# Accumulation mechanism of crust-mantle mixing helium-rich reservoir: A case study of the Subei basin (Eastern China)

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**Abstract:**

Helium reservoirs, as an indispensable and scarce strategic resource, can be categorized into two primary origins: crust- and mantle-sourced. Understanding the mechanisms of its formation and accumulation is a crucial challenge in helium exploration. Previous work on helium exploration has mainly focused on crustal helium, while mantle-sourced helium-rich reservoirs have been overlooked. Helium reservoirs with both a crustal and a mantle source exhibit higher helium abundance than that of crustal helium reservoirs and are sporadically distributed in Neogene basins worldwide, but their formation and evolution is poorly understood. In eastern China, several Neogene basins preserve high quality crust/mantle helium-rich reservoirs, and in this study, we use the Subei Basin as a case study to investigate processes controlling He accumulation and storage. The helium reservoirs can be classified into two types based on the lithological nature of the structural traps: sand reservoir with mud cap and basalt reservoirs with mud cap. The main controlling factors for the formation of crust-mantle helium-rich reservoirs include deep-seated faults, magmatic activity, and mineralization of mantle-derived $CO_2$. Deep-seated faults, along with their associated strike-slip faults, serve as favorable pathways for mantle-derived helium migration and magma

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upwelling. Magmatic activities serve as the material source for mantle-derived helium as well as the carrier medium in the migration of mantle-derived volatiles. The presence of well-developed sandstone and basalt reservoirs, along with mudstone cap rocks and the dissolution and mineralization caused by mantle-derived $CO_2$ are important factors in helium accumulation and preservation.

Keywords: crust-mantle mixing helium, helium-rich reservoir, $^3He/^4He$, accumulation mechanism

## 1. Introduction

Helium is one of noble gases with special properties: chemical inertness, low boiling point, and low density. It has extensive applications in high-tech fields, such as cryogenic superconductivity, aerospace, nuclear industry, and medical technology therefore helium is regarded as a crucial resource for modern industry (Cai et al., 2010; Chen, et al., 2021). Generally, helium cannot accumulate independently to form reservoirs but is found in association with inorganic or organic gases, existing as part of natural gas reservoir components. Helium in natural gas of sedimentary basins has three sources: the atmosphere, the crust and the mantle. These different sources can be discriminated by their isotope compositions. Helium (He) has two isotopes, with $^3He$ being primordial and $^4He$ produced primarily by the decay of uranium and thorium. Atmospheric helium the helium in the air with a concentration of $5.24 \times 10^{-6}$, it was mainly produced from volcanic eruption, magma degassing, and rock weathering, with $^3He/^4He$ of $1.4 \times 10^{-6}$, which is referred as 1 Ra (Mamyrin et al., 1970).The helium origin can be determined by $^3He/^4He$ ratios (R/Ra values), which have been widely used to trace the mantle-derived volatiles (Wakita and Sano, 1983; Oxburgh et al, 1986; Poreda et al, 1988; Xu et al, 1996). R/Ra >1 suggests the input of considerable mantle-derived helium, whereas R/Ra $\leqslant$0.1 implies mainly crustal helium (Oxburgh et al, 1986). Atmospheric helium enters the basin fluid system through groundwater recharge.

Crustal helium is predominantly composed of radiogenic $^4He$. Meanwhile, mantle-derived helium is primarily from mantle degassing.

Worldwide large-scale helium-bearing reservoirs, such as those in the United States, Qatar, Algeria, Russia, and Canada, are predominantly crustal helium (Yakutseni, 2014). In contrast to crustal helium reservoirs, which tends to accumulate in stable craton basins, crust-mantle mixing helium-rich reservoirs with both crustal and mantle derived helium are usually found within tectonically and magmatically active regions (Figure 1), such as the active continental margins encircling the Pacific Ocean including the Taupo Arc, the Kurile-Honshu-Ryukyu Arc, the Aleutian-Alaskan Arc, and the western margin of North America. However, the helium content in these reservoirs is not high enough to be economically viable (Poreda et al., 1986, 1988; Motyka et al., 1989). Furthermore, some previously presumed helium reservoirs of mixed crustal and mantle origin within the Rukawa Rift Basin of the East African Rift have been identified as crustal helium origin (Kimani et al., 2021; Mtili et al., 2021). In eastern China, several Neogene basins (such as Songliao, Bohai Bay, Subei and Sanshui basins) preserved crust-mantle mixing helium-rich reservoirs. These basins are distributed in a narrow belt along the active continental margin in western Pacific Ocean, providing an excellent opportunity for studying processes of accumulation, migration, and storage of these types of helium-rich reservoirs (Xu et al. 1996).

In comparison to crustal helium reservoirs, Helium-rich reservoirs with a mantle component are characterized by higher helium contents, than those with only crustal source. They also exhibit younger formation period (mainly in Neogene) and occur in active tectonic-magmatic settings. However, the accumulation mechanisms of crust-mantle mixing helium-rich reservoirs remain enigmatic. The Subei Basin is a typical Neogene basin with crust-mantle mixing helium-rich helium accumulations where crust-mantle mixing helium-rich reservoirs have highest helium contents (up to 1.32%) in China. Therefore, we focus on the Subei Basin as a case study for comparison of accumulation and enrichment of helium in both stable cratonic basins and tectonic-magmatic active regions.


Figure 1. Global distribution map of helium resources (modified after Furnes et al., 2015). Helium date sources are from: Wakita and Sano, (1983); Poreda et al. (1986, 1988); Marty et al. (1989); Motyka et al. (1989); Merrill et al (2014); Yakutseni (2014); Xu et al. (2017); Mtili et al. (2021); Halford et al. (2022). The average $^{3}He/^{4}He$ ratio of MORB (8 Ra) is considered as the end member for the upper mantle in calculations.

## 2. Spatiotemporal distribution of worldwide crust-mantle mixing helium-rich reservoirs

Commercial helium systems worldwide primarily have been found in helium-bearing fields within sedimentary basins (Danabalan, 2017). According to Dai et al. (2017) classification criteria for helium reservoirs, fields with reserves exceeding $1.0\times10^{8}m^{3}$ are referred to as extra-large gas fields. Those with reserves ranging from $5.0\times10^{7}$ to $1.0\times10^{8}m^{3}$ are classified as large gas fields. Reserves falling between $2.5\times10^{7}$ to $5.0\times10^{7}m^{3}$ are termed as medium gas fields, while fields with reserves between $5.0\times10^{6}$ to $2.5\times10^{7}m^{3}$ are categorized as small gas fields. It is generally considered that natural gas reservoirs with helium content below 0.05% are categorized as helium-depleted gas reservoirs, while those with helium content exceeding 0.1% are referred to as helium-rich natural gas reservoirs, meeting the threshold for economic viability.

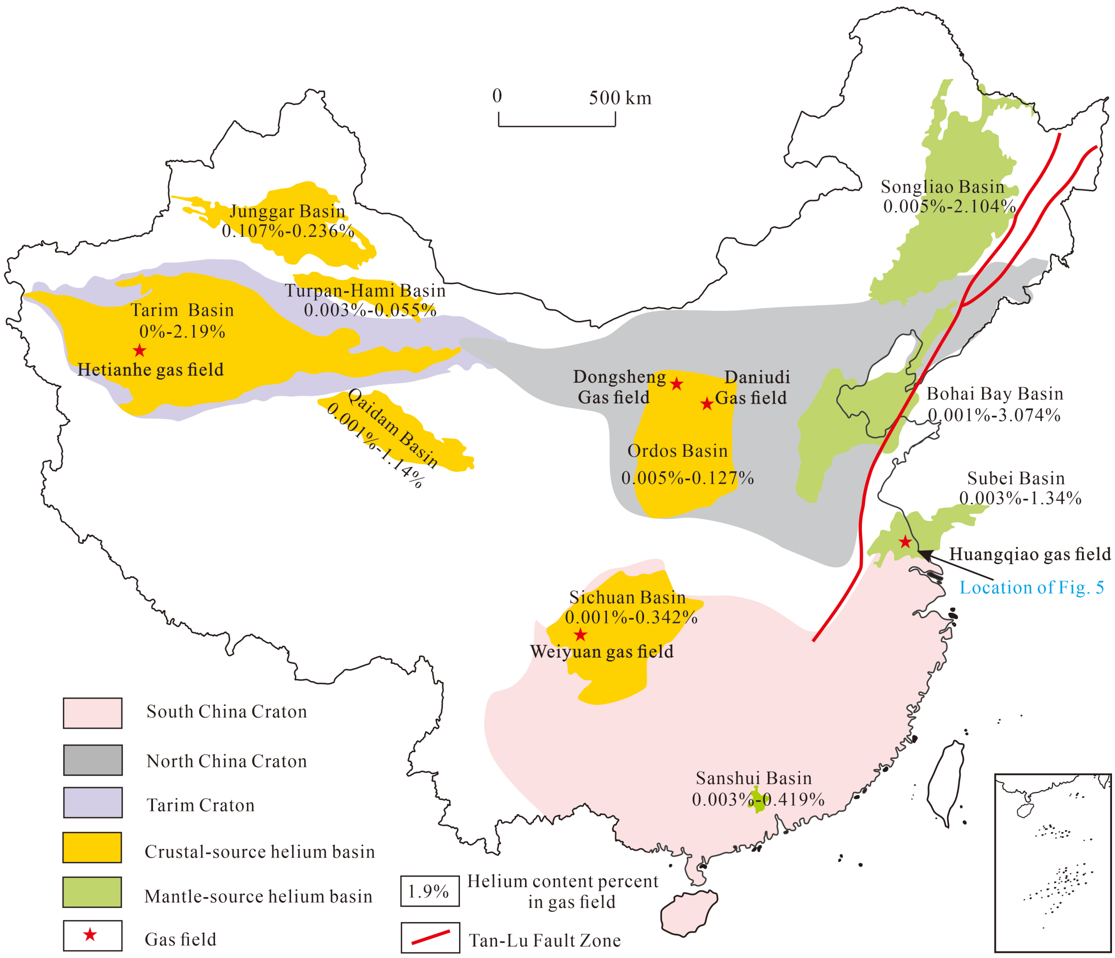


Figure 2. Distribution of helium resources in China.

Helium data sources are from: Songliao Basin (Xu et al., 1996; Feng et al., 2001; Wang et al., 2006; Yang et al., 2014), Bohai Bay Basin (Zheng et al., 1996; Cao et al., 2001; Dai et al., 2017; Ni et al., 2022), Subei Basin (Xu et al., 1996; Guo et al., 1999; Ye et al., 2003; Liu et al., 2017), Sanshui Basin (Du and Liu, 1991; Dai et al., 1995; Xu et al., 2000), Sichuan Basin (Du and Liu, 1991; Ni et al., 2014; Wei et al., 2014; Liu et al., 2017), Ordos Basin (Liu et al., 2007; Ni et al., 2010; Dai et al., 2017), Tarim Basin (Xu et al., 1998; Liu et al., 2009; Liu et al., 2012; Yu et al., 2013; Wang et al., 2016; Wang et al., 2018; Tao et al., 2019), Qaidam Basin (Cao et al., 2016; Zhang et al., 2016; Xu et al., 2017), Turpan-Hami Basin (Xu et al., 2017).

Table 1. Global distribution of mantle-derived helium resources. Helium data from: Poreda et al.

(1986, 1988); Motyka et al. (1989) and references within Figure 2.

| Location | Basin | Gas feild | Strata | Depth/m | Reservoir | $CO_2$/% | He/% | R/Ra |
|---|---|---|---|---|---|---|---|---|
| New Zealand | Taranaki, North Island | Maui | Paleogene-Neogene | / | Sandstone | 4.8 | 0.0182 (n=1) | 3.5 |
| | | Kapuni | Paleogene- Neogene | / | Sandstone | 39.2 | 0.0013 (n=1) | 0.19 |
| Philippines | Palawan | Matinloc *P-1* | Neogene | 2234-2246 | Carbonate | 5.4 | 0.0010 (n=1) | 0.1 |
| | | Nido BW | Neogene | 2051-2103 | Carbonate | 20 | 0.0093 (n=1) | 3.34 |
| Taiwan, China | / | Chinsui | Neogene | 3840-4214 | Sandstone | 11.2 | 0.0027 (n=1) | 1.55 |
| | / | Yunghoshan | Neogene | 4787-4913 | Sandstone | 10.9 | 0.0014 (n=1) | 1.65 |
| | / | Chingtsaohu | Neogene | 3861-3870 | Sandstone | 3.7 | 0.0034 (n=1) | 3.22 |
| | / | Tienchenshan | Neogene | 2706-3057 | Sandstone | 2.2 | 0.0039 (n=1) | 1.4 |
| | / | Chuhuangkeng | Neogene | 4116-4421 | Sandstone | 45.3 | 0.0038 (n=1) | 3.4 |
| | / | Pachangchi | Neogene | 1882-1922 | Sandstone | 0.7 | 0.0063 (n=1) | 1.04 |
| | / | K-16 | / | / | Sandstone | 53.9 | 0.0138 (n=1) | 3.84 |
| | / | K-16 | / | / | Sandstone | 2.9 | 0.0072 (n=1) | 2.6 |
| U. S. A | Cook Inlet | McArthur River | Paleogene- | / | Sandstone | 0.8 | 0.0130 (n=1) | 0.75 |
| China | Songliao Basin | Wanjinta | Cretaceous | 800-1400 | Sandstone | 90-99.5 | 0.07-0.08 (n=4) | 4.5-5.1 |
| | | Gulong depression | Saertu Formation | 1100-1600 | Sandstone | | | 0.9-1.9 |
| | | Daqing Changhuan | Saertu Formation | 900-1200 | Sandstone | 0.08-45.2 | 0.102-0.404 (n=50) | 1.32-2.18 |
| | | Sanzhao Depression | Fuyu Formation | 1200-1350 | Sandstone | | | 0.72-3.05 |
| | | | Jurassic | 3600-2620 | Sandstone | | | |
| | | Chaochang | Fuyu Formation | 950-1100 | Sandstone | | | 1.02-2.06 |
| | Subei Basin | Huangqiao | Yancheng Formation | 350-400 | Sandstone | 15 | 0.013-1.34 (n=5) | 2.65-3.96 |
| | | Qintong Depression | Yancheng Formation | 2300-2600 | Sandstone | 15.5-92.06 | 0.089-0.096 (n=3) | 2.54-2.74 |
| | | Jinhu Depression | Funing Formation | 1650 | Basalt | 0.55 | 0.10 (n=6) | 1.25 |
| | Sanshui Basin | / | Paleogene | 700-1800 | Sandstone | 1.45-99.6 | 0.08-0.26 (n=7) | 1.22-4.56 |

Mantle-derived helium reservoirs worldwide located along the margins of active tectonic plates are generally relatively associated with deep-seated faults and magmatic activity. Mantle-derived helium reservoirs in China show relatively shallow burial depths, averaging between 1 km to 4 km, and are located in the Neogene basins near the Tan-Lu Fault Zone (Figure 2). The Tan-Lu Fault Zone has played an important role in the formation, evolution and the distribution of hydrocarbon-bearing Neogene basins on both sides, as well as in the genesis and distribution of natural gas (Tao et al., 2001).

Helium-bearing reservoirs in the Songliao Basin are located in the southeastern and northern areas, including the Wan Jinta gas field, Gulong Depression, Daqing Changyuan, Sanzhao Depression, and Chaolang Platform. In the Wanjinta gas field, the R/Ra values range from 4.5 to 5.1(Xu et al., 1995, 1996). The proportion of mantle-derived helium can reach as high as 57.2% to 65.4%. Furthermore, in Wells Wan 5 and Wan 6, of which the helium contents are 0.07% to 0.08%, approaching industrial helium values. The relatively high proportion of mantle-derived helium in the Wanjinta gas field may be associated with its structural position, where is in close proximity to the western side of the Tan-Lu Fault Zone. It is also possible that the Wanjinta gas field is located directly above an ancient volcanic caldera, leading to the high proportion of mantle-derived helium (Xu et al., 1996). Mantle-derived helium reservoirs exhibit burial depths ranging from 589.6 to 3630 meters in northern Songliao Basin. The helium content typically ranges between 0.102% and 0.404%, with exceptionally high helium content reaching 2.104% in Wells Wang 9-12. $^3He/^4He$ ratios range from 0.1 to 3.0 (Zhong et al., 2017). The mantle-derived helium proportion of northern Songliao Basin varies in proportion from 1.3% to 38.2%. Specifically, the Gulong Depression (11.1%-24%), Daqing Changyuan (16.9%-27.7%) and Sanzhao Depression (9.1%-38.2%), which exhibit relatively higher proportions of mantle-derived helium. In contrast, the Chaolang Platform (1.3%-2.6%) has a relatively lower proportion of mantle-derived helium.

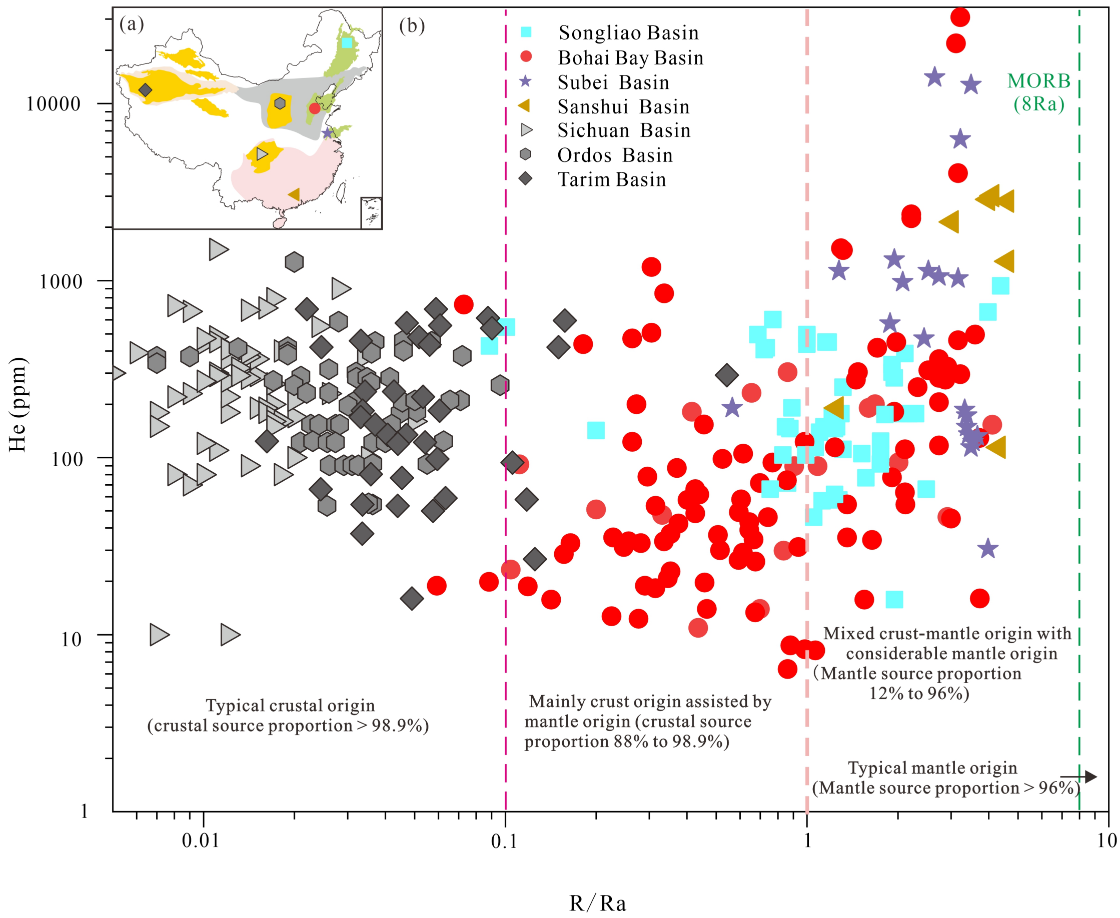

Figure 3. Genesis types of helium in Chinese sedimentary basins. Helium data sources are the same as in Figure 2. The average $^3He/^4He$ ratio of MORB (8 Ra) is considered as the end member for the upper mantle in calculations.

$$R/Ra = (^3He/^4He)_{sample} / (^3He/^4He)_{atmosphere}$$

$$Helium_{mantle} (\%) = [(^3He/^4He)_{sample} - (^3He/^4He)_{crust}] / [(^3He/^4He)_{mantle} - (^3He/^4He)_{crust}] * 100$$

Helium-bearing reservoirs in the Bohai Bay Basin have been found in the Jiyang, Dongpu and Huanghua depressions. The helium contents of natural gas from the Bohai Bay Basin range from 0.0005% to 0.26% with an average of 0.0197% (Zhang et al., 2008; Dai et al., 2017). The R/Ra ratios of natural gas from the Bohai Bay Basin range from 0.059 to 3.74 with an average of 1.013, indicating general mixing of mantle-derived helium by various degrees (Zhang et al., 2008; Dai et al., 2017; Figure 3). Natural gas from the Dongpu Sag has the helium contents ranging from 0.0031% to 0.0217% averaging 0.0133% (Ni et al., 2022). The R/Ra ratios of natural gas from the Dongpu Sag range from 0.011 to 0.856, the proportion of mantle-derived helium in the gas ranges from 0.01% to 10.72% with an average of 2.39%, displaying the characteristics of mixing between crustal and mantle-derived helium.

The Sanshui Basin is a Cenozoic to Neogene basin, located in the western part of the Pearl River Delta, with an area of 3380 $km^2$. During the Cretaceous to Paleogene, the Sanshui Basin experienced intense volcanic activity, with magma events primarily controlled by the intersecting extensional faults oriented in the northeast and northwest directions. The R/Ra ratio is from 1.22 to 4.56 in the Sanshui Basin. The mantle-derived helium proportion constitutes 15.6% to 58.1%, with an average value of 43%. Among the eight industrial wells tested for helium content, six wells have helium concentrations that meet industrial helium values, ranging from 0.085% to 0.259% (Xu et al., 1996).

## 3. Accumulation conditions of helium reservoir in Subei Basin

### 3.1 Helium sources

Natural gas of the Subei Basin is composed of $C_1$-$C_5$ alkane gas, $CO_2$, $N_2$, and trace noble gases. The helium concentration in natural gas varies greatly from 13 to 13400 ppm. Helium-rich natural gases in the Subei Basin are primarily located in the Huangqiao gas field, the Qintong Depression and the Jinhu Depression (Xu et al., 1996). Huangqiao gas field is mainly composed of $N_2$, $CH_4$ and $CO_2$, with $N_2$ contents exceeding 56%. The $CH_4$ and $CO_2$ contents are approximately 24% to 28% and around 15%, respectively. The He contents range from 0.013% to 1.34%, with highest contents of 1.34% in the Huangqian 14 well (Yang et al., 1991). In the Qintong Depression, Well Su203 is rich in $CO_2$ with a concentration of 92.06%, and the He concentration is 0.089%. In Well Su190, $N_2$ is predominant at 33.07%, and the helium concentration is 0.096%. The helium contents in the Jinhu Depression range from 0.081% to 0.096%, essentially meeting industrial helium value. In the Subei Basin both hydrocarbon and non-hydrocarbon natural gases could be helium enriched as shown in Figure 4(a). Helium contents show positive correlation with $N_2$ levels, but variable correlation with $CO_2$ contents. Main reason for such correlations and some low $CO_2$ contents is that the mineralization of $CO_2$ leading to the dissolution of minerals in reservoir such as feldspar and chlorite and self-sealing effect in the cap rock caused the loss of mantle-derived $CO_2$, which will be discussed in section 3.3.

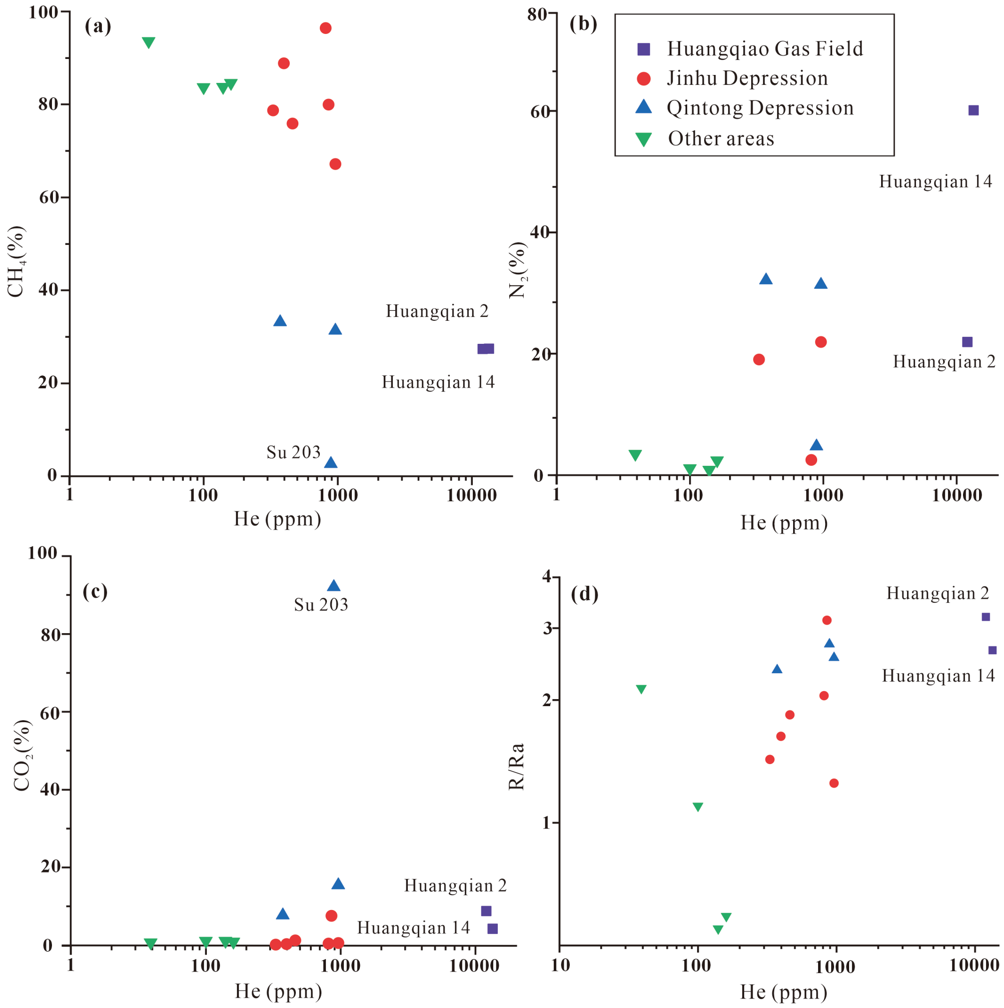


Figure 4. Chemical composition of natural gas in Subei Basin.

Helium data sources are from Xu et al. (1996); Yang et al. (1991); Dai et al. (1994); Tao et al. (1997); Guo et al. (1999). The average $^3He/^4He$ ratio of MORB (8 Ra) is considered as the end member for the upper mantle in calculations.

The three different sources (atmosphere, crust, and mantle) of helium in natural gases could be discriminated by their $^3He/^4He$ ratios (Ballentine and O'Nions, 1992). $^3He/^4He$ ratios of atmosphere and crust have been identified to be $1.4 \times 10^{-6}$ and $2.0 \times 10^{-8}$, respectively. However, $^3He/^4He$ ratio of the mantle remains controversial as the Earth's mantle is chemically and isotopically heterogeneous (Wang et al., 2022). For example, mid-ocean ridge basalts, formed by melting of the upper mantle, demonstrate a relatively consistent $^3He/^4He$ ratio, with an average value of 8±1 Ra, reflecting the composition of the upper mantle (Allègre et al., 1995). By comparison, ocean island basalts formed at intraplate volcanic hotspots, believed to be melts from buoyant mantle plumes originating in the deep mantle, erupt lavas with $^3He/^4He$ ratios ranging from 4 to 42.9 Ra (Moreira et al., 1999). In addition, olivine phenocrysts and xenoliths in samples from the sub-continental lithosphere mantle (SCLM) show a homogeneous helium isotopic ratio (R/Ra=6.1±0.9) (Gautheron and Moreira, 2002). The heterogeneity of the mantle is mainly caused by metasomatism of subducted oceanic crust (Ma et al., 2006; Dai et al., 2019). The Subei basin in eastern China are located in active continental margin of western Pacific Ocean, and sub-continental mantle in Subei basin has been severely metasomatized by subducted oceanic crust (Wang et al., 2022). Mantle xenoliths in different regions of eastern China exhibit variable $^3He/^4He$ ratios, which are notably lower than those of typical MORB and OIB (Xu et al., 1995; Lai et al., 2002; Li et al., 2002; Ma et al., 2006). The $^3He/^4He$ ratio of metasomatized mantle xenoliths in eastern China has been reported to be 5 Ra (Lai et al, 2002), so we use this ratio as the end member for mantle-derived helium in our mixing calculations. The $^3He/^4He$ ratios of natural gas in Subei Basin has a range of 0.55-3.2 Ra (Figure 4(d)), an average 1.95 Ra, resulting in the contribution of mantle-derived helium ranging from 10% to 78%, with an average of 40.1%. Previous studies by Xu et al. (1998) and Wang et al. (2022) calculated the ratios of mantle helium contribution to be 10% to 60%, with an average of 34.6% due to use of typical MORB as the mixing endmember of the mantle.

The average contribution of mantle-derived helium is 40.1% with the remainder (59.9%) assumed to be crustal in origin. This reflects the addition of radiogenic helium to the mantle derived helium during magma ascent. The R/Ra ratio show positive correlations with the helium contents (Figure 4(d)) supports the idea of magmatic helium with a crustal addition.

### 3.2 Migration of mantle-derived helium

During the process of helium migration, deep-seated faults serve as the primary conduit for the ascending mantle-derived helium. As the deep-seated faults cut through the lithospheric mantle, they provide favorable migration paths for mantle-derived volatiles. These deep-seated faults effectively connect reservoirs in both vertical and planar dimensions through secondary faults derived in the shallow subsurface (Wang, et al., 2008). Moreover, magmatic activity can facilitate the upward migration of mantle-derived helium through deep-seated faults (Tao et al., 1996, 2001). Similarly, migration of crustal helium to shallow sedimentary layers is dependent on basement faults.

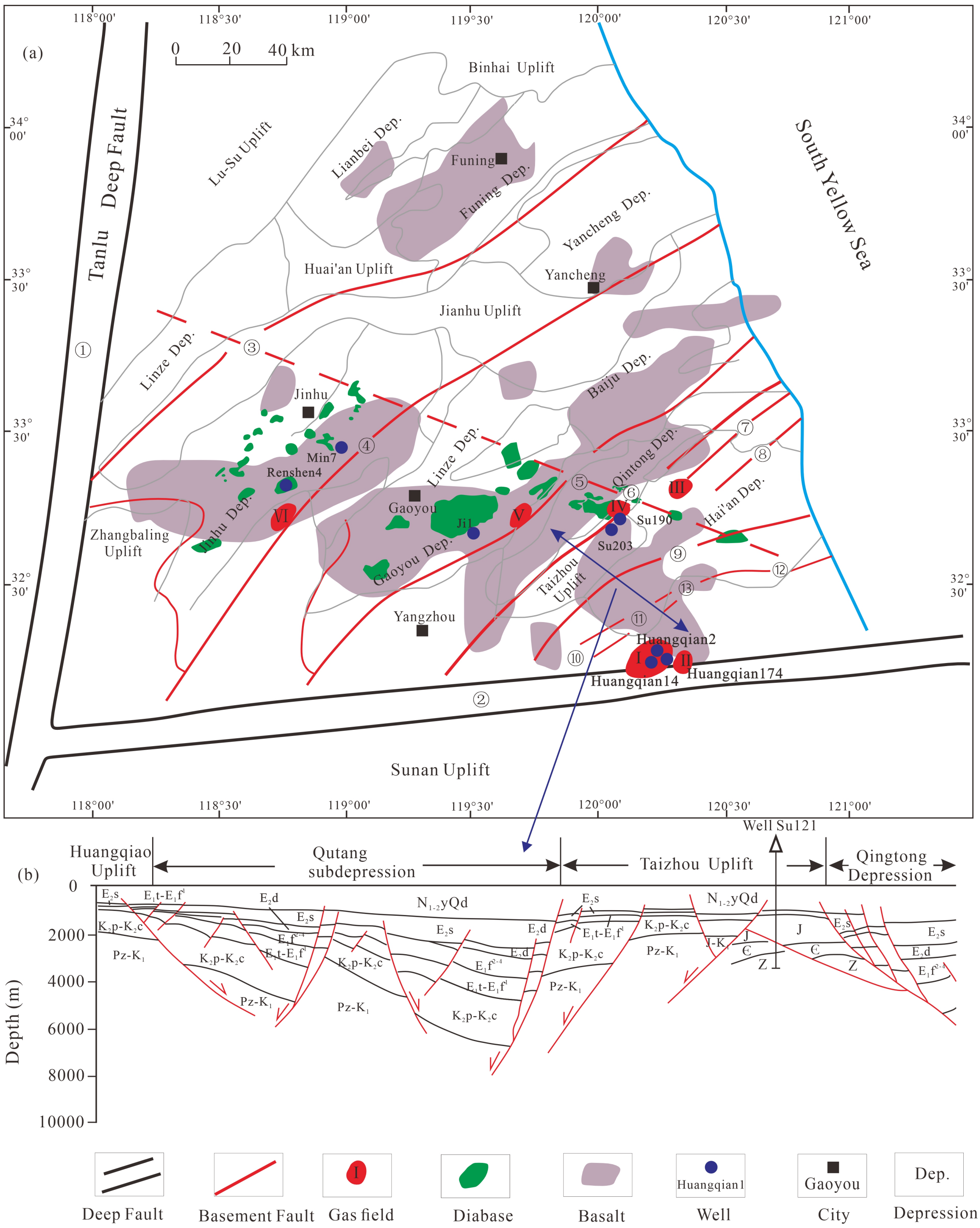

Figure 5. Fault system and distribution of major mantle-derived gas fields in the Subei Basin (modified from Wang et al., 2008 and Luo et al., 2011).

(I Huangqiao gas field; II Xiqiao gas field; III Anfeng gas field; IV Hongzhuang $CO_2$ gas field; V Xiaoji $CO_2$ gas field; VI Tianchang-Tianshen 1 Well $CO_2$ gas field; ① Tanlu Fault; ② Along the Yangtze Fault; ③ Hongze-Funing Fault; ④ Tianchang-Liupu West Fault; ⑤ Gaolizhuang-Xiaoji Fault; ⑥ Qintong Fault; ⑦ Liangduo Fault; ⑧ Fuan Fault; ⑨ Zhangjiaduo-Beiling Fault; ⑩ Nanxinjie Fault; ⑪ Tazili Fault; ⑫ Lifa-Xichang Fault; ⑬ Yazhou Fault).

The western boundary of the Subei Basin closely abuts the Tan-Lu Fault Zone, while the southern margin is defined by the Jiangnan Fault. Both faults traverse the lithospheric mantle, effectively connecting with the mantle-derived helium source and serving as conduits for the migration of mantle-derived helium (Xu et al., 1996; Wang et al., 2008; Figure 5(a)). The basement faults, as shown in Figure 5(b), serve as favorable migration paths for crustal helium. The Huangqiao gas field is located closely to the Jiangnan Fault. Multiple significant basement faults with a north-northeast and north-northeast to east-northeast orientation have been discovered in the Neogene strata. The Jiangnan Fault and these basement faults, potentially branches of the Jiangnan Fault, are considered as the primary controlling faults for the communication of mantle-derived helium and crustal helium in the Huangqiao slope (Cao et al., 2021).

Mantle-derived helium gas and Neogene magmatic activity are closely associated in extensional tectonic regions (Sano et al., 1984; O'Nions and Oxburgh, 1988; Kennedy and van Soest, 2006). Mantle sourced magma serves as the carrier for the reservoir and migration of deep-seated gas source. Magmatic activities are widespread in eastern China during the Neogene. In the Subei Basin, Neogene magmatic activities are characterized by three rock types, basalt, diabase and gabbro, and three distinct episodes, at approximately 64.5–54.6 Ma, 49.4–39.2 Ma, and 36.7–28.1 Ma. These magma activities align closely with the gas reservoir formation periods in the Huangqiao gas field (as mentioned in section 3.1), being slightly earlier than the accumulation periods.

The deep-seated faults and branched basement faults effectively connect the shallow helium reservoirs with the deep mantle and crust (Wang et al., 2008). Moreover, magmatic activity can facilitate the upward migration of mantle-derived helium through deep-seated faults (Tao et al., 1996, 2001). Deep-seated faults and magmatic activity serve as principal determinants in the migration process of mantle-derived and crustal helium.

### 3.3 Reservoir and seal conditions of crust-mantle mixing helium accumulation.

The chemical inertness and high diffusivity of helium requires the preservation conditions to be more stringent. This includes both the reservoir conditions and the sealing conditions of the cap rock.

The reservoir lithologies of helium-bearing reservoirs in the Subei Basin are primarily sandstone reservoirs with mudstone caps and basalt reservoirs with shale caps. The Huangqiao gas field and the Qintong Depression are mainly characterized by sandstone reservoirs from the Yancheng Formation. In the Jinhu Depression, the reservoirs consist of the upper part of the Funing Formation and the middle part of the second section, mainly comprising olivine basalt.

The Huangqiao Slope and the Qintong Depression consist of sandstone reservoirs with mudstone caps. The gas reservoir exhibits a favorable logging response, with gas-bearing characteristics of high porosity and sonic time difference (Figure seen in Supplemental data): In Well Huangqian1, the log response of gas-bearing layer shows high resistivity, a porosity curve with gas-bearing characteristics, an induction resistivity of 12.5 ohms, a sonic time difference of 520 microseconds/m (significantly higher than the non-gas-bearing layers above and below), and a porosity of 43%(Guo et al., 1999). Well Min 7 is located in the Minqiao gas field within the Jinhu Depression., with reservoirs of the upper section of the Funing Formation consisting predominantly of olivine basalt, including vesicular basalt, amygdaloidal basalt, and dense basalt (Zhang et al., 2001).

The properties of the cap rock are crucial in determining whether natural gas can be efficiently accumulated or not. For an efficient natural gas reservoir, the thickness of direct cap rock should exceed 100 meters, and the cap rock capillary pressure should not be less than 20 MPa. In the Subei Basin, the caprock of the Lower Yancheng is composed of mudstone with a thickness ranging from 60 to 100 meters. The breakthrough pressure is suggested to exceed 12 MPa (Sun et al., 2008). The thickness of cap rock within helium-bearing reservoirs in the Subei Basin does not meet the criteria for an efficient cap rock, and the sealing integrity required for helium is even more stringent compared to conventional natural gas implying the preservation of helium need other important factors.

In addition, the dissolution and mineralization caused by injection of mantle-derived $CO_2$ plays an important role in the enrichment and preservation of helium. Mantle-derived $CO_2$ fluids enter the reservoir along the pathways of the deep-seated fault and fault systems, undergoing physical and chemical reactions through $CO_2$-water-rock interactions. After mantle $CO_2$ fluids enters the reservoir, it dissolves in water to form carbonic acid, providing a substantial amount of $H^+$ and $HCO_3^-$, leading to the dissolution of minerals such as feldspar and chlorite. This process generates a certain quantity of ions such as $Ca^{2+}$, $Mg^{2+}$, $Fe^{2+}$ and $AlO_2^-$(Liu, et al., 2017; Xu et al., 2019). Due to the abundant presence of $CO_3^{2-}$ and $HCO_3^-$ ions in the fluid system, ions such as $Ca^{2+}$, $Mg^{2+}$, $Fe^{2+}$, and $AlO_2^-$ react with them, resulting in the precipitation of new minerals, which including illite, calcium montmorillonite, albite, siderite, and calcite (Gao et al., 2005, 2007; Yang et al., 2014).

In the high-temperature reservoir zone near the fault, where the $CO_2$ partial pressure is higher, the formation fluids are acidic. In this setting, feldspar dissolves, giving rise to minerals such as albite, kaolinite, and secondary quartz. On the other hand, in the cap rock above the reservoir, which is in the medium-low-temperature zone and experiences lower $CO_2$ partial pressure, the formation fluids undergo a transition from acidity to neutral to weak alkalinity. This results in the formation of substantial carbonate minerals, such as calcite, siderite, and ankerite, within the fractures of the cap rock, leading to cementation and sealing of the cap rock and further reducing its permeability (Zhang, 2017; Liu et al., 2023). Numerical simulations of the filling and sealing of calcite veins in the cap rock of the Huangqiao gas field indicate that after a simulation time of 0.01 million years, the permeability of the cap rock with calcite-filled fractures has decreased by four orders of magnitude compared to the cap rock permeability before $CO_2$ fluid intrusion (Xu et al., 2019).

By the comparison of helium-rich gas fields in Subei Basin with those in the United States (Figure 6(a)), the results show that the helium-rich $CO_2$ gas fields in the United States have higher He content as salt-anhydrite shows better sealing integrity than shale and mudstone. However, the Helium content of Huangqiao gas field is much higher than that that of other gas field, indicating that the lithology of caprock not the controlling factor influencing the sealing of caprock. In addition, by the contrast of the $CO_2$ content of different gas fields (Figure 6(b)), the $CO_2$ content of shallow Huangqiao gas field is extremely low, while the $CO_2$ content of deeper Huangqiao gas field in Longtan formation is over 90%. We infer that the dissolution and mineralization of mantle $CO_2$ contributes to the sealing of caprock.

The intrusion of deep-seated $CO_2$ fluids into the reservoir and overlying cap rock leads to dissolution of minerals in the reservoir and a self-sealing effect in the cap rock through $CO_2$-water-rock reactions. Dissolution of existing minerals consumes $CO_2$, reduces the concentration of $CO_2$ in the reservoir which has the effect of enriching the proportion of mantle-derived helium. The self-sealing effect further reduces the permeability of the cap rock, allowing the helium to be preserved effectively. The self-sealing effect induced by the intrusion of $CO_2$ fluids is a key factor influencing the preservation conditions of helium accumulation.

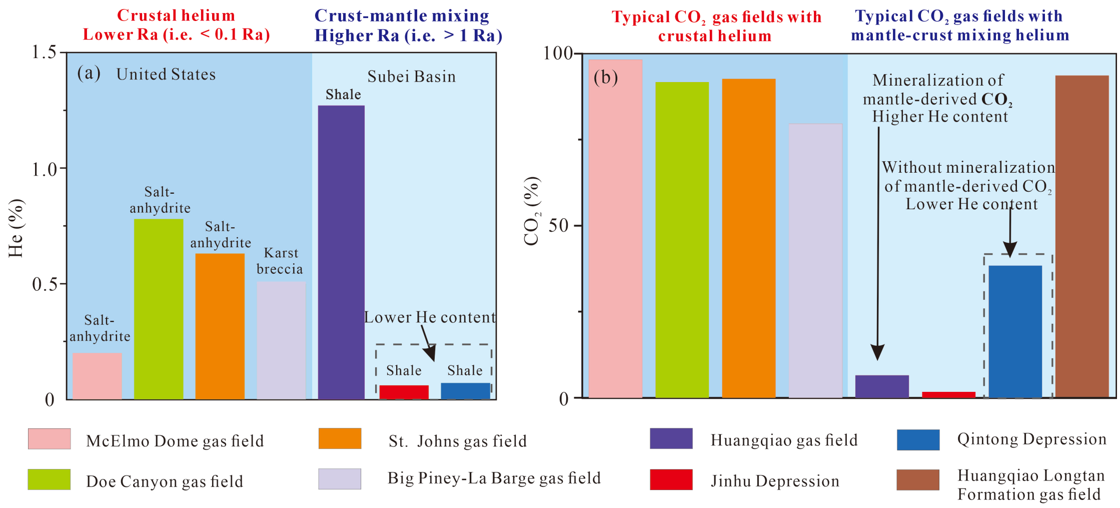


Figure 6. The comparison of helium-rich gas fields in Subei Basin with Colorado Plateau United States. (a) The relationship between He content and the lithography of the caprock. (b) The $CO_2$ content of the different gas fields. Helium data sources are from: Xu et al. (1996); Guo et al. (1999); Ye et al. (2003); Liu et al. (2017); Nichols et al. (2014); Tedesco (2022).

## 4. The mechanism of crust-mantle mixing helium accumulation

Crust-mantle mixing helium reservoirs in eastern China are formed in a rift environment characterized by specific tectonic features. These features include mantle upwelling, thinning of the crust, extensive development of faults, long-term inheritable activity of lithospheric faults connecting the upper mantle to the shallow subsurface, and high geothermal gradients favorable for the migration of mantle-derived helium (Tao et al., 1997).

Figure 7(a, b) shows the regional differences across China in terms of crustal vs mantle He sources. The crust-mantle mixing helium is mainly distributed in back-arc basins of subduction zone of Eastern China, with the characteristic of higher Ra value (i.e. ＞1 Ra). While the crustal helium is predominantly distributed in intracratonic basins of Central and Western China, with the characteristic of lower Ra value (i.e. ＜ 0.1 Ra). The tectonic environments of crust-mantle mixing helium and crustal helium exhibit significant differences corresponding to the sources of helium (Figure 7(b)).

In Eastern China, Mantle fluids and basaltic magma carried helium migrating directly upward through the deep-seated fault, entering traps and accumulating through branches and derivative strike-slip faults of the deep-seated fault in the shallow subsurface (Figure 7(c)). By contrast, the crustal helium was being stored within U-Th-rich crustal rocks and released during tectonic events in Central and Western China. The migration paths are depended on basement faults. The crustal helium can be migrated to the shallow sedimentary layers through basement faults during tectonic activities (Figure 7(d)).

Generally, helium is commonly associated with natural gas reservoirs. Therefore, the accumulation of helium in the gas reservoirs depends on the charging episodic periods of natural gas. Taking the Huangqiao gas field as an example, the inorganic gas reservoirs in the Subei Basin generally underwent three phases of charging and reservoir formation processes (Wang et al., 2008). The first phase occurred in the early Late Cretaceous period (90 Ma), was primarily characterized by the charging and reservoir formation dominated by oil and gas. The second phase, transpiring around the Paleogene period (60 Ma), was characterized by dominant oil and gas charging, accompanied by the phenomenon of $CO_2$ migration and accumulation. The third phase, taking place in the Neogene period (25 Ma), involved $CO_2$ charging, displacing the hydrocarbons formed in the early stages, which corresponds to the formation period of the Xiqiao gas reservoirs. The deep $CO_2$ reservoirs in the Huangqiao gas field experienced multiple phases of accumulation, with deposition periods occurring during the Paleogene (60 Ma) and the Neogene (25 Ma) epochs, respectively (Wang et al., 2008). Inclusion data indicates that the formation period of helium-bearing $CO_2$ reservoirs occurred later than the period of oil and gas reservoir formation, primarily during the Paleogene to Neogene, approximately 25 Ma. The main period of oil and gas reservoir formation took place during the Late Cretaceous (90 Ma) in the late Yanshan period, while the Xishan period (25 Ma) witnessed the accumulation of mantle-derived helium.

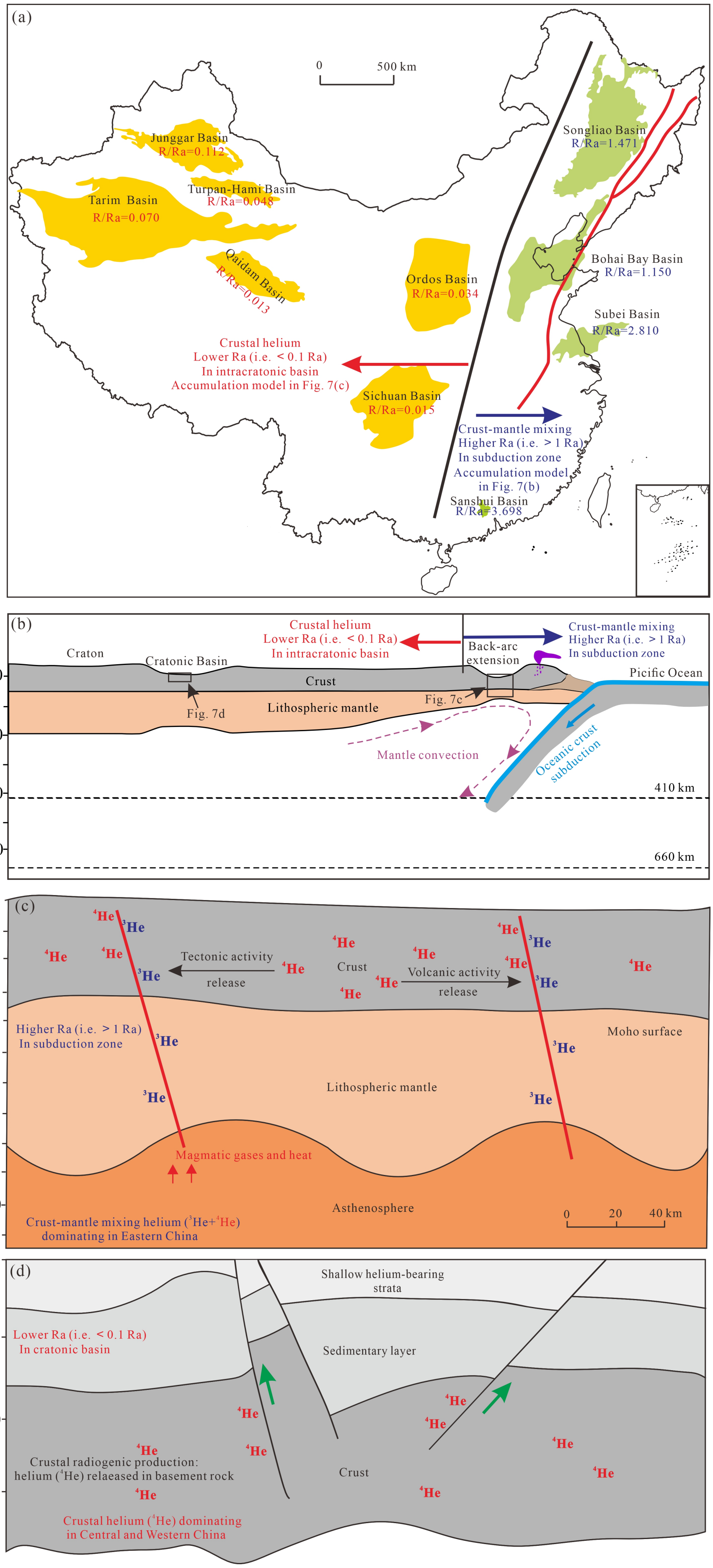
(a)
0 500 km
Junggar Basin
R/Ra=0.112
Turpan-Hami Basin
R/Ra=0.048
Tarim Basin
R/Ra=0.070
Qaidam Basin
R/Ra=0.013
Ordos Basin
R/Ra=0.034
Songliao Basin
R/Ra=1.471
Bohai Bay Basin
R/Ra=1.150
Subei Basin
R/Ra=2.810
Crustal helium
Lower Ra (i.e. < 0.1 Ra)
In intracratonic basin
Accumulation model in Fig. 7(c)
Sichuan Basin
R/Ra=0.015
Crust-mantle mixing
Higher Ra (i.e. > 1 Ra)
In subduction zone
Accumulation model
in Fig. 7(b)
Sanshui Basin
R/Ra=3.698
(b)
Crustal helium
Lower Ra (i.e. < 0.1 Ra)
In intracratonic basin
Crust-mantle mixing
Higher Ra (i.e. > 1 Ra)
In subduction zone
Craton
Cratonic Basin
Back-arc extension
Crust
Picific Ocean
Fig. 7c
Fig. 7d
Lithospheric mantle
Mantle convection
Oceanic crust subduction
410 km
660 km
Depth (km)
0
200
400
600
(c)
Tectonic activity
release
Crust
Volcanic activity
release
Higher Ra (i.e. > 1 Ra)
In subduction zone
Moho surface
Lithospheric mantle
Magmatic gases and heat
Asthenosphere
Crust-mantle mixing helium ($^3He$+$^4He$)
dominating in Eastern China
0 20 40 km
Depth (km)
0 10 20 30 40 50 60 70 80 90 100 110
(d)
Shallow helium-bearing
strata
Lower Ra (i.e. < 0.1 Ra)
In cratonic basin
Sedimentary layer
Crustal radiogenic production:
helium ($^4He$) relaeased in basement rock
Crust
Crustal helium ($^4He$) dominating
in Central and Western China
Depth (km)
0 10 20 30

Figure 7. A schematic conceptual model illustrating the regional differences across China in terms of crustal vs mantle He sources. (a) The horizontal regional differences between Eastern China and Central and Western China in terms of crustal vs mantle He sources. (b) The differences of tectonic environments between Eastern China and Central and Western China. (c) Crust-mantle mixing helium dominating in Eastern China. (d) Crustal helium dominating in Central and Western China. Helium data sources are the same as in Figure 2. The average $^3He/^4He$ ratio of MORB (8 Ra) is considered as the end member for the upper mantle in calculations.

The main controlling factors for the formation of crust-mantle mixing helium reservoirs include deep-seated faults, magmatic activity, and mineralization of mantle-derived $CO_2$. Deep-seated faults, along with their associated strike-slip faults, serve as favorable pathways for magma upwelling and mantle-derived helium migration. Magmatic activities serve as the material source for mantle-derived helium as well as the carrier medium in the migration of mantle-derived volatiles. The presence of well-developed sandstone and basalt reservoirs, along with mudstone cap rocks and the dissolution and mineralization of mantle-derived $CO_2$ are considered to be dominant mechanisms for mantle-derived helium accumulation and preservation.

## 5. Conclusion

(1) The helium in the Subei Basin is derived from a crust-mantle mixed source. The average contribution of mantle-derived helium is about 40.1%, which is higher than that of previous studies, based on our new calculating method using the new mixing endmember of the mantle.

(2) The main controlling factors for the accumulations of mantle-derived helium include deep-seated faults, magmatic activity, and mineralization of mantle-derived $CO_2$.

(3) The dissolution and mineralization of mantle-derived $CO_2$ are considered to be predominant mechanisms for mantle-derived helium accumulation and preservation.

### Acknowledgments

We thank the editor for handling this manuscript and reviewers for helpful comments and suggestions that have improved the manuscript.

### Disclosure statement

No potential conflict of interest was reported by the author(s).

### Funding

This work was financially supported by National Key Research and Development Program of China (2021YFA0719000), and China Sponsorship Council (202306440071).

## References

Allègre, C. J., Moreira, M., and Staudacher, T., 1995, $^4He/^3He$ dispersion and mantle convection: Geophysical Research Letters, v. 22, no. 17, p. 2325-2328.

Ballentine, C. J., and Burnard, P. G., 2002, Production, release and transport of noble gases in the continental crust: Reviews in Mineralogy & Geochemistry, v. 47, no. 1, p. 481-538.

Ballentine, C. J., and O'Nions, R. K., 1992, The nature of mantle neon contributions to Vienna Basin hydrocarbon reservoirs: Earth and Planetary Science Letters, v. 113, no. 4, p. 553-567.

Burnard, P., Bourlange, S., Henry, P., Geli, L., Tryon, M., Natal'In, B., Sengör, A., Özeren, M., and Çagatay, M., 2012, Constraints on fluid origins and migration velocities along the Marmara Main Fault (Sea of Marmara, Turkey) using helium isotopes: Earth and Planetary Science Letters, v. 341, p. 68-78.

Cai, Z., Clarke, R. H., Glowacki, B. A., Nuttall, W. J., and Ward, N., 2010, Ongoing ascent to the helium production plateau--Insights from system dynamics: Resources Policy, v. 35, no. 2, p. 77-89.

Cao, J., Li, D., and Wang, H., 2021, Analysis and considerrations on the relationship between strike-slip faults and non-hydrocarboin gas migration and accumulation in Huangqiao area: Geeophysical Prospecting for Petroleum, v. 60, no. S, p. 149-155.

Chen, J., Liu, K., Dong, Q., Wang, H., Luo, B., and Dai, X., 2021, Research status of helium resources in natural gas and prospects of helium resources in China: Natural Gas Geoscience, v. 32, no. 10, p. 1436-1449.

Dai, J., Ni, Y., Qin, S., Huang, S., Gong, D., Liu, D., Feng, Z., Peng, W., Han, W., and Fang, C., 2017, Geochemical characteristics of He and $CO_2$ from the Ordos (cratonic) and Bohaibay (rift) basins in China: Chemical Geology, v. 469, p. 192-213.

Dai, H., Zheng, J., O’Reilly, S., Griffin, W., Xiong, Q., Xu, R., Su, Y., Ping, X. and Chen, F.. 2019. Langshan basalts record recycled Paleo-Asian oceanic materials beneath the northwest Nor th China Craton. Chemical Geology, v.524, p.88-103

Danabalan, D., 2017, Helium: Exploration Methodology for a Strategic Resource [Doctor: Durham University.

Deng, J., and Du, Z., 2023, Primordial helium extracted from the Earth's core through magnesium oxide exsolution: Nature Geoscience.

Doğan, T., Sumino, H., Nagao, K., and Notsu, K., 2006, Release of mantle helium from forearc region of the Southwest Japan arc: Chemical Geology, v. 233, no. 3, p. 235-248.

Doğan, T., Sumino, H., Nagao, K., Notsu, K., Tuncer, M. K., and Çelik, C., 2009, Adjacent releases of mantle helium and soil $CO_2$ from active faults: Observations from the Marmara region of the North Anatolian Fault zone, Turkey: Geochemistry, Geophysics, Geosystems, v. 10, no. 11, p. Q11009.

Du, J., and Liu, W., 1991, The helium and Argon isotopic geochemistry analysis in natural gas in Sanshui Basin: Natural Gas Geoscience, v. 6, p. 283-285.

Feng, Z., Huo, Q., and Wang, X., 2001, A study of helium reservoir formation characteristic in the North part of Songliao Basin: Nature gas Industry, v. 21, no. 5, p. 27-30.

Fu, X., and Song, Y., 2005, Inorganic gas and its resource in Songliao Basin: Acta Petrolei Sinica, v. 26, p. 23-28.

Furnes, H., Dilek, Y., and de Wit, M., 2015, Precambrian greenstone sequences represent different ophiolite types: Gondwana Research, v. 27, no. 2, p. 649-685.

Gao, Y., Liu, L., and Qu, X., 2005, Dawsonite from Wuerxun Depression in Halaer Basin and its Implication: Geological Science and Techology Information, v. 24, p. 45-50.

Gao, Y., Liu, L., Yang, H., You, L., and Liu, N., 2007, Characteristics and origin of dawsonite in Gudian carbon dioxide gas field of Songliao Basin: Acta Petrolei Sinica, v. 28, p. 62-67.

Gautheron, C., and Moreira, M., 2002, Helium signature of the subcontinental lithospheric mantle: Earth and Planetary Science Letters, v. 199, no. 1, p. 39-47.

Guo, N., You, X., and Xu, J., 1999, Geological character of Xiqiao helium-bearing gas field and prospecting of helium-bearing natural gas in North Jiangsu basin: Petroleum exploration and Development, v. 26, no. 5, p. 24-26.

Halford, D. T., Karolytė, R., Barry, P. H., Whyte, C. J., Darrah, T. H., Cuzella, J. J., Sonnenberg, S. A., and Ballentine, C. J., 2022, High helium reservoirs in the Four Corners area of the Colorado Plateau, USA: Chemical Geology, v. 596, p. 120790.

Hu, W., Lu, X., and Fan, M., 2019, Advances in the research of shale caprocks: type, micropore characteristics and sealing Mechanisms: Bulletin of Mineralogy Petrology and Geochemistry, v. 38, p. 885-896.

Kennedy, B. M., Kharaka, Y. K., Evans, W. C., Ellwood, A., DePaolo, D. J., Thordsen, J., Ambats, G., and Mariner, R. H., 1997, Mantle Fluids in the San Andreas Fault System, California: Science, v. 278, no. 5341, p. 1278-1281.

Kennedy, B. M., and van Soest, M. C., 2006, A helium isotope perspective on the Dixie Valley, Nevada, hydrothermal system: Geothermics, v. 35, no. 1, p. 26-43.

Kimani, C. N., Kasanzu, C. H., Tyne, R. L., Mtili, K. M., Byrne, D. J., Kazimoto, E. O., Hillegonds, D. J., Ballentine, C. J., and Barry, P. H., 2021, He, Ne, Ar and $CO_2$ systematics of the Rungwe Volcanic Province, Tanzania: Implications for fluid source and dynamics: Chemical Geology,

v. 586, p. 120584.

Lages, J., Rizzo, A. L., Aiuppa, A., Robidoux, P., Aguilar, R., Apaza, F., and Masias, P., 2021, Crustal controls on light noble gas isotope variability along the Andean Volcanic Arc: Geochemical Perspectives Letters.

Lai, Y., Liu, Y. L., Huang, B. L., and Chen, Y. J., 2005, The characteristics of noble gases in mantle-derived xenoliths in Wudalianchi and Kuandian, NE China: MORB-like mantle and metasomated mantle: Acta Petrologica Sinica, v. 21, no. 5, p. 1373-1381.

Li, Y., Zhang, W., Wang, L., Zhao, F., Han, W., and Chen, G., 2017, Henry's Law and accumulation of crust-derived helium: A case from Weihe Basin, China: Natural Gas Geoscience, v. 28, p. 495-501.

Liu, Q., Dai, J., and Jin, Z. J., 2009, Geochemistry and Genesis of Natural Gas in the Foreland and Platform of the Tarim Basin: Acta Geologica Sinica, v. 83, p. 107-114.

Liu, Q., Jin, Z., Chen, J., Krooss, B. M., and Qin, S., 2012, Origin of nitrogen molecules in natural gas and implications for the high risk of $N_2$ exploration in Tarim Basin, NW China: Journal of Petroleum Science and Engineering, v. 81, p. 112-121.

Liu, Q., Liu, W., and Xu, Y., 2007, Geochemosty of natural gas and crude computation of gas-generated contibution for various source rocks in Sulige Gas field, Ordos Basin: Natural Gas Geoscience, v. 18, p. 697-702.

Liu, Q., Wu, X., Jia, H., Ni, C., Zhu, J., Miao, J., Zhu, D., Meng, Q., Peng, W., and Xu, H., 2022, Geochemical characteristics of helium in natural gas from the Daniudi gas field, Ordos Basin, central China: Frontiers in Earth Science, v. 10, p. 823308.

Liu, Q., Zhu, D., Jin, Z., Meng, Q., Wu, X., and Hu, H., 2017, Effects of deep $CO_2$ on petroleum and thermal alteration: The case of the Huangqiao oil and gas field: Chemical Geology, v. 469, p. 214-229.

Liu, Q., Zhu, D., Jin, Z., Tian, H., Zhou, B., Jiang, P., Meng, Q., Wu, X., Xu, H., Hu, T., and Zhu, H., 2023, Carbon capture and storage for long-term and safe sealing with constrained natural $CO_2$ analogs: Renewable and Sustainable Energy Reviews, v. 171, p. 113000.

Luo, H., Liang, X., Zhang, J., and Yao, Q., 2011, Exploration potential and favorable play identification in the Taizhou low salient of the Subei Basin: Natural Gas Industry, v. 31, p. 42-46.

Ma, J., Tao, M., and Ye, X., 2006, Characteristics and origins of primary fluids and noble gases in mantle-derived minerals from the Yishu area, Shandong Province, China: Science in China Series D, v. 49, no. 1, p. 77-87.

Mamyrin, B. A., 1970, Determination of the isotopic composition of astamospheric helium: Geochemistry International, v. 7, p. 498-505.

Marty, B., Jambon, A., and Sano, Y., 1989, Helium isotopes and $CO_2$ in volcanic gases of Japan: Chemical Geology, v. 76, no. 1, p. 25-40.

Merrill, M. D., Hunt, A. G., and Lohr, C. D., 2014, Noble gas geochemistry investigation of high $CO_2$ natural gas at the LaBarge Platform, Wyoming, USA: Energy Procedia, v. 63, p. 4186-4190.

Moreira, M., Doucelance, R., Kurz, M. D., Dupré, B., and Allègre, C. J., 1999, Helium and lead isotope geochemistry of the Azores Archipelago: Earth and Planetary Science Letters, v. 169, no. 1, p. 189-205.

Motyka, R. J., Poreda, R. J., and Jeffrey, A. W., 1989, Geochemistry, isotopic composition, and origin of fluids emanating from mud volcanoes in the Copper River basin, Alaska: Geochimica et Cosmochimica Acta, v. 53, no. 1, p. 29-41.

Mtili, K. M., Byrne, D. J., Tyne, R. L., Kazimoto, E. O., Kimani, C. N., Kasanzu, C. H., Hillegonds, D. J., Ballentine, C. J., and Barry, P. H., 2021, The origin of high helium concentrations in the gas fields of southwestern Tanzania: Chemical Geology, v. 585, p. 120542.

Ni, C., Wu, X., Liu, Q., Zhu, D., Yang, F., Meng, Q., Xu, H., Xu, S., and Xu, T., 2022, Helium signatures of natural gas from the Dongpu Sag, Bohai Bay Basin, Eastern China: Frontiers in Earth Science, v. 10, p. 862677.

Ni, Y., Dai, J., Tao, S., Wu, X., Liao, F., Wu, W., and Zhang, D., 2014, Helium signatures of gases from the Sichuan Basin, China: Organic geochemistry, v. 74, p. 33-43.

Nichols, C., Eppink, J., Marquis, M., Alvarado, R., Heidrick, T., DiPietro, P., and Wallace, R., 2014, Subsurface sources of $CO_2$ in the Contiguous United States. Volume 1: Discovered Reservoirs.

O'Nions, R. K., and Oxburgh, E. R., 1988, Helium, volatile fluxes and the development of continental crust: Earth and Planetary Science Letters, v. 90, no. 3, p. 331-347.

Oxburgh, E. R., O'Nions, R. K., and Hill, R. I., 1986, Helium isotopes in sedimentary basins: Nature, v. 324, no. 6098, p. 632-635.

Poreda, R., and Craig, H., 1989, Helium isotope ratios in circum-Pacific volcanic arcs: Nature, v. 338, no. 6215, p. 473-478.

Poreda, R. J., Jeffrey, A. W. A., Kaplan, I. R., and Craig, H., 1988, Magmatic helium in subduction-zone natural gases: Chemical Geology, v. 71, no. 1, p. 199-210.

Poreda, R. J., Jenden, P. D., Kaplan, I. R., and Craig, H., 1986, Mantle helium in Sacramento basin natural gas wells: Geochimica et Cosmochimica Acta, v. 50, no. 12, p. 2847-2853.

Sano, Y., Nakamura, Y., Wakita, H., Urabe, A., and Tominaga, T., 1984, Helium-3 Emission Related to Volcanic Activity: Science, v. 224, no. 4645, p. 150-151.

Sun, M., Liu, G., and Li, J., 2008, Features of cap rocks of gas pools and criteria of dientification: Natural Gas Industry, v. 28, p. 36-38.

Tao, M., Shen, P., and Xu, Y., 1997a, The characteristic and formation condition of mantle-derived heliumaccumulations in Subei Basin. : Natural Gas Geoscience, v. 8, no. 3, p. 1-8.

Tao, M., Xu, Y., and Han, W., 2001, Active characteristics and accumulative effects of mantle-derived fluids in Eastern China.: Geotectonic et Metallogenia, v. 25, no. 3, p. 265-270.

Tao, M., Xu, Y., Shen, P., and Liu, W., 1997b, Tectonic and geochemical characteristics and reserved conditions of a mantle source gas accumulation zone in Eastern China: Science in China Series D: Earth Sciences, v. 40, no. 1, p. 73-80.

Tao, X., Li, J., Zhao, L., Li, L., Zhu, W., Xing, L., Su, F., Shan, X., Zheng, H., and Zhang, L., 2019, Helium resources and discovery of first supergiant helium reserve in China: Hetianhe Gas field: Journal of Earth Science, v. 44, p. 1024-1041.

Tedesco, S. A., 2022, Geology and production of helium and associated gases, Amsterdam, Elsevier.

Umeda, K., Asamori, K., and Kusano, T., 2013, Release of mantle and crustal helium from a fault following an inland earthquake: Applied geochemistry, v. 37, p. 134-141.

Umeda, K., and Ninomiya, A., 2009, Helium isotopes as a tool for detecting concealed active faults:

Geochemistry, Geophysics, Geosystems, v. 10, no. 8, p. Q08010.

Wakita, H., and Sano, Y., 1983, $^3He/^4He$ ratios in $CH_4$-rich natural gases suggest magmatic origin: Nature, v. 305, no. 5937, p. 792-794.

Wang, J., Liu, W., Qin, J., Zhang, J., and Shen, B., 2008, Reservoir forming mechanism and origin characteristics in Huangqiao carbon dioxide gas field, North Jiangsu Basin: Natural Gas Geoscience, v. 19, no. 6, p. 827-834.

Wang, X., Liu, Q., Liu, W., Zhang, D., Li, X., and Zhao, D., 2022, Accumulation mechanism of mantle-derived helium resources in petroliferous basins, eastern China: Science China Earth Sciences, v. 65, no. 12, p. 2322-2334.

Wang, X., Wei, G., Li, J., Chen, J., and Gong, S., 2018, Geochemical characteristics and origins of noble gases of the Kela 2 gas field in the Tarim Basin, China: Marine & Petroleum Geology, v. 89, p. 155-163.

Wei, G., Wang, D., Wang, X., Li, J., Li, Z., Xie, Z., Cui, H., and Wang, Z., 2014, Characteristics of noble gases in the large Gaoshiti-Moxi gas field in Sichuan Basin, SW China: Petroleum Exploration and Development, v. 41, no. 5, p. 585-590.

Wei, L., Lu, X., and Song, Y., 2009, Formation and pool-forming model of $CO_2$ gas pool in eastern Changde area, Songliao Basin: Petroleum Exploration and Development, v. 36, no. 2, p. 174-180.

Xu, D., Zhou, Y., and Zhu, Y., 1999, The $CO_2/^3He$ ratio and formation mechanism of mantle-derived $CO_2$ accumulations in Eastern China.: Oil & Gas Geology, v. 20, p. 290-294.

Xu, S., Nakai, S. I., Wakita, H., Xu, Y., and Wang, X., 1995, Helium isotope compositions in sedimentary basins in China: Applied Geochemistry, v. 10, no. 6, p. 643-656.

Xu, S., Zheng, G., Zheng, J., Zhou, S., and Shi, P., 2017, Mantle-derived helium in foreland basins in Xinjiang, Northwest China: Tectonophysics, v. 694, p. 319-331.

Xu, T., Zhu, H., Feng, G., Yang, Z., and Tian, H., 2019, Numerical simulation of calcite vein formation and its impact on caprock sealing efficiency-Case study of a natural $CO_2$ reservoir: International Journal of Greenhouse Gas Control, v. 83, p. 29-42.

Xu, Y., Liu, W., P., S., and Tao, M., 1998, Geochemistry of noble gases in natural gases, Beijing, Science Press.

Xu, Y., Shen, P., Tao, M., and Liu, W., 1996, Geochemistry on mantle-derived volatiles in natural gases from eastern China oil/gas provinces (I): Science in China Series D: Earth Sciences, v. 40, no. 2, p. 120-129.

Xu, S., Nakai, S., Wakita, H. and Wang, X., 1995. Mantle-derived noble gases in natural gases from Songliao Basin, China. Geochimica et Cosmochimica Acta, 1995, v. 59, no. 22), p. 4675-4683.

Yakutseni, V. P., 2014, World helium resources and the perspectives of helium industry development: Petroleum Geology, v. 9, no. 1, p. 11.

Yang, C., Tao, S., and Hou, L., 2014a, Accumulative Effect of Helium Isotope in Gas Volcanic Reservoirs in Songliao Basin: Natural Gas Geoscience, v. 25, p. 109-115.

Yang, F., Wang, J., and Pan, Q., 1991, Discussion on orgin of upper Neogene helium-rich gases in Huangqiao, North Jiangsu: Oil & Gas Geology, v. 12, p. 340-345.

Yang, G., Li, Y., Ma, X., and Dong, J., 2014b, Effect of Chlorite on $CO_2$-water-rock Interaction: Earth Science Frontiers, v. 39, p. 462-472.

Ye, X., 2003, Enrichment and resource roreground of helium natural gas in Xiqiao area Jiangsu Province: Jiangsu Geology, v. 27, p. 207-210.

Zhang, Y., 2017, Study on sandstone reservoir cahracteristics of Permian Longtan Formation, ineraction with $CO_2$ rich fluid and petroleum accumulation in Huangqiao area, Subei Basin: Nanjing University.

Zhang, Z., Yang, X., and Cai, H., 2001, Characteristics of basalt reservoir in Minqiao area, Jinhu sag.: Speical Oil and Gas Reservoirs, v. 8, no. 3, p. 1-5.

Zheng, L., Feng, Z., Xu, S., and Liao, Y., 1996, $CO_2$ gas pools from the earth interior in Jiyang Depression: Chinese Science Bulletin, v. 41, no. 8, p. 663-666.

Zhong, X., 2017, Distribution characteristics and control factors of helium gas in Northern Songliao basin: Geological Survey and Research, v. 40, no. 4, p. 300-305.