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Helium signatures of gases from the Sichuan Basin, China

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ABSTRACT

Natural gases from the Sichuan Basin, China were analyzed to investigate helium abundances and isotopic composition in order to assess crustal vs. mantle inputs into the Sinian to Jurassic gas reservoirs that occur at depths up to 4900 m. In general, gases from the Sinian and pre-Sinian strata in south Sichuan have relatively high abundances of helium compared to those from the east, central and west Sichuan, implying an increase of crustal helium with time. All gas samples demonstrate very low helium isotopic ratios ($^3He/^4He$ designated R) with an average of 0.016 Ra ($n = 78$, where Ra is the isotope ratio found in the atmosphere), indicative of a crustal origin. This is further supported by the relatively stable upper mantle found in west China. In contrast, the thin and active lithosphere in the east part of China is favorable for the injection of mantle-derived volatiles into gas reservoirs. This explains why gases from the east part of China generally have R/Ra > 1 while those in the west have R/Ra $\leqslant$ 0.1.

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1. Introduction

Since the discovery of the ^3He anomaly in the East Pacific Rise (Craig and Lupton, 1981), helium isotopic variations ($^3He/^4He$) have been widely used as a tracer for mantle volatiles (Oxburgh et al., 1986; O'Nions and Oxburgh, 1988; Poreda and Craig, 1989; Giggenbach et al., 1993; Jenden et al., 1993; Charlou et al., 1996; Ballentine et al., 2000; Jean-Baptiste et al., 2004; Du et al., 2006). Due to the different origin of the two stable isotopes of helium, ^3He and ^4He, helium can be divided into three different types: atmospheric helium in which $^3He/^4He = 1.4 \times 10^{-6}$, i.e., Ra (Mamyrin et al., 1970); crustal helium, the product of radioactive decay of U and Th (yielding ^4He) and the (n, α) reaction of ^6Li (yielding ^3He); $^3He/^4He$ is normally < 0.05 Ra (Mamyrin and Tolstikhin, 1984; Andrews, 1985); and mantle helium, a mixture of radiogenic and primordial helium, the latter has $^3He/^4He$ of 100–300 Ra (Craig and Lupton, 1981; Mamyrin and Tolstikhin, 1984). Many studies have demonstrated that the spatial variation of $^3He/^4He$ ratios in gas reservoirs can be used to identify the possible addition of mantle volatiles and provide valuable information about the regional tectonic environments and petroleum exploration (Jenden et al., 1993; Xu et al., 1994; Dai et al., 1995, 2005, 2008; Zheng and Liao, 1998; Jin et al., 2009). Etiope and Sherwood Lollar (2013) have made a detailed review of the relationship between the helium and the carbon systems. Giggenbach et al. (1993) commented that the helium and carbon systems are likely decoupled due to multiple sources of CO_2 and CH_4 as well as loss of the carbon gases due to secondary reactions. Such situations may not be unusual in the case of CH_4 in ultramafic rock obducted onto continents (i.e., ophiolites) where additional sources of enriched carbon from the decomposition of limestone or incorporation of atmospheric CO_2 via circulating meteoric waters may introduce multiple carbon sources. Similarly near-surface circulation of meteoric waters through these fractured rocks may introduce more depleted carbon sources from microbial or fossil organic matter (Szponar et al., 2013). Additionally, mantle helium may not be preserved in highly disrupted and fractured ophiolites (Hoke et al., 2000).

The Sichuan Basin is one of the most important gas producing provinces in China. It has the most discovered gas fields (125) and the greatest annual gas production (17.16×10^9 m^3 in 2007) in China (Ma et al., 2010). Many studies have been carried out on the natural gases in the Sichuan Basin (Xiong et al., 2004; Hao et al., 2008; Dai et al., 2009, 2012; Zhang et al., 2009), and we have already performed a detailed study on the gas-source correlation of coal-derived gases from the Triassic Xujiahe Formation in the Sichuan Basin based on compound specific carbon isotopes and chemical molecular composition of alkane gases (Dai et al., 2009). In 2012, the authors further compared the stable hydrogen

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and carbon isotopic characteristics of natural gases from the Triassic Xujiahe Formation and used them successfully for gas source correlation (Dai et al., 2012). However, to date, no systematic study has been carried out on the helium isotopic variations of gases from the Sichuan Basin. The limited available data provide a rough spatial distribution of helium abundances in the basin (Zhang, 1992; Xu et al., 1998), but these studies do not discuss the origin of helium and its implications for regional tectonic environments and gas exploration. In order to understand the complexity of origins and source of gases in the Sichuan Basin (Dai et al., 2010 and references therein), systematic studies of helium abundances and isotopic characteristics may shed light on regional tectonic environments and provide clues for gas-source correlation studies in this basin. Hence, the aim of this paper is to investigate systematically the isotopic composition and abundances of helium in gases from the Sichuan Basin. Our main interest is to examine the origins of helium, its spatial distribution patterns and possible causes for this in support of future petroleum exploration in the Sichuan Basin.

2. Geological setting

The Sichuan Basin is located in eastern Sichuan (Fig. 1), and is one of the most tectonically stable sedimentary basins in China. It has an area of 180×10^3 km^2 according to the distribution of its terrigenous strata. It is a diamond shaped tectonic basin surrounded by the Micang and Daba mountains in the north, the Daliang mountains in the south, the Longmen and Qionglai mountains in the west and Qiyao mountains in the east. Tectonically, the Sichuan Basin can be divided into East, South (including South and Southwest), West and Central Sichuan gas-oil accumulation zones (Fig. 1).

The Sichuan Basin is a late Mesozoic–Cenozoic foreland basin overlying a Sinian–Middle Mesozoic passive margin (Ma et al., 2007). Since the Proterozoic, the Sichuan Basin has experienced nine tectonic episodes or movements: Jinning (± 850 Ma), Chengjiang (± 700 Ma), Tongwan (± 570 Ma), Caledonian (± 320 Ma), Yunnan (± 270 Ma), Dongwu (± 256 Ma), Indosinian (205–195 Ma), Yanshanian (180–140 Ma) and Himalayan (80–3 Ma) movements (Fig. 2). The Yanshanian-Himalayan movement, especially the Himalayan folding movement, formed local structural traps in groups and zones, providing a firm basis for the accumulation of natural gases.

This typical tectonic, superimposed basin has experienced two tectonic deposition cycles, i.e., Sinian–Middle Triassic passive continental margin tectonic evolution and Late Triassic–Eocene foreland basin and depression evolution. This led to the deposition of superthick Sinian–Middle Triassic marine carbonates (4–7 km), the early stage of Late Triassic marine-terrigenous transitional deposition (300–400 m) and the middle stage of Late Triassic–Eocene terrige-

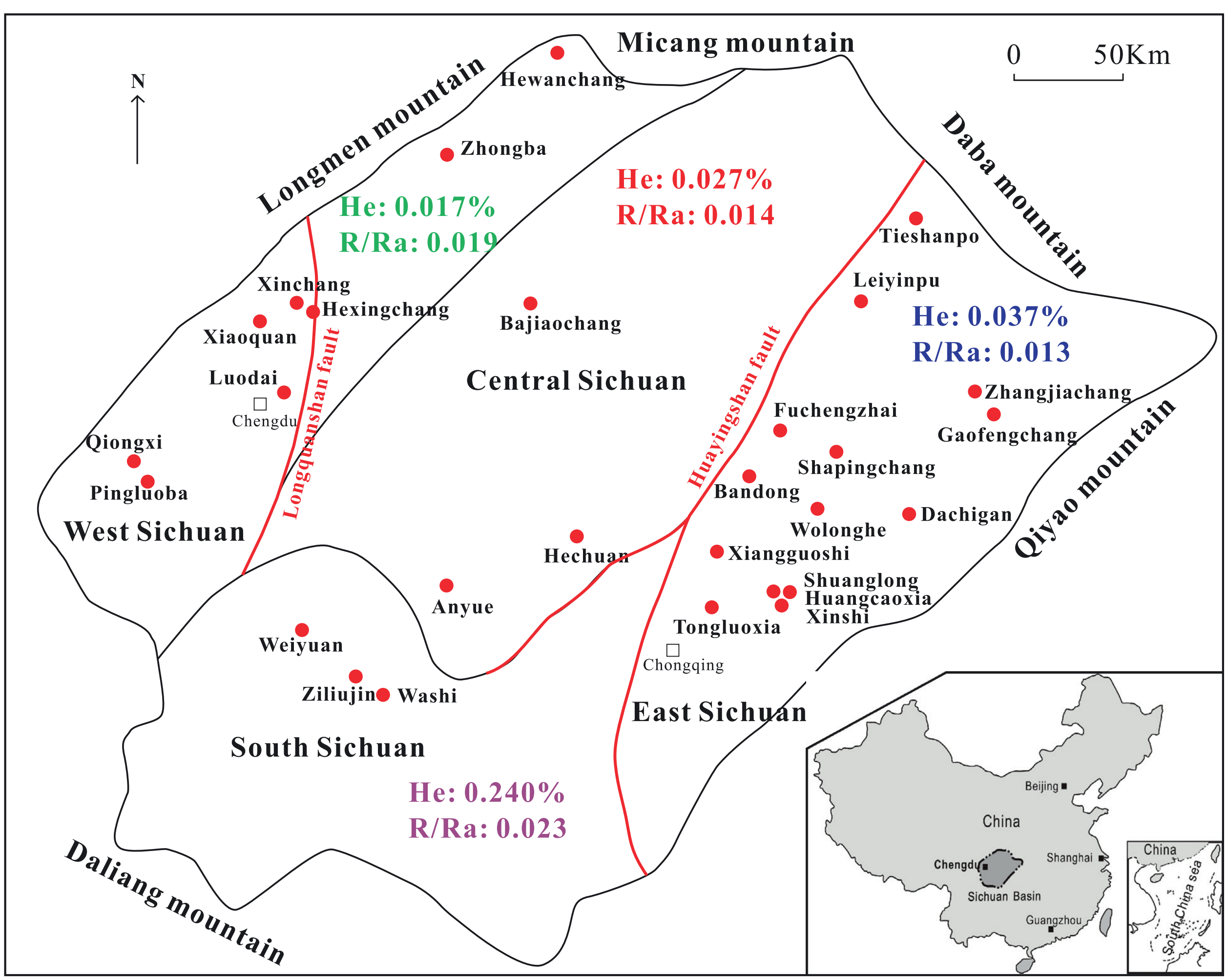

Fig. 1. Location map of the Sichuan Basin. The basin can be divided into four oil–gas accumulation districts, i.e., East, Central, West and South (including south and southwest) Sichuan. Also shown are the locations of related gas fields/areas and the averaged values of helium content and isotopes measured in this study for all gas samples from these four districts.

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