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Helium and carbon isotope variations in Liaodong Peninsula, NE China

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ABSTRACT

Chemical and C–He isotopic compositions have been measured for N_2-rich hydrothermal gases from the Liaodong (abbreviation of East Liaoning Province) Peninsula from which the oldest crustal rocks in China with ⩾3.8 Ga outcrop. With the exception of one sample containing tritogenic ^3He and atmospheric ^4He in Liaoyang, the observed $^3He/^4He$ ratios from 0.1 Ra to 0.7 Ra indicate 1–8% helium from mantle, 92–98% from crust and 0.1–0.8% from atmosphere. Despite the lack of Quaternary volcanism, such $^3He/^4He$ ratios suggest, together with geophysical evidences, the existence of intrusive magmas that contain mantle helium and heat within the Liaodong middle-lower crust. The $^3He/^4He$ ratios are high along the NE-trending Jinzhou faults and gradually decrease with the increase of distance from the faults. Such a spatial distribution suggests that the mantle helium exsolves from magmatic reservoir in the middle-lower crust, becomes focused into the root zones of Jinzhou faults, and subsequently traverses the crust via permeable fault zones. When transversely migrated by groundwater circulation in near surface, mantle helium with high $^3He/^4He$ ratio may have been further diluted to the observed values by addition of radiogenic helium produced in the crust. This pattern shows strong evidence that the major faults played an important role on mantle-derived components transport from mantle upwards.

1. Introduction

The isotopic composition of terrestrial helium varies by more than three orders of magnitude from a typical radiogenic value of ~0.02 Ra where Ra is atmospheric $^3He/^4He$ of 1.4×10^{-6}, produced through the decay of uranium and thorium series isotopes in crust, to 8 ± 1 Ra in mantle (e.g., Mamyrin and Tolstikhin, 1984). Therefore, $^3He/^4He$ is a powerful indicator to identify the source of volatile entering the crust and therefore sensitive to discern changes in the balance between crustal and mantle-derived volatiles contributing to the total volatile inventory. In continental environments, it has been established that the mantle-derived helium has a close relationship with recent magmatic activity (i.e., Sano et al., 1984) and can also present in areas of active extensional environment without recent surface volcanism (O'Nions and Oxburgh, 1988; Kennedy and van Soest, 2006). Recently, mantle-derived helium has been observed in tectonically compressional areas (Kennedy et al., 1997; Umeda et al., 2008). Since Kennedy et al. (1997) first reported high $^3He/^4He$ ratios along the San Andreas Fault, recent studies suggest that the mantle-derived helium can be transported from the mantle through fault fractures (Kulongoski et al., 2005; Kennedy and van Soest, 2006, 2007; Doğan et al., 2006; Doğan et al., 2009; Umeda et al., 2008; Umeda and Ninomiya, 2009; Klemperer et al., 2013).

$^3He/^4He$ ratios have been extensively investigated for natural gases and hydrothermal gases in the Chinese continent during last 20 years (i.e., Xu et al., 1995, 2004; Yokoyama et al., 1999; Dai et al., 2005; Du et al., 2006; Klemperer et al., 2013). However, detailed studies of mantle-derived components associated with the non-volcanic areas are sparse (Yokoyama et al., 1999; Du et al., 2006; Klemperer et al., 2013). Thus, this paper examines regional spatial distribution of $^3He/^4He$ ratios in hydrothermal fluids in Liaodong Peninsula, a non-volcanic area (Fig. 1). The general aim is to refine the relationships between $^3He/^4He$ ratios, tectonics and recent seismic activities.

2. Geological backgrounds

The Liaodong Peninsula is geologically located in the eastern margin of the North China Craton which is one of the world's oldest Archean cratons and preserves crustal remnants as old as ⩾3.8 Ga in Anshan regions (Liu et al., 1992). In addition to the Archean and

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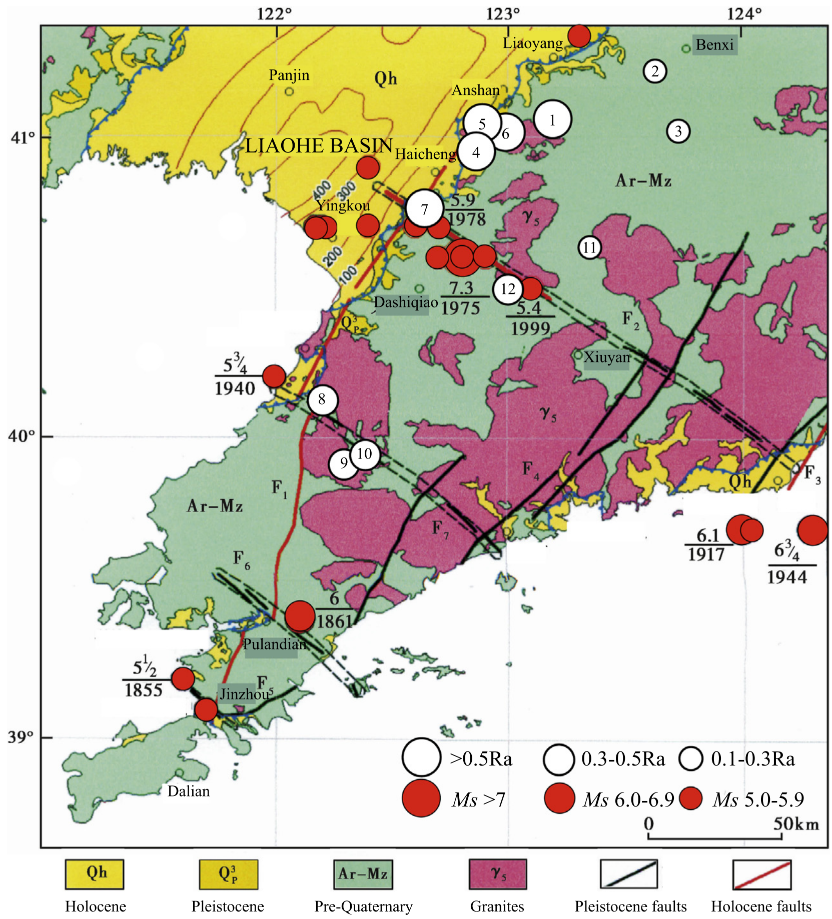

Fig. 1. Simplified geological map of Liaodong Peninsula (modified from Wan et al., 2013). Distributions of $^3He/^4He$ ratio (white circles) and historical earthquake (red circles) are shown. The regional major faults are labeled as F1–F7 (F1, Jinzhou; F2, Haichenghe; F3, Yalujiang; F4, Zhuanghe; F5, Daheshangshan; F6, Pulandian-changhai; F7, Xiongyue-zhuanghe). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Proterozoic metamorphic rocks, there are regional outcrops of Paleozoic and Mesozoic sedimentary rocks. These include Cambrian calcirudite, shale and dolomite, and Carboniferous sandstone, mudstone and conglomerate. Volcanic rocks include Archean granite, Permian diorite, Jurassic adamellite and Cretaceous granite. The most recent and extensive igneous activities are the Early Cretaceous granites with the age of 126 Ma, indicating Mesozoic extensional tectonic structures in Liaodong Peninsula (Wu et al., 2005; Yang et al., 2006; Liu et al., 2011).

The region is mainly controlled by the NE–SW and NW–SE trending active fault systems (Lei et al., 2008). The NE–SW trending Jinzhou fault is considered as one of the boundary faults to separate the Mesozoic-Cenozoic extensional Liaohe basin in west and the uplifted Liaodong Peninsula in east. Along the 220 km long Jinzhou fault, there are numerous hot springs and occurrence of historic earthquakes. Zhong and Xiao (1990) pointed out the fact that the hydrothermal fluids emerge in places where the NE–SW and NW–SE fracture systems intersect (Fig. 1). Moderate-strong earthquakes happened frequently in the Liaodong Peninsula. In addition to the well-known Haicheng M7.3 earthquake (40°42′N, 122°42′E), which occurred in 1975, there are 19 historical earthquakes of $M \geqslant 5$ recorded in this region since 1855 (Wan et al., 2013). Seismic and gravity evidences show that the crustal thickness under Liaodong today is approximately 32–36 km, significantly greater than the adjacent Liaohe basin (30–32 km). The regional terrestrial heat flow has been measured to 50–117 mW m^{-2} (Wang et al., 1987; Hu et al., 2000). Therefore, it is evident that recent seismic activity, hydrothermal activity and active faults are spatially coupling in the Liaodong Peninsula (Lu et al., 1990, 2002).

3. Sampling and experiments

Liaodong Peninsula is one of the strongest geothermal zones in China. There are more than 40 hot springs with temperature of over 20 °C and dominantly Na^+, SO_4^- and HCO_3^- types in water chemistry (Zhong and Xiao, 1990). The hydrothermal gases in this study were emanating from hot springs and geothermal wells with the temperatures from 13 °C to 80 °C. The bubbling gas samples were collected into a 50-mL volume glass container with vacuum valves in both sides using the water displacement method.

About 1 ml gases were introduced into a vacuum system to separate helium from other gas components. ^4He and ^{20}Ne concentrations were measured by a built-in quadrupole mass spectrometer. After helium being further separated from neon under temperature condition of 40 K, $^3He/^4He$ ratio was determined using a static mass spectrometer (VG5400, Micromass). Air was used as a standard for noble gas isotope analyses. Detailed description of the analysis procedure can be found elsewhere (Xu et al., 1995).

The $\delta^{13}C$ of CO_2 and CH_4 were measured by a conventional isotope ratio mass spectrometer (Delta S). The results are expressed as per mil derivations from the Pee Dee Belemnite (PDB) standard. The typical analytical precision is around ±0.3‰ on the δ scale.

4. Results and discussion

The analytic results of gas chemical and isotopic compositions are listed in Table 1. With the exception of sample No. 10 from Jiantang that contains 25% CO_2 and $\delta^{13}C$ value of −4.8‰, the other