However, the production and gas content of the Wufeng-Longmaxi shale are much greater than those of the Qiongzhusi shale (Zou et al., 2016).

Recently, isotope geochemistry has become a useful tool for shale gas exploration (Tilley and Muchlenbachs, 2013). The geochemical characteristics of shale gas and its utility for the shale gas industry have been discussed extensively (Martini et al., 2003; Zumberge et al., 2012; Wang et al., 2013). Numerous issues in shale gas systems can be examined with isotope geochemical data. Fluid and gas geochemical data are useful indicators in regional and

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tectonic studies (Yang, 2013). The major gas components (H_2O, CO_2, N_2, CH_4, S, and the halogens) and gas isotopes (of C, H, O, S, N, and the noble gases) are unique tracers that characterize the sources of gas and fluid samples and permit interpretation of their origin and migration behaviour (Yang et al., 2009). Wang et al. (2013) used carbon molecular moieties and isotopic data to trace the origins and migration process of natural gas in the northern Sichuan Basin. Zumberge et al. (2009) first observed and discussed isotopic reversal in gases within source-rock reservoir. Later, isotopic reversals were commonly considered restricted in sealed and self-contained system with mixing and accumulation of gases generated from diverse precursors (kerogen, retained oil and wet gas) at different thermal maturities (Hao et al., 2013; Xia et al., 2013; Curiale and Curtis, 2016). Furthermore, Tilley and Muchlenbachs (2013) used isotopic data and gas maturation levels to determine the relationship between high productivity shale and isotopic reversals, as well as trends of gas maturation in a sealed petroleum system. Additionally, the distribution of bitumens can indicate the presence of palaeo oil reservoirs as well as the pathways of hydrocarbon migration (Li et al., 2015). Therefore, isotope geochemistry, when associated with additional data, can be used to address diverse problems in shale gas systems and in other systems.

Source rock hydrocarbon generation, migration and accumulation are critically important in determining the present gas content of shale (Zhou et al., 2013). However, few studies have examined the differential gas content between the Cambrian and Silurian shale, nor have previous studies explained the poor gas content of the Cambrian shale. In this study, gas isotopic reversals, pressure coefficients and the geochemistry and distribution of bitumens in the Cambrian and Silurian shale gas reservoirs were used to identify the origin and migration of gas, to assess the sealing of the two shale gas systems and to examine the impact of tectonic movement in the Cambrian.

2. Geological setting

The Sichuan Basin is located to the east of the Tibetan Plateau, southwestern China (Fig. 1). The Sichuan Basin is in the transition zone between the Palaeo-Pacific Tectonic area and Tethys-Himalayan Tectonic area, bounded by the Longmen Mountains to the west, Micang and Daba Mountains to the north, Qiyue and Dalou Mountains to the east, and Daliang Mountains and Yunnan-Guizhou Plateau to the south (Liu et al., 2016). The tectonic evolution of the Sichuan Basin occurred in two stages: an earlier cratonic depression in the Palaeozoic and a later foreland basin stage in the Triassic (see Fig. 2).

The Sichuan Basin is a structurally complex, superimposed basin with prolific oil and gas production: it contains 106 gas fields and 14 oil fields. The largest shale gas fields (Fuling, Weiyuan, Changning) are found in the Sichuan Basin and the surrounding area, causing the Sichuan Basin to be regarded as the main productive shale gas area in China. Shale gas accumulations occur mainly in the Lower Cambrian Qiongzhusi shale formation (termed the Qiongzhusi Formation in most of the intrabasinal area but also called the Niutitang Formation along the basin's periphery) and the Lower Silurian Wufeng-Longmaxi shale formation. These two formations are mainly composed of marine, organic-rich shale with good shale gas potential. The primitive organic matter is dominated by amorphous macerals and belongs to type I and/or IIa kerogens (Dai et al., 2016). The equivalent vitrinite reflectance (EqVRo, %)

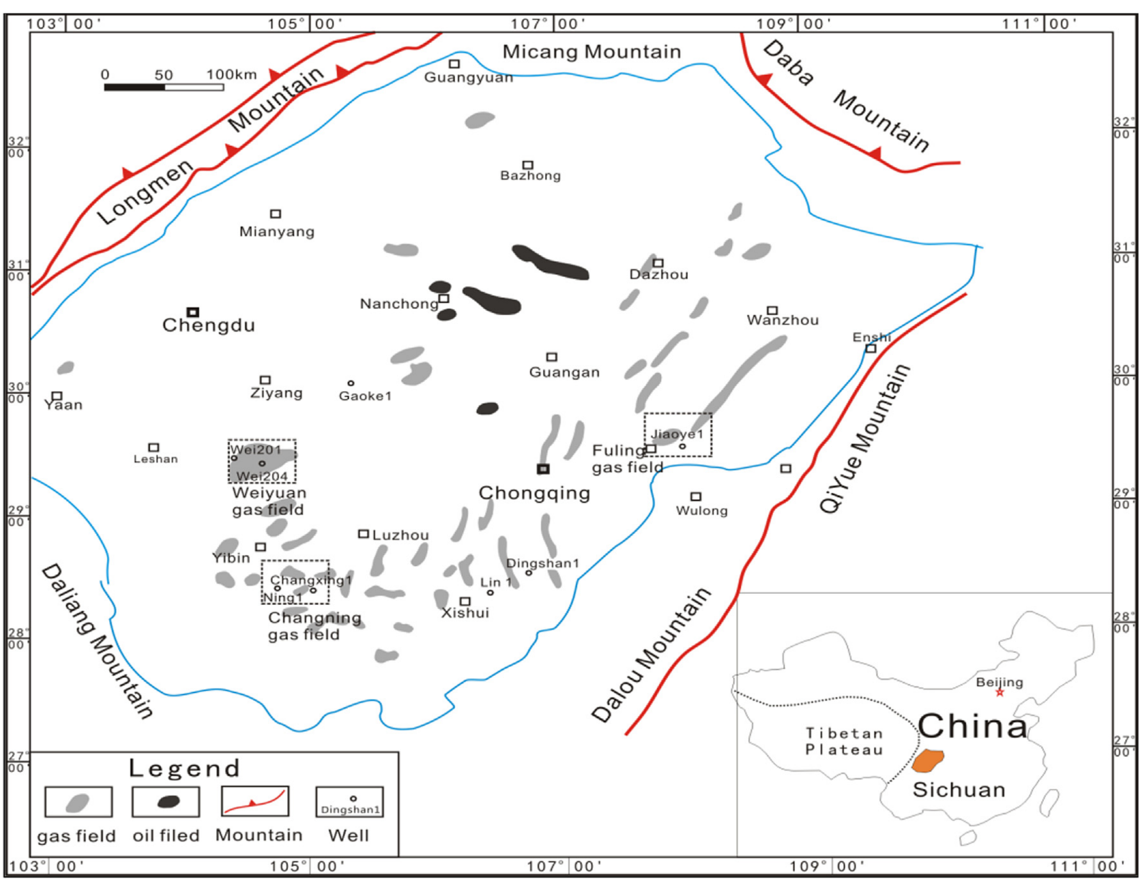

Fig. 1. Sketch map showing the structural outline of the Sichuan Basin and the location of major gas and oil fields.