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Origin and enrichment factors of natural gas from the Lower Silurian Songkan Formation in northern Guizhou province, south China

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ABSTRACT

The northern Guizhou area, located near the southwestern margin of the Yangtze Block and south of the Sichuan Basin, is a promising area for shale gas exploration and development. The discovery of a natural gas accumulation in the Lower Silurian Songkan Formation in the study area is the first discovery of natural gas in this stratum in China, marking an exciting breakthrough in natural gas exploration in northern Guizhou area. This paper presents an investigation of this accumulation using gas geochemistry, including gas composition, carbon and hydrogen isotopes, in context with geological information available for the study area.

Our results indicate that the natural gas accumulation in Songkan Formation is probably sourced from the Lower Silurian Wufeng-Longmaxi shale. The $\delta^{13}C(CH_4)$ values range from −33.9‰ to −33.2‰, the $\delta^{13}C(C_2H_6)$ values range from −37.0‰ to −36.2‰, and the $\delta^{2}H(CH_4)$ values range from −157‰ to −144‰. These results indicate that the gases are of thermogenic origin and are oil-derived. Furthermore, isotopic rollovers seen in the natural gas is similar to that seen in the natural gas from the local Wufeng-Longmaxi shale, which is identified as carbon exchange at high temperature. The $\delta^{13}C(CO_2)$ values range from −20.8 to −17.1‰, suggesting that carbon dioxide was mainly generated by thermogenic processes. The fracture investigation indicates that the large development of horizontal fractures in calcareous mudstone is one of the reasons for the high yield of natural gas in Songkan Formation. The petrophysical parameters suggest that limestone with low porosity and permeability effectively prevents natural gas escaping and seals natural gas into calcareous mudstone with horizontal fractures.

1. Introduction

Marine black shales were widely developed in the Upper Yangtze region of South China during the Early Cambrian, Late Ordovician-Early Silurian periods (Dai et al., 2016). The Upper Yangtze region is considered as an extremely promising area for exploration and development of shale gas resources (Zhang et al., 2008; Xiao et al., 2015; Zou et al., 2015). The Upper Ordovician-Lower Silurian Wufeng-Longmaxi Formation in the Sichuan Basin and its peripheral areas has become the focus of shale gas development in China (Wang et al., 2015).

In recent years, significant attention has been paid to the Wufeng-Longmaxi shale in the Sichuan Basin and the peripheral area for the high shale gas potential (Zhang et al., 2008; Zou et al., 2015; Wang et al., 2015), and the gas fields in Changning-Zhaotong, Fushun-Yongchuan, Weiyuan and Jiaoshiba areas have been discovered (Dai et al., 2016). Daily production in a single well ranges from 3×10^3 m^3/day to 430×10^3 m^3/day (Dai et al., 2014b; Guo and Zhang, 2014). The Wufeng-Longmaxi shale in the Sichuan Basin is characterized by large thickness, high organic matter abundance, high thermal maturity, strong gas generation capability and good rock brittleness, which are all conducive to the formation and enrichment of shale gas (e.g., Zhang et al., 2008; Zou et al., 2010; Dai et al., 2016). The Wufeng-Longmaxi shale is thought to have over one hundred billion cubic meters of gas reserves (Dai et al., 2016).

In 2016, the vertical drill (well AY-1) in the Lower Silurian Songkan Formation in the northern Guizhou province, identified the first accumulation of natural gas in this formation. The maximum initial production of well AY-1 reached 420×10^3 m^3/day, with an average yield of 95×10^3 m^3/day. This marked a major breakthrough in the exploration of natural gas in this area.

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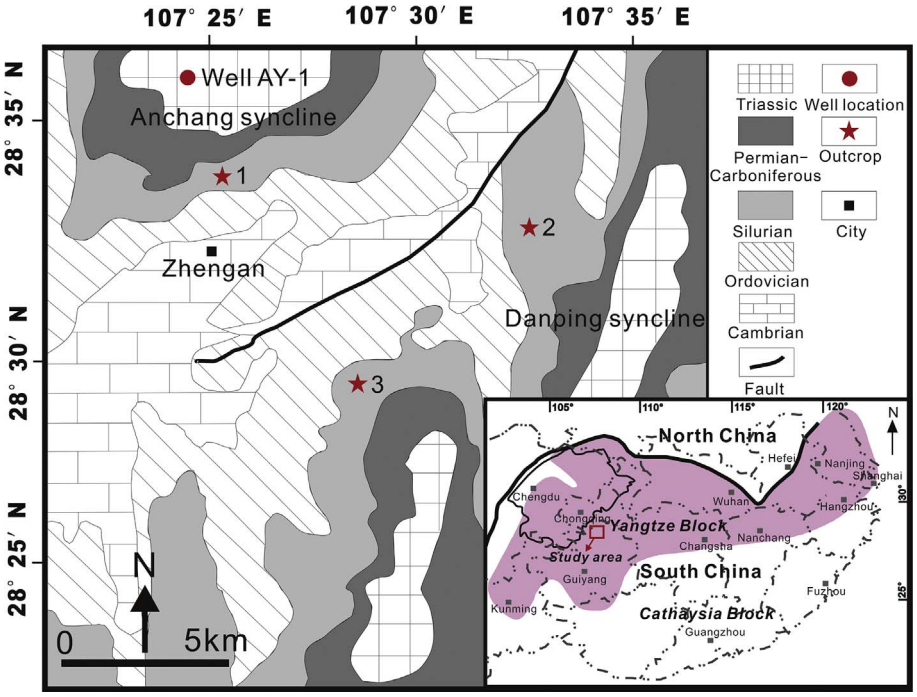

Fig. 1. Geological sketch map of the study area showing the location of outcrop and gas sampling sites.

The objective of this study is to determine the origin of natural gas in the Lower Silurian Songkan Formation using molecular and stable isotopic compositions of gaseous hydrocarbons and CO_2. By investigating the lithology in combination with the fracture characteristics, the main factors affecting gas accumulation were investigated.

2. Geological setting

The South China Block consists of the Yangtze Block in the northwest and the Cathaysia Block in the southeast. In the early and late Paleozoic, several large-scale transgression events have resulted in the formation of several black shale in southern China, i.e., the Lower Cambrian, Upper Ordovician-Lower Silurian, Lower Permian, and Upper Permian (Wen et al., 2001).

The northern Guizhou area is located near the southwestern margin of the Yangtze Block, south of the Sichuan Basin (Fig. 1). The exposed stratigraphic sequence in this area mainly consists of Cambrian, Ordovician, Silurian, Carboniferous, Permian, Triassic, Jurassic and Quaternary. There are mainly two black shale formations developed in the northern Guizhou area, the Niutitang shale formation in the Lower Cambrian and the Wufeng-Longmaxi shale formation in the Upper Ordovician-Lower Silurian. Both of them have good hydrocarbon generation capability, but differ greatly in results of shale gas exploration.

The lithology of the Upper Ordovician-Lower Silurian Wufeng-Longmaxi Fm. in the study area is mainly the marine organic-rich shale. The bottom of the formation is black carbonaceous shale, siliceous shale and grayish-black graptolite rich shale, while the upper of the formation is dark gray silty shale variably interbedded with dark gray argillaceous limestone and siltstone (Chen et al., 2014; Wang et al., 2014; Yan et al., 2015). Shallow-marine carbonate facies of the Lower Silurian expanded on the upper Yangtze Platform, mainly composed of Songkan and Shiniulan Formation (Rong et al., 2003). The lithology of the Lower Silurian Songkan Fm. in the study area is characterized by frequent interbeds of calcareous mudstone and limestone. The thickness of calcareous mudstone decreases from bottom to top, while the thickness of limestone increases gradually (Figs. 2, 3). The lithology of the overlying Shiniulan Fm. is bioclastic and reef limestone.

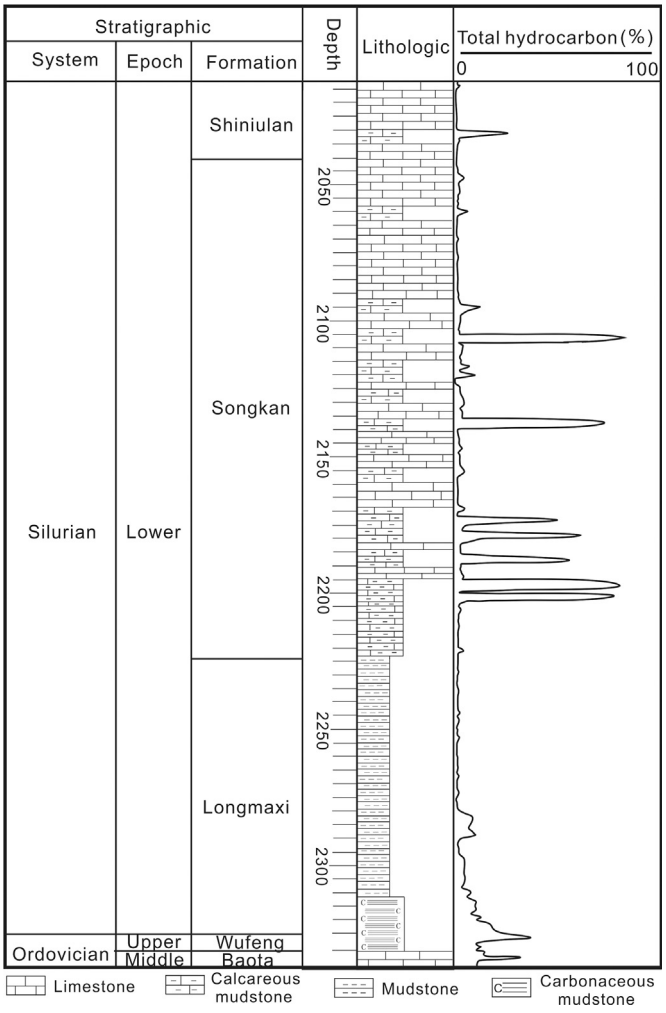

Fig. 2. The stratigraphic column of the Lower Silurian Wufeng-Longmaxi and Songkan Formation in northern Guizhou area.