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Mantle-derived helium in foreland basins in Xinjiang, Northwest China

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A B S T R A C T

Hydrocarbon-rich natural gases from the Tarim, Junggar, Turpan-Hami and Santanghu basins in Xinjiang, Northwest China have measured $^3He/^4He$ ratios from 0.01 to 0.6 times higher than the atmospheric value, indicating 0–7% helium derived from the mantle. The mantle-derived helium is high in foreland basins associated with the Tianshan, Kunlun and Zhayier-Halalate orogenic mountains, but low towards the center of basins. This spatial distribution suggests that the mantle-derived helium originates either from fluids or small scale melts in the upper asthenospheric or lithospheric mantle which have found pathways into the root zones of the major faults defining these mountains, but do not significantly move into the basins themselves. During upward transport to near the surface, the mantle-derived helium is significantly diluted by radiogenic helium produced in the crust. Despite the lack of recent magmatic activity or extensional tectonics within the basins, this pattern shows strong evidence that the major faults play an important role in mantle-derived components degassing from the mantle to the surface.

1. Introduction

The terrestrial $^3He/^4He$ ratio (R) varies from a typical radiogenic value of 0.01–0.05 R_a (where R_a is the atmospheric $^3He/^4He$ ratio of 1.4×10^{-6}), produced through the decay of radioactive elements uranium and thorium in the crust, to ~8 R_a in the mantle (e.g., Mamyrin and Tolstikhin, 1984). Therefore, R is a powerful indicator to quantitatively and qualitatively discern changes in the balance between the crustal and mantle-derived volatiles that contribute to the total volatile inventory. It is well documented that the mantle-derived helium has a close relationship with Cenozoic magmatic/volcanic activity and can occur in areas of extensional tectonic activity (Sano et al., 1984; O'Nions and Oxburgh, 1988; Kennedy and van Soest, 2006). On the other hand, since Kennedy et al. (1997) first reported high $^3He/^4He$ ratios along the San Andreas Fault, mantle-derived helium has been observed in areas of tectonic compression or non-volcanic activity (Doğan et al., 2006, 2009; Umeda et al., 2008; Umeda and Ninomiya, 2009; Umeda et al., 2013; Burnard et al., 2012; Klemperer et al., 2013). In these areas, it was found that the mantle-derived helium is transported from the mantle through deep fault fractures.

For gases sampled from surface springs and fumaroles, correction of measured $^3He/^4He$ values for possible atmospheric contamination (R_c) is essential. All the data presented here are sampled at the well-head of oil/gas wells, so that air-contamination is far less likely. Nonetheless, as a unique proxy for the mantle-derived component, $^3He/^4He$ ratios of natural gases have been extensively investigated in China during the last 30 years (i.e., Xu, 1994; Xu et al., 1995, 1998; Du et al., 1998; Zheng et al., 2004, 2005; Tao et al., 2005). In sedimentary basins along the eastern Chinese coast, the R_c/R_a and R/R_a values are generally high (>1) due to the wide occurrence of Cenozoic magmatic activity and extensional tectonics. On the other hand, the R_c/R_a and R/R_a values in sedimentary basins in central China (i.e., the Sichuan and Ordos basins) are typical of a crustal-radiogenic helium component. In the sedimentary basins of northwestern China, the R_c and R values lie between those found in central and eastern China. Although the majority of natural gases in northwestern China have R_c/R_a and R/R_a values (<0.1) close to typical crustal radiogenic helium, a few samples have elevated R/R_a values up to 0.3, which were attributed to the presence of a mantle-derived component (Xu, 1994; Xu et al., 1995, 1998; Du et al., 1998). With the development of oil/natural gas exploration during the last decade, more commercial oil/gas wells have entered production and extensive sampling has become available. As a result, additional elevated $^3He/^4He$ ratios have been observed (Zheng et al., 2004, 2005; Tao et al., 2005; Zhang et al., 2005a), confirming the contribution of mantle-derived helium in the sedimentary basins. However, it has not been documented how the mantle-derived helium occurs in such thickened crust which, in non-volcanic areas, is a result of tectonic compression and associated with large orogenic belts surrounding the sedimentary basins. Thus, based on datasets newly analyzed and previously

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published, this paper examines the regional spatial distribution of $^3He/^4He$ ratios in the Tarim, Junggar, Turpan-Hami and Santanghu sedimentary basins of Xinjiang to understand the relationships between $^3He/^4He$ ratios and tectonic activity in the orogenic belts.

2. Geological backgrounds

Xinjiang is the largest province (1.665 million km^2) in China. It has five major sedimentary basins (Fig. 1): Tarim (560,000 km^2), Junggar (134,000 km^2), Turpan-Hami (53,500 km^2), Yili (38,600 km^2) and Santanghu (23,000 km^2) (e.g., Guo et al., 2006; Qiu et al., 2008; Xu et al., 2001; Zhao et al., 2003; Fu et al., 2003; Zhu et al., 2009; Yu et al., 2012; Tao et al., 2013; Gao et al., 2013; Jiang et al., 2013). The tectonic summary is as follows: Since the Hercynian, western China was located on the southern margin of the Eurasian plate, controlled by the multi-stage subduction of Tethys. With the extinction of the ancient Asian Ocean in the Late Carboniferous–Early Permian periods and the closure of eastern parts of Paleo-Tethys in the Late Triassic epoch, small cratons such as Tarim, North China, and Yangtze collided. This resulted in a series of geological and tectonic activities including the uplift of Hercynian–Indo orogenic belts, the formation of foreland basins, and thrust faults along the peripheral Tarim basin. During the Himalayan period extinction of Neo-Tethys subduction, the India–Tibet collision, and internal deformation within the Eurasia continent occurred. Due to uplift of the Tibetan plateau, the ancient Tianshan, Qilian and Kunlun orogenic belts were reactivated, and the Tarim and Junggar basins underwent rapid subsidence. This resulted in the formation of foreland basins in a ring peripheral to the Tibetan Plateau. The reactivated Himalayan foreland basins and thrust faults were developed on previously formed forelands, creating a terrestrial sedimentary system, and thrust–strike slip faults (Gao et al., 2013; Jiang et al., 2013).

The Tarim basin is bounded by the Tianshan Mountains to the northwest and north, and by the Kunlun and Altun mountains to the south (Fig. 2A). The strata consist of Precambrian–Permian marine and Mesozoic–Cenozoic terrestrial sedimentary rocks up to 10,000 m thick. The foreland sub-basins are distributed in front of the Tianshan and Kunlun Mountains. The Junggar basin, bounded by the Qinggelidi Mountains to the northeast, by the Yilinheibiergen and Bogda Mountains of the Tianshan range to the south, and by the Zhayier-Halalate Mountains to the northwest (Fig. 2B) is an upper Paleozoic, Mesozoic and Cenozoic superimposed basin with stratigraphy ranging from the Carboniferous to the Cretaceous (Cao et al., 2012). The foreland sub-basins are distributed in front of the Tianshan and Zhayier-Halalate Mountains. The Turpan-Hami and Santanghu basins are typical foreland basins located on the southern and northern side of the eastern Tianshan (Bogda) Mountains, respectively. The Turpan-Hami basin is bounded by the Tianhsan (Bogda) Mountains to the north and by the Jueluotage Mountains to the south (Fig. 2C). The Santanghu basin is bounded by the Suhaitu Mountains to the northeast and by the Moqin-Urals to the southwest (Fig. 2D). Each basin can be divided into several sub-structural units (Tao, 2010; Zhang et al., 2010; Cao et al., 2012; Li et al., 2013).

The last extensive igneous activities in Xinjiang are the Late Devonian to Late Carboniferous (361–306 Ma) volcanic rocks, mainly consisting of basalt, trachyte, trachy-andesite, andesite and rhyolite (Zhu et al., 2009; Zhang et al., 2010; Yu et al., 2012). In addition, as shown in Fig. 1, Tertiary-Quaternary volcanics scattered in transition zones between Tianshan Mountains and Tarim basin (20–40 Ma in TY and PQ), between Kunlun Mountains and Tarim basin (20–0.1 Ma in KXW, DHLT, PL and ASKL), and between Altai Mountains and Junggar basin (17 Ma in HLQL) (Turner et al., 1996; Liu and Maimaiti, 1989; Luo et al., 2003; Chung et al., 2005; Huang et al., 2006). Most earthquakes in the study area occur within the orogenic

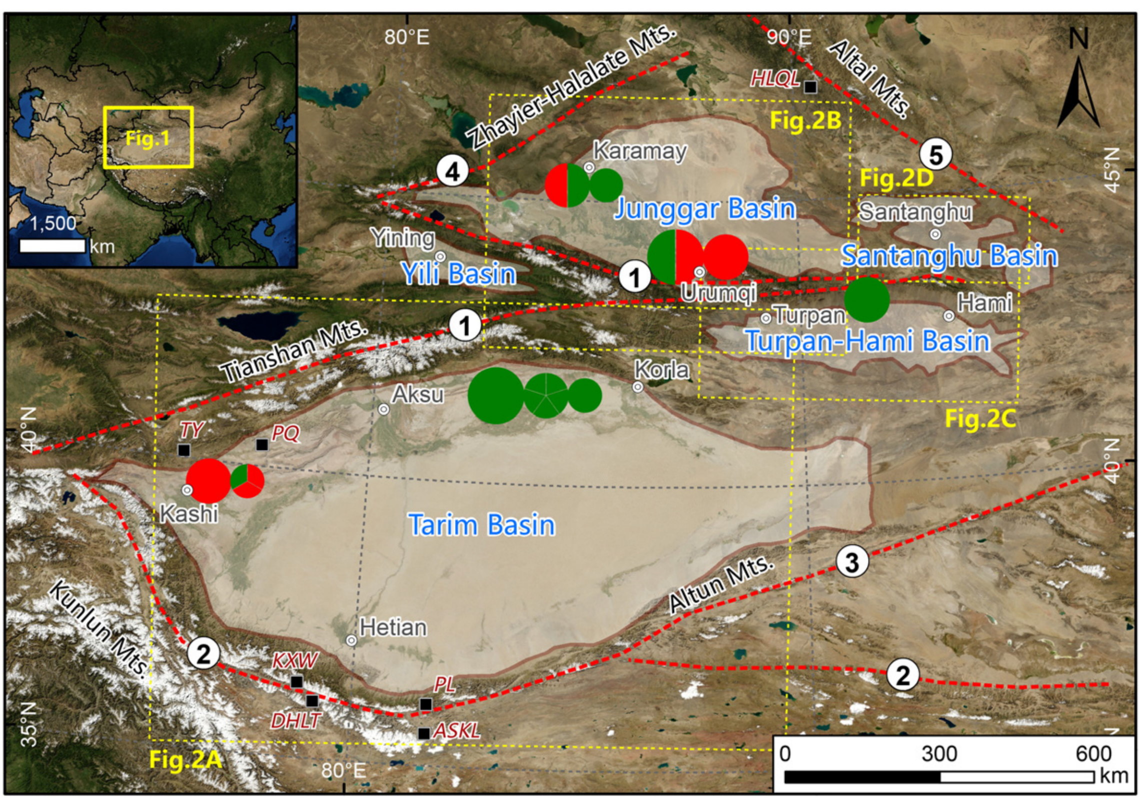

Fig. 1. Simplified map of northwestern China showing major sedimentary basins and adjacent orogenic mountains. The circles indicate the orogenic belts: 1, Tianshan; 2, Kunlun; 3, Altun, 4, Zhayier-Halalate; and 5, Altai Mountains. The squares denote occurrence of the Cenozoic volcanic rocks; PG: Piqiang, TY: Tuoyun, KXW: Kangxiwa, PL: Pulu, DHLT: Dahongliutan, ASKL: Ashikule, HLQL: Halaqiaola. Occurrence of mantle-derived helium is shown with red or green Pie chart (counted numbers, see legend in Fig. 2 for details).