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Thermal evolution and maturation of Sinian and Cambrian source rocks in the central Sichuan Basin, Southwest China

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ABSTRACT

The Sichuan Basin is among the basins with the most abundant oil and gas resources in China. The Sinian and Cambrian strata are the most important source rocks. Previous studies of the thermal history of the central Sichuan Basin have focused on the Late Paleozoic and studies of the Early Paleozoic thermal history are not available in literature and the thermal evolution of the Sinian and Cambrian source rocks are yet to be examined. A new thermal history was reconstructed using integrated thermal indicators, including apatite and zircon (U-Th)/He, zircon fission tracks, and equivalent vitrinite reflectance. The modeled results indicated that the heat flow was relatively low ($< 65\ mW/m^2$) from the Sinian to Early Permian. During the Middle-Late Permian, the heat flow reached a maximum value ($75–100\ mW/m^2$) which may have been controlled by the heating effect of the Emeishan mantle plume and crustal extension. Following the Triassic, the heat flow gradually decreased to its present value of $60–70\ mW/m^2$. The maturity histories of the source rocks, modeled based on the new thermal histories, indicate that the Sinian and Cambrian source rocks were slowly maturing during the Early Paleozoic, underwent rapid maturation during the Mesozoic, and reached the dry-gas stage during the Late Cretaceous. These new data on the thermal history and source rock maturity histories of the central Sichuan Basin provide new insights to guide oil and gas exploration of the basin.

1. Introduction

The central Sichuan Basin (CSB) is among the primary gas-producing regions in China (Fig. 1a and b). Hydrocarbon exploration in the CSB began during the 1960s. In 1964, the oldest Sinian gas field in China was discovered in the Weiyuan structure southwest of the Leshan-Longnüsi paleo-uplift (Xu et al., 1989). In 2013, the huge Anyue gas field was discovered in the Moxi-Gaoshiti block northeast of the paleo-uplift. The producing formations mainly developed in the Sinian Dengying Formation (Z_2dn) and Cambrian Longwangmiao Formation ($Є_1$l), with $779.9\ km^2$ of proven gas-bearing area and $4403.8 \times 10^8\ m^3$ of proven gas reserves (Zou et al., 2014a).

Thermal history is a thermodynamic response to tectonic evolution in a region controlling the maturation of source rocks (Qiu et al., 2010; Sahu et al., 2013; Zuo et al., 2015) and hydrocarbon generation and expulsion (Pang et al., 2012; Kosakowski et al., 2013). Sedimentary basins are generally subjected to complex thermal histories, such as subsidence (heating) and uplift (cooling), which are always difficult to reconstruct. The current methods typically include paleo-thermal indicators for sedimentary basins (Zuo et al., 2011; Qiu et al., 2012) and geodynamic models for the lithosphere (He et al., 2001, 2014); the former method is more accurate for sedimentary basins. Because of the complicated tectonic evolution of the Sichuan Basin, previous studies of the thermal history in the CSB have mainly focused on the Late Paleozoic and Mesozoic (Yang et al., 2004; An et al., 2008; Wang et al., 2011; He et al., 2011); only a few scholars have recovered the thermal history prior to the Paleozoic using geodynamic methods (He et al., 2014). However, the source rocks in the CSB mainly developed during the Sinian and Cambrian. As the main controlling factor for source rock maturity, the thermal history of the CSB prior to the Early Paleozoic should be recovered to determine the hydrocarbon generation and expulsion and resource potential of the source rocks from the Sinian and Cambrian.

This study contributed to the understanding of the thermal history of the CSB with a new interpretation by applying equivalent vitrinite reflectance (R_{equ}) and low-temperature thermochronological data as thermal indicators. Furthermore, this work modeled the maturity histories of the Sinian and Cambrian source rocks based on the new

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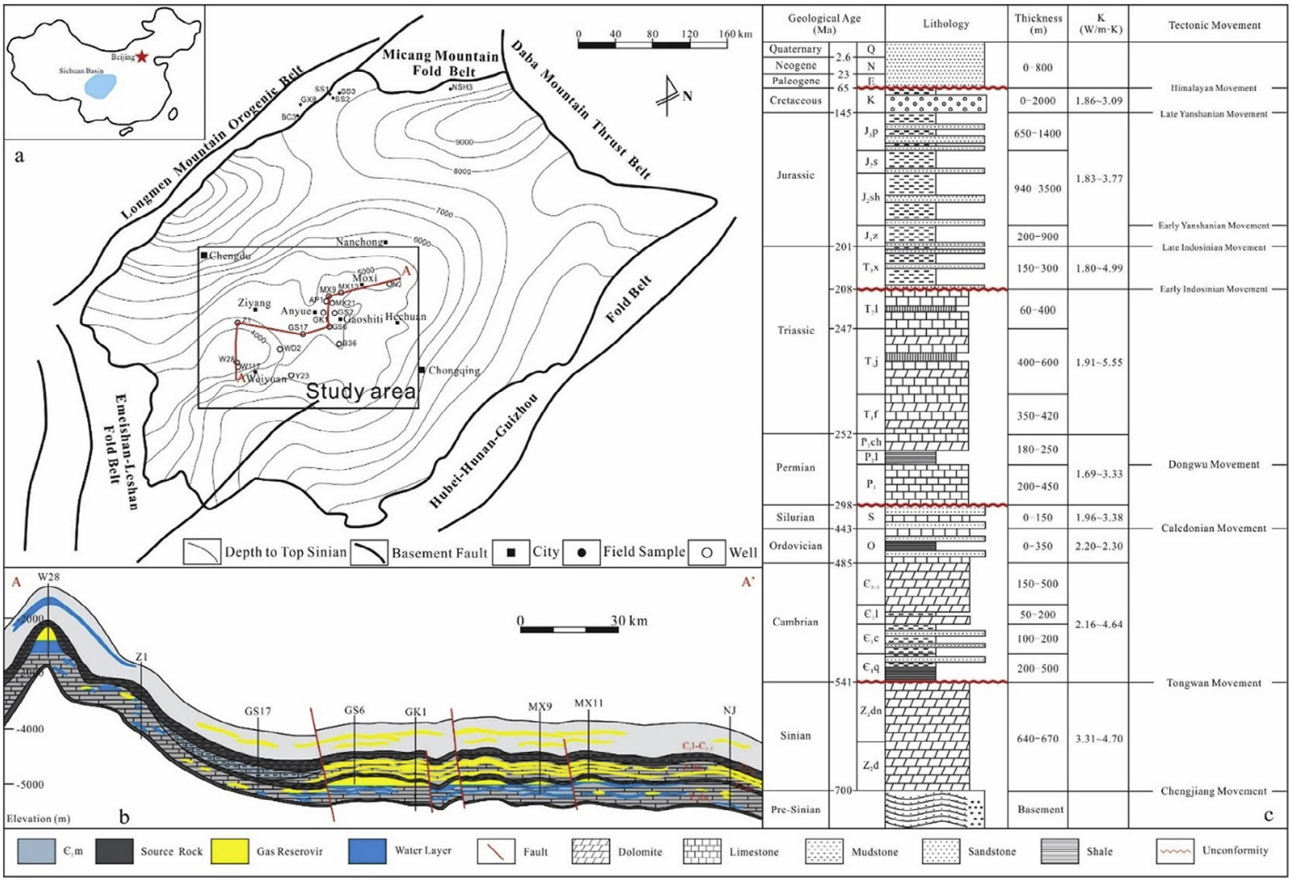

Fig. 1. (a) Tectonic map of the top surface of the Sinian system of the Sichuan Basin, (b) transverse section of the study area, (c) composite columnar section of the lithology. (Thermal conductivities are from Xu et al., 2011). (Modified from Zhu et al., 2015; Du et al., 2014; Tian et al., 2013).

thermal history. This study may provide fundamental information for further hydrocarbon exploration in the Sichuan Basin.

2. Geological settings

The Sichuan Basin is a diamond-shaped basin in southwestern China, covering an area of 230,000 km^2. Structurally, the basin is northwest of the Yangtze platform, bounded by the Longmen Mountain orogenic belt to the northwest, the Micang Mountain fold belt to the north, the Daba Mountain thrust belt to the northeast, the Emeishan-Leshan fold belt to the southwest, and the Hubei-Hunan-Guizhou fold belt to the southeast (Fig. 1a). The tectonic evolution of the Sichuan Basin after the Sinian is complicated, including differential uplift in an extensional system from the Sinian to the Late Triassic (Z-T_3), folding and thrusting under the background of compression from the Late Triassic to the Eocene (T_3-E), and further uplifting during the folding process from the Oligocene to the present (E-Q) (Liu et al., 2014a) (Fig. 1c). Several unconformities developed during this tectonic evolution: (1) the unconformity between the Late Sinian strata and the Early Cambrian strata during the Tongwan movement, (2) the unconformity between the Permian strata and the underlying strata during the Caledonian movements, (3) the unconformity between the Late Triassic strata and the Middle Triassic strata during the Early Indosinian movement, and (4) the unconformity between the Paleogene strata and the underlying strata during the Himalayan movement (Fig. 1c).

The formations developed in the Sichuan Basin can be classified into two sedimentary systems (Liu et al., 2016): the lower marine carbonate sedimentary system (from the Sinian to the Middle Triassic) and the upper continental clastic sedimentary system (from the Late Triassic to the Eocene). The Sinian strata are the oldest carbonate layers in the Sichuan Basin with black muddy dolomites in the lower Doushantuo Formation (Z_2d) and micritic dolomites in the upper Dengying Formation (Z_2dn). In the Early Paleozoic strata, thin layers of argillaceous siltstone and shale are developed at the bottom of the Cambrian and the thick carbonate rocks are developed in the Late Cambrian strata (Liu et al., 2014b); the Ordovician and the Silurian strata are also primarily composed of marine carbonate sediments. In the Late Paleozoic strata, the Devonian and the Carboniferous are generally absent in the basin affected by the Caledonian movement, but the Permian strata are characterized by the development of a carbonate platform with biolithite limestone, shale, and flagstone (Ma et al., 2007). The lithofacies in the Triassic strata are important evidence of the changing of the sedimentary environment: limestones, dolomites, and multiple sets of gypsolytes are developed in the Early Triassic strata; the Middle Triassic strata have developed transitional facies, and the Late Triassic Xujiahe Formation (T_3x) shows a transformation into continental deposition of mudstone and sandstone (Cao et al., 2018). Following these varying environments, the Jurassic and Cretaceous strata are primarily composed of shallow lacustrine and fluvial facies with the development of magenta sandstone. However, influenced by the Himalayan movement since the Late Cretaceous, the overlying strata above the Jurassic are nearly completely eroded (Deng et al., 2009; Zhu et al., 2009; Liu et al., 2012).

The CSB is a part of the Leshan-Longnüsi paleo-uplift. This paleo-uplift was controlled by the basement and structurally formed prior to 600 Ma (Xu et al., 2012). The main source rocks of the Anyue gas field are the Sinian Doushantuo Formation mudstone, the 3rd member of the Dengying mudstone, and the Cambrian Qiongzhusi shale, which overmatured with a burial depth greater than 4000 m (Zou et al., 2014b).