



Original Paper

Helium dynamic accumulation process in the Hetianhe gas field, Tarim Basin, northwest China

Jia-Hao Lv^{a,b}, Quan-You Liu^{c,*}, Peng-Peng Li^c, Jia-Run Liu^c, Yu Gao^c, Zheng Zhou^d^a Key Laboratory of Deep Petroleum Intelligent Exploration and Development, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029, China^b College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, 101408, China^c Institute of Energy, Peking University, Beijing, 100871, China^d Lancaster Environment Centre, Lancaster University, Lancaster, LA14YQ, UK

ARTICLE INFO

Article history:

Received 16 September 2024

Received in revised form

11 June 2025

Accepted 15 September 2025

Available online 19 September 2025

Edited by Xi Zhang and Jie Hao

Keywords:

Noble gas

Helium source

Natural gas

Helium accumulation process

Hetianhe gas field

ABSTRACT

Helium (He) is considered an indispensable rare resource due to its critical applications in high-tech fields such as low-temperature superconductivity, magnetic resonance imaging, and aerospace. However, the sources of helium and its accumulation processes in hydrocarbon basins (such as the Hetianhe gas field) are still unclear.

but also shows promising exploration potential. Helium tends to accumulate in structural highs within the field. Quantifying the helium isotope ratios (R/Ra) reveals that the helium in the Hetianhe gas field is of typical crustal origin. From a "source-reservoir dual control" perspective, it is calculated that 62% of the helium is sourced from the basement helium source rocks, while 38% comes from sedimentary helium source rocks. The study indicates that the Paleoproterozoic granite basement provides a sufficient helium source, with the fault systems serving as effective migration pathways for helium. The concentration of ⁴He and ²⁰Ne in natural gas is positively correlated, which reflects the close relationship between He migration and groundwater. In addition, N₂ and He in natural gas in the Tarim Basin show a good positive correlation, which further indicates that ⁴He dissolves into the groundwater system before degassing into a gas reservoir and that the variations in the ⁴He concentration in the gas phase are caused by the difference of natural gas lateral migration and charging intensity. Notably, a comparison with the reservoir characteristics of globally recognized He-rich fields reveals that "shallow depth, low pressure, and high structural uplift" are key geological factors for helium accumulation.

© 2025 The Authors. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

Helium possesses unique physical and chemical properties that grant it significant industrial value. In nature, helium is primarily found in natural gas, geological fluids, and sedimentary rocks rich in uranium and thorium elements (Ballentine and Burnard, 2002;

Anderson, 2018). To date, no independent gas reservoirs consisting mainly of helium have been discovered. Helium is always found as an associated gas, closely related to the accumulation of hydrocarbon and non-hydrocarbon gases (Liu et al., 2023, 2024; Wang, X. et al., 2023; Tao et al., 2024). Currently, the main source of commercially available helium is derived from the purification of He-rich natural gas, with only those natural gases containing more than 0.1% helium deemed industrially viable for helium extraction (Dai et al., 2017).

Helium has three primary sources: atmospheric, crustal, and mantle-derived (Ballentine and Burnard, 2002; Brown, 2010; Danabalan et al., 2022). The concentration of helium in the

* Corresponding author.

E-mail address: liuqy@pku.edu.cn (Q.-Y. Liu).

Peer review under the responsibility of China University of Petroleum (Beijing).

atmosphere is exceedingly low, at just 5.24×10^{-6} . Consequently, the amount of atmospheric helium introduced into subsurface fluid systems via the hydrological cycle is negligible. Therefore, the helium present in petroleum systems within sedimentary basins primarily originates from crustal and mantle sources (Wang, X. et al., 2023; Liu et al., 2024). The helium resources currently utilized worldwide are almost exclusively crustal in origin, generated from the radioactive decay of uranium (^{235}U , ^{238}U) and thorium (^{232}Th) within rocks (Ballentine and Sherwood Lollar, 2002; Brown, 2019). Regarding the specific source of helium, Pierce et al. (1964) were among the first to propose that the majority of helium in hydrocarbon reservoirs is produced through the radioactive decay of uranium and thorium. They suggested that helium in the Panhandle Field in the United States originates from the shallow basin's pegmatite and granite, while helium in the Kansas Field is derived from sedimentary rocks in the basin. Building on this, Ballentine and Sherwood Lollar (2002) posited that the helium in the Panhandle Field is sourced from shallow crustal granite and is co-genetic with high-maturity nitrogen. In Johnson's (2012) study on helium in British Columbia, Canada, it was found that the helium originates from hydrothermal brines in basement granite. While there is consensus that crustal helium is generated by the radioactive decay of helium source elements such as uranium and thorium, there is significant debate regarding the specific type of helium source rock responsible for this generation.

Helium, a quintessential inorganic gas, differs significantly from natural gas in its generation mechanism, trans-lithospheric transport system, and accumulation process (Liu et al., 2023, 2024; Wang, X. et al., 2023). Despite these differences, helium resources commonly co-exist with natural gas, sharing key similarities in the four fundamental elements: reservoir, trap, seal, and preservation. Therefore, the enrichment mechanisms of helium cannot be directly applied from conventional natural gas accumulation models. Based on previous research, He-rich reservoirs can be classified into three types according to their enrichment mechanisms: basement accumulation type, self-generation and self-preservation type, and crust-mantle composite type (Wang, X. et al., 2023). Previous studies have consistently recognized that an effective helium source, efficient migration pathways, and an appropriate carrier gas are the critical factors for helium enrichment and accumulation (Zhang et al., 2019a; Wang et al., 2019; Danabalan et al., 2022; Tao et al., 2024). Additionally, noble gases are valuable tracers for understanding the origins and migration processes of subsurface fluids, and they can be used to quantify the complex interactions (mixing, dissolution/exsolution, diffusion) within subsurface fluid systems. Earlier research has utilized noble gases to reveal the significant roles of groundwater, basement helium flux, and carrier gases in the mechanisms of helium enrichment (Zhou et al., 2005; Barry et al., 2017; Chen et al., 2019; Brown, 2019; Byrne et al., 2020; Cheng et al., 2023).

The Tarim Basin Hetianhe gas field is China's first supergiant He-rich gas field, providing a natural laboratory for understanding the helium accumulation process. This study focuses on the Hetianhe He-rich gas field to examine the genesis and sources of helium, evaluate the key factors for He-rich gas accumulation, and reconstruct the helium dynamic accumulation process. This research further advances the theoretical knowledge of helium enrichment in natural gas systems.

2. Geological setting

The Hetianhe gas field is located in the Mazatag structural belt on the southern side of the Bachu Uplift in the Tarim Basin, northwest China (Fig. 1(a) and (b)). This structural belt is a nearly east-west oriented, long-axis anticline structure, constrained by

two reverse faults, with the axial direction aligning closely with the fault trends (Cai et al., 2002; Tao et al., 2019). The study area is located between two north-south trending reverse faults, covering a structural area of approximately 450 km^2 (Zhu et al., 2019). The gas-bearing area extends over 76.6 km^2 . It has been confirmed to have a total geological gas reserve of $228.75 \times 10^8 \text{ m}^3$ (data from reports of China Petroleum Tarim Company). Tectonically, the area exhibits a general low-eastern and high-western trend. It comprises the Eastern production Area (Ma4 and Ma5 production zones), the Central production Area (Ma2 production zone), and the Western production Area (Ma3 and Ma8 production zones) from east to west (Fig. 1(c)). The geological strata of the Hetianhe gas field predominantly consist of Paleozoic and Cenozoic formations, including two sets of source rocks: the Carboniferous-Permian and Cambrian systems (Fig. 2). The primary source of natural gas in the Hetianhe gas field is the Cambrian Yurtusi Formation source rock (Song et al., 2015; Zhu et al., 2019). The main productive layers of the gas field include Carboniferous clastic rocks, bioclastic limestone, and Ordovician carbonates. The Carboniferous deposits are shallow-water continental shelf sediments, while the Ordovician deposits represent carbonate platform sediments (Wu et al., 2011). The Carboniferous formations are characterized by multiple sets of regional cap rocks. The gas field operates under a normal temperature and pressure system, with a geothermal gradient ranging from 2.3 to $2.4 \text{ }^\circ\text{C}/\text{cm}$ (Wang et al., 2000).

The Hetianhe gas field has undergone multiple tectonic events, including the Caledonian, Hercynian, and Himalayan orogenies. The current faulted and uplifted structural pattern was established during the Himalayan orogeny

while individual hydrocarbon gases, including CH₄, were analyzed using a continuous flow gas chromatograph (Agilent 6980 GC). The final CH₄ concentrations were calibrated based on measurements from the MAT271 mass spectrometer, reconciling the results from both analytical instruments. The content and isotopic composition of rare gases was measured using the Noblesse SFT rare gas mass spectrometry system. The detailed experimental procedures are described in [Cao et al. \(2023\)](#). First, the samples were purified using the instrument's pre-treatment equipment. The purified rare gases were then sequentially introduced into the noble gas isotope mass spectrometer for measurement. Given the significant differences in concentration between different rare gases, the FarapN JYNlypphfiVkentially

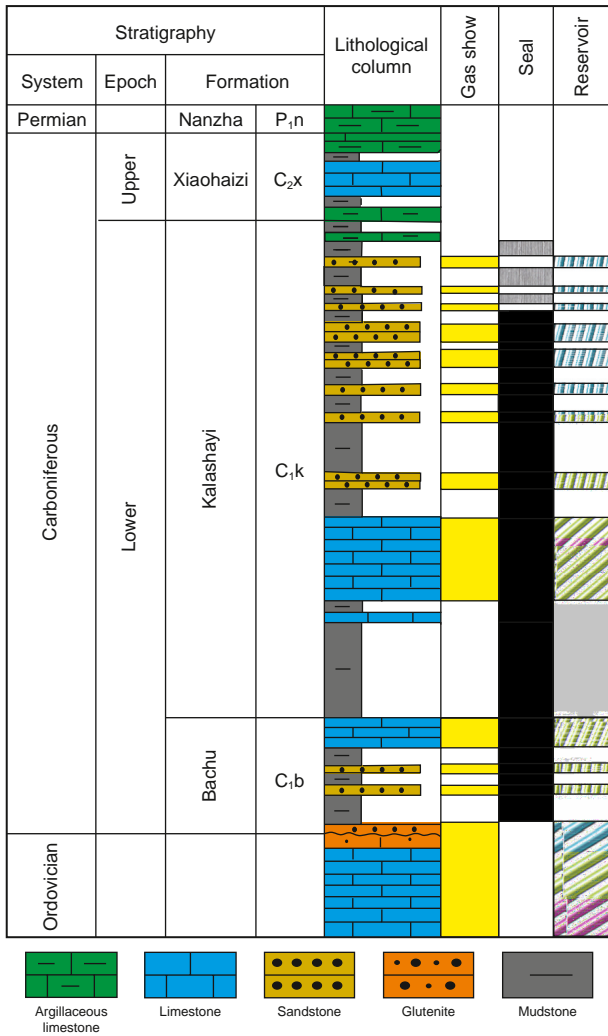


Fig. 2. Comprehensive stratigraphic column diagram of Hetianhe gas field (modified from Zhu et al., 2019).

Table 1 Major components of natural gas in Hetianhe gas field.

Well	Depth, m	Formation	Gas compositions, %				
			He	N ₂	CO ₂	C ₁	C ₂₊
Ma4-H6	2782.00	O	0.29	14.76	0.25	81.59	2.54
Ma4-H3	2265.02	C	0.30	16.85	0.41	79.36	2.91
Ma4-H2	2283.00	O	0.31	14.30	1.36	81.17	2.78
Ma4-H1	1931.00	C	0.33	13.52	0.55	82.77	2.83
Ma4-B2H	2116.73	O	0.33	14.84	1.30	80.58	2.85
Ma4-8H	2274.27	O	0.32	16.40	0.22	80.06	2.87
Ma4-7H	2600.00	C	0.35	16.87	0.10	79.68	2.91
Ma4-12H	2130.00	O	0.32	18.83	1.85	76.45	2.44
Ma4-10H	2352.00	O	0.31	13.13	2.00	81.38	2.99
Ma4	2238.00	O	0.30	14.86	1.12	81.18	2.84
Ma5-8H	2363.14	O	0.30	9.16	6.17	82.80	1.53
Ma5-6H	2131.94	O	0.33	9.24	6.09	82.60	1.65
Ma5-4H	2459.00	O	0.27	9.22	4.19	83.60	2.55
Ma5-2H	2326.00	O	0.36	13.15	3.02	81.11	2.27
Ma5-1H	2219.00	C	0.31	13.40	0.46	83.30	2.84
Ma5	1960.00	C	0.28	12.94	5.71	79.22	1.64
Ma3-1H	1596.00	C	0.40	10.67	12.02	74.18	1.62
Ma2-1H	1950.00	O	0.35	8.15	7.45	82.27	1.76
Ma2	1462.00	C	0.32	9.00	4.21	84.99	1.46
Ma8	1637.00	O	0.42	7.72	15.23	72.11	0.74

elevated structural regions (Fig. 3). In the vertical reservoirs, the helium concentration in the overlying Carboniferous strata is slightly higher than in the Ordovician reservoir. However, the difference in helium concentration between the two is minimal, indicating that further research is needed to explore the vertical distribution characteristics in greater detail.

4.2. Origin and sources of helium

4.2.1. Origin of helium

Helium has two isotopes: ³He and ⁴He. ³He primarily originates from primordial helium captured during earth's formation, while ⁴He is mainly produced through the radioactive decay of uranium and thorium. Helium primarily has three sources: atmospheric source, crustal source, and mantle source (Xu et al., 1990; Ballentine et al., 1991; Ballentine and Burnard, 2002; Liu et al., 2022; Wang, X. et al., 2023). Typically, a ³He/⁴He ratio of 2.2 × 10⁻⁸ is considered representative of crustal helium, while a ratio of 1.1 × 10⁻⁵ is characteristic of mantle-derived helium. The typical ³He/⁴He ratio for atmospheric helium is 1.4 × 10⁻⁶ (Ballentine and Burnard, 2002; Ozima and Podosek, 2004; Wang et al., 2020).

The concentrations and isotopic compositions of noble gases are presented in Table 2. The ³He/⁴He values in the samples range from 6.33 × 10⁻⁸ to 1.06 × 10⁻⁷, with an average of 8.01 × 10⁻⁸. The R/Ra values range from 0.045 to 0.076, with an average of 0.057. The ⁴He/²⁰Ne values in the samples, which reach up to 180,000, are significantly higher than those in ASW (0.288, Kipfer et al., 2002) or air (0.318, Sano et al., 2013), indicating that the contribution of atmospheric helium is negligible. Thus, the helium in the Hetianhe gas field can be considered a binary mixture of mantle and crustal components. Using R/Ra = 8.0 and R/Ra = 0.02 as the end-members for mantle and crustal radiogenic sources, respectively (Ballentine and Burnard, 2002; Dunai and Porcelli, 2002), the contribution of mantle-derived and crust-derived helium in natural gas can be quantified. The results indicate that the helium in the Hetianhe gas field is almost entirely crustal in origin (99%), characterizing it as a typical crust-derived helium source. Basins such as Songliao, Subei, Sanshui, and Bohai Bay exhibit high R/Ra values, indicating a strong mantle-derived contribution. In contrast, the Hetianhe gas field and other central and western basins in China display characteristics typical of crustal helium sources. Overall, the distribution pattern of the ³He/⁴He (R/Ra) ratio is influenced by the tectonic setting (Fig. 4).

4.2.2. Sources of helium

For He-rich natural gas fields within sedimentary basins, helium primarily originates from the mid to upper crust. It migrates to shallower depths through mantle-derived diffusion processes associated with tectonic events, along with subsurface fluids such as formation water, CO₂, N₂, and CH₄ (Ballentine and Sherwood Lollar, 2002; Wang, X. et al., 2023; Cheng et al., 2023). Based on their genesis mechanisms, helium source rocks can be categorized into sedimentary helium source rocks (SHSR) and basement helium source rocks (BHSR). Sedimentary helium source rocks are further subdivided into in-situ reservoir source rocks and underlying source rocks. The helium sources in the Hetianhe gas field involve multiple stratigraphic layers, with both basement and sedimentary helium source rocks exhibiting strong helium generation capabilities (see Section 4.3.1). Due to the inability to determine the volume of the basement helium source rocks, their respective helium contribution fluxes cannot be calculated through genetic methods. Therefore, to better constrain the contribution of sedimentary and basement helium source rocks, the primary "helium source rocks" of the Hetianhe gas field are

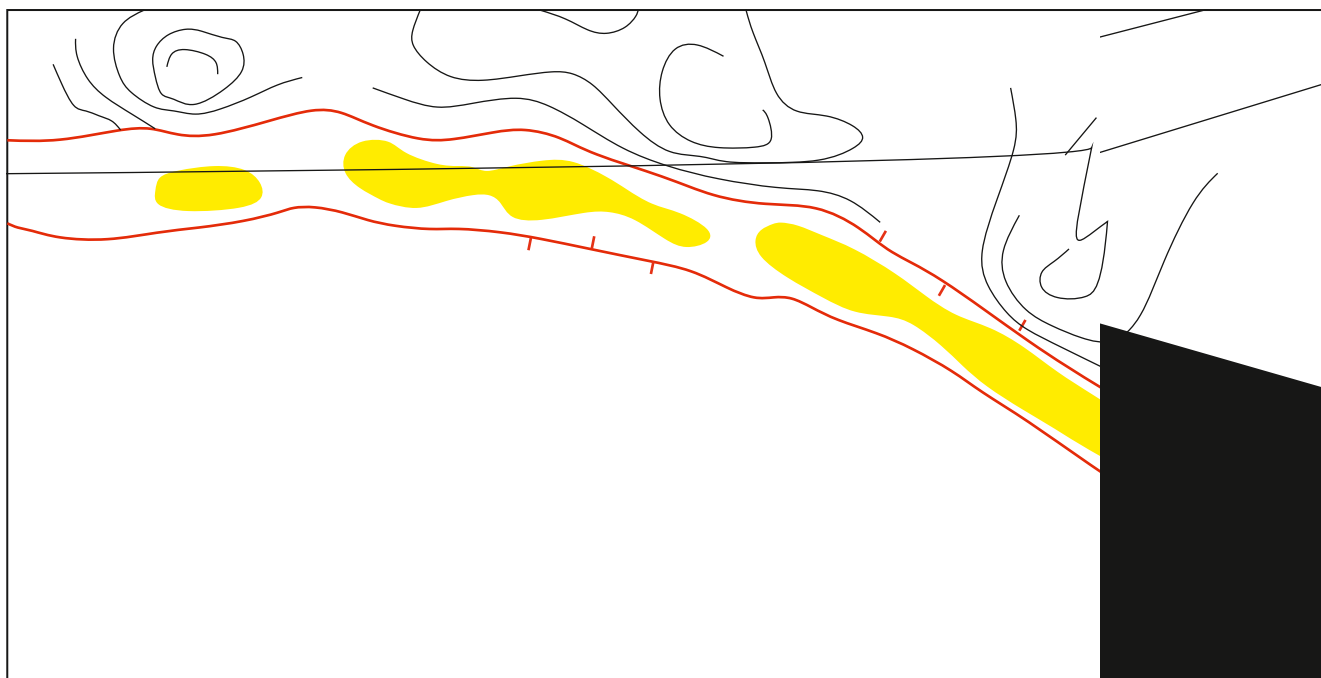


Fig. 3. Helium concentration distribution of natural gas in Hetianhe gas field.

Table 2

Isotopic characteristics of noble gases in natural gas from Hetianhe gas field (modified from Lv et al., 2025).

Well	^4He , $\times 10^{-4}$ $\text{cm}^3 \text{ STP/cm}^3$	^{20}Ne , $\times 10^{-7}$	^{40}Ar	$^3\text{He}/^4\text{He}$ (R/Ra)	$^{40}\text{Ar}/^{36}\text{Ar}$	$^{20}\text{Ne}/^{22}\text{Ne}$	$^{21}\text{Ne}/^{22}\text{Ne}$	$^4\text{He}/^{20}\text{Ne}$
Ma3-1H	40	7.63	0.00089	0.054	2798	9.2	0.043	5240
Ma2-1H	35	3.86	0.00078	0.061	2460	9.4	0.030	9066
Ma5-2H	36	1.54	0.00077	0.053	2402	9.0	0.045	23422
Ma4-B2H	33	0.89	0.00076	0.052	2181	9.0	0.045	36950
Ma4-7H	35	1.07	0.00079	0.060	2129	9.3	0.044	32566
Ma4-H2	31	0.79	0.00073	0.045	2050	9.1	0.044	39079
Ma4-12H	32	1.02	0.00082	0.076	2290	9.0	0.045	31409

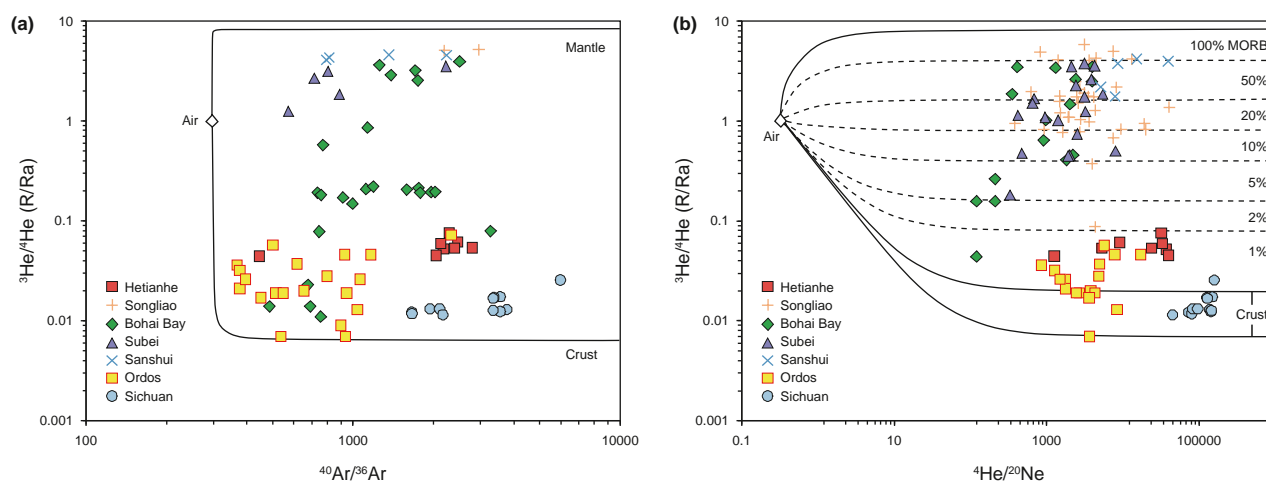


Fig. 4. Helium genesis identification in the Hetianhe gas field compared to typical oil and gas basins in China. The helium in the Hetianhe gas field is of typical crustal origin. The distribution of $^3\text{He}/^4\text{He}$ (R/Ra) is controlled by tectonic environment. The eastern coastal basin is dominated by mantle He, and the central and western basin is dominated by crustal He. Data source (Xu et al., 1995a, 1995b; Tao et al., 1996; Liu et al., 2016, 2022; Li et al., 2020; Ni et al., 2022).

quantitatively defined from a “source-reservoir dual-control” perspective.

According to the law of material conservation, the cumulative amount of ^4He in a natural gas reservoir can be expressed as:

$$^4\text{He} = ^4\text{He}(\text{BHSR}) + ^4\text{He}(\text{SHSR}) \quad (1)$$

According to the volumetric method, the cumulative amount of ^4He in a natural gas reservoir can be expressed as:

$$^4\text{He} = Q_{(\text{gas})} \times C_{(\text{He})} \quad (2)$$

where $Q_{(\text{gas})}$ represents the proven geological gas reserves of the gas field, and $C_{(\text{He})}$ denotes the average helium concentration in the natural gas.

The ^4He production from sedimentary helium source rocks can be calculated using the following Eq. (1) (Halford et al., 2022):

$$^4\text{He}(\text{SHSR}) = \rho J_4 \lambda k (1 - \phi) VT \quad (3)$$

where ρ is the rock density, in g/cm^3 ; λ is the release efficiency, taken as 1; k is the migration efficiency factor, taken as 1; V is the rock volume, in cm^3 ; ϕ is the rock porosity; T is the helium generation time, years (a); J_4 is the helium production rate from the rock, $\text{cm}^3/(\text{g}\cdot\text{a})$. The helium production rate J_4 can be calculated as a function of U and Th concentrations in the crust, ZYd O 2 ypt gcyp, T d fl6Q

indicates that the Precambrian basement primarily consists of Paleoproterozoic granite and gneiss (Cao et al., 2023). Studies have shown that granite is a significant helium source rock, as evidenced by its presence in various gas fields such as the Hugoton-Panhandle field in the United States, the Weiyuan field in the Sichuan Basin, and the Dongping field in the Qaidam Basin (Brown, 2019; Zhang et al., 2019b; Liu et al., 2023). Analysis of granite basement samples from the southern margin of the Bachu Uplift reveals uranium and thorium concentrations of 2.6 and 11.5 ppm, respectively (Li et al., 2018). These values are broadly consistent with the uranium and thorium concentrations in the basement granites of the Hugoton-Panhandle field in the United States (U = 2.5 ppm, Th = 10.7 ppm) (Brown, 2019). This indicates that the Paleoproterozoic granite basement near the Hetianhe gas field can serve as a substantial helium source rock, providing ample helium through radioactive decay.

In addition to the basement rocks, uranium and thorium concentrations are relatively high in organic-rich mudshales. The natural gas in the Hetianhe gas field primarily originates from the Cambrian Yurtus Formation source rocks (Zhu et al., 2019; Tao et al., 2019). Within the LT1 well in the Tabei Uplift, uranium concentrations in this source rock layer can reach up to 123.8 ppm (Zhu et al., 2022), making it a potential helium source rock capable of continuously generating helium. Additionally, the productive layers of the He-rich Hetianhe gas field are from the Ordovician and Carboniferous periods. Although uranium and thorium concentrations in the in-situ reservoirs are relatively low, the ancient age of these reservoirs means that the generated helium flux is not negligible (Table 3).

4.3.2. Fracture system between source and reservoir

The fault system controls the structural pattern of the basin, the development of traps, and the transport system. Most of the currently discovered He-rich natural gas reservoirs are found in fields near deep-seated faults that cut through the basement (Xu et al., 1995b; Liu et al., 2024). Helium primarily migrates vertically through these deep-seated faults (Brown, 2019; Danabalan et al., 2022; Tao et al., 2024). These He-rich gas reservoirs are typically situated above active tectonic uplifts along plate boundaries, where intense faulting facilitates connectivity between helium source rocks and the reservoirs, enabling helium migration from deep strata to the reservoir. Consequently, the fault system plays a crucial role for the formation of He-rich gas reservoirs.

The Hetianhe gas field is located at the boundary between the Maigaiti Slope and the Bachu Uplift, and is divided into two hydrocarbon accumulation systems by the Cambrian salt layer. Below the salt layer, large anticlines have developed, while above the salt layer, fault-related folds are present. The fault system consists of multi-phase strike-slip faults penetrating the salt layer and deep-seated faults. The combination of strike-slip faults penetrating the salt layer and deep-seated faults establishes connectivity between deep fluids and the reservoir, providing an effective pathway for the vertical migration of helium and natural gas (Fig. 6(a)). Additionally, the Hetianhe gas field not only features trap-controlling faults parallel to the structural strike but also has a geological background conducive to the formation of faults perpendicular to the structural strike. During the Late Caledonian to Early Hercynian period, the Mazatag structural belt was

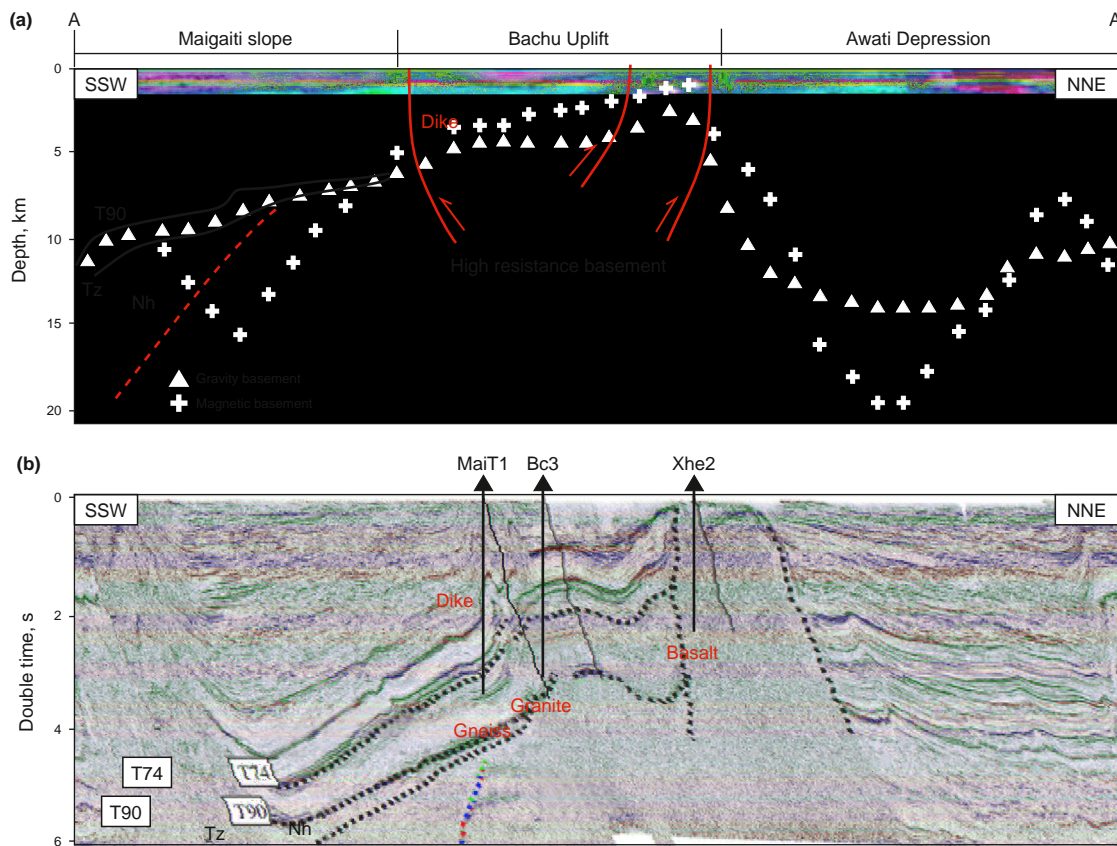


Fig. 5. Inversion section of electric sounding (a) and corresponding seismic section (b) of the traverse Awati Depression-Bachu Uplift and Maigaiti slope (modified from Cao et al., 2023). (T90 is the low interface of the Cambrian system; T74 is the top surface reflection of middle and lower Ordovician series; Nh is Nanhua series; see Fig. 1(b) for the section location).

subjected to northwest–southeast compressional thrust forces, which are evident in the east–west stratigraphic profile of the Hetianhe, where five major deep-seated faults can be clearly observed (Fig. 6(b)). These faults play a crucial role in facilitating the vertical migration of deep helium.

4.3.3. Helium migration carrier

Helium is generated through the radioactive decay of uranium and thorium within geological formations. Due to its extremely low generation rate and the absence of a distinct generative period, it exhibits weak source potential. Therefore, the effective migration and diffusion of helium largely depend on the transport of carrier phases (Ballentine and Sherwood Lollar, 2002; Brown, 2019; Cheng et al.,

observed in the Hugoton-Panhandle gas field in the United States (Brown, 2019). This further provides additional evidence that helium was primarily dissolved in the groundwater system before entering the hydrocarbon gas phase.

In summary, both groundwater and natural gas serve as effective carriers for helium migration. On one hand, helium generated in the crust is preserved in formation water and migrates along with it. Although variations in temperature, pressure, and solubility conditions can cause some exsolution, this effect is generally limited in scale. On the other hand, natural gas generated in source rocks extracts helium from He-rich formation water during migration, allowing it to enter the gas phase and accumulate within reservoirs. It is noteworthy that the natural gas carrier fulfills a dual role: Firstly, it acts as a carrier gas, extracting helium from formation water and migrating with the natural gas to accumulate. Secondly, excessive hydrocarbons can dilute the helium, which is detrimental to helium enrichment. Therefore, the enrichment of helium within a natural gas system requires a balance between adequate supply and dilution.

4.4. Helium accumulation process in Hetianhe gas field

Based on the analysis of helium accumulation factors in the Hetianhe gas field, the deep section of the field features an extensive area of ancient granite basement and uranium- and thorium-rich sedimentary layers, providing a robust foundation as helium source rocks. The fault system, composed of multiple phases of salt-piercing strike-slip faults and deep-seated faults, offers effective migration pathways for helium. Groundwater and natural gas act as excellent preservation media and migration carriers for helium. Additionally, the Carboniferous gypsum-mudstone caprock serves as an effective seal, preventing the escape of helium.

In summary, the helium dynamic accumulation process in the Hetianhe gas field is proposed as follows (Fig. 9). The helium in the Hetianhe gas field originates from two primary sources: 62% is contributed by basement helium source rocks, and 38% by sedimentary helium source rocks. Uranium- and thorium-rich

basement and sedimentary layers generate ^4He through radioactive decay, which then dissolves in formation water. As the formation water migrates along the fault systems towards shallower layers, it disperses the helium throughout the sedimentary sequences. With extensive hydrocarbon generation from Cambrian source rocks, natural gas migrated along fault systems toward low-potential zones. During migration, helium was progressively extracted from helium-enriched formation waters into the gas phase, resulting in co-accumulation of helium with the carrier natural gas. The presence of gypsum-mudstone cap rocks further facilitated the concentration of helium continuously, ultimately leading to the formation of a He-rich natural reservoir.

4.5. Implications for helium exploration

This study investigates the helium enrichment mechanism within the natural gas system by analyzing the large-scale He-rich gas field of the Hetianhe. The findings demonstrate that the formation of He-rich reservoirs requires stringent geological conditions, as well as a complex interplay of spatial, temporal, and material factors. The main controlling factors of helium enrichment in the Hetianhe gas field include the development of uranium- and thorium-rich basement rocks as the foundational source, an effective fracture system as the migration pathway, the synergy between groundwater and natural gas as the transport carriers, and the spatiotemporal alignment of these elements as the critical factor. Helium resources in the Hetianhe gas field are primarily distributed in shallow, low-pressure structural highs. Notably, the deep, stable sub-salt structures of the Cambrian strata in the Hetianhe gas field may harbor rich oil and gas resources. It is hypothesized that these primary sub-salt oil and gas reservoirs are widely He-rich, making them a promising direction for future helium exploration efforts.

Based on the analysis of the Hetianhe He-rich gas field, the study indicates that helium enrichment in

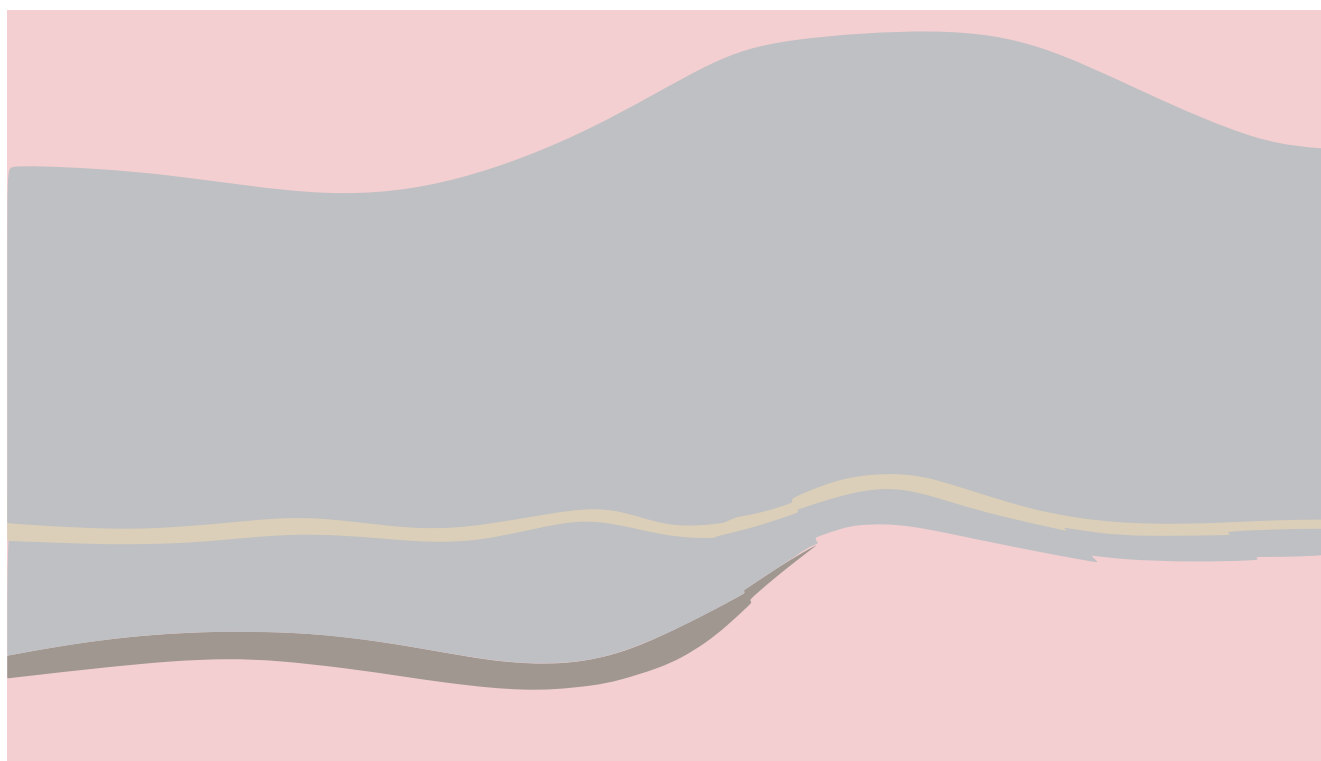


Fig. 9. Helium dynamic accumulation process in Hetianhe gas field.

Table 4

Reservoir formation characteristics of typical He-rich fields discovered so far around the world (primary data are from Krivanek, 1978; Danie, 1978; Bon, 1999; Rauzi, 2003; Dubois et al., 2007; Brown, 2010; Ni et al., 2014; Halford, 2018; Brown, 2019; Wang, J. et al., 2023).

Typical gas field	Structural feature	Formation	Depth, m	Helium content, %	Gas reservoir pressure, MPa
Hugoton-Panhandle	On the Amarillo-Wichita Uplift of the North American Craton	Permian sandstone formations	780–900	0.10–1.05	2.1–3.8 (average 3)
Harley Dome	On the Uncompahgrw Uplift	Jurassic sandstone formations	164–288	2.25–7.31	6.2–6.9
McElmo Dome	On the high Uplift of McElmo Dome salt Dome in the northern Paradox Basin	Leadville Formation (Mississippian)	2000–2545	0.014–0.28	17.8; which is underpressured
Dineh-Bi-Keyah	On the northern edge of the Defiance Uplift	Pennsylvanian Paradox Barker Creek substage, and Devonian Elbert Formation McCracken	866–874	3.49–5.00	5.0
Tocito Dome	A structural dome located northwest - southeast	Pennsylvanian Paradox Formation	1925–1970	0.51	22.2
Hassi R'Mel	On the East African Craton Tilegame Uplift	Sandstone and limestone from the Devonian and Permian periods	3200–3600	0.13–0.69	20.7–34.5
Weiyuan	Leshan - Longnv Temple ancient Uplift	Sinian and Pre-Cambrian	1520–3609	0.03–0.81	20–40
Dongsheng	On the Yimeng Uplift at the northern margin of the Ordos Basin	Permian sandstone formations	1979–3111	0.05–0.49	14.07–28.02
Hetianhe	South of the Bachu Uplift in the Tarim Basin	Carboniferous, Ordovician	1462–2782	0.27–0.42	14.9–23.8

5. Conclusions

To better understand the helium enrichment process, this study focuses on China's first supergiant He-rich gas field—the Hetianhe gas field. The paper reports on the gas composition and noble gas data from wells in the Hetianhe gas field, and collects geological data from known He-rich gas fields around the world. The study provides a detailed analysis of the Hetianhe He-rich gas field, discussing the genesis and sources of helium in natural gas, and reveals the enrichment process of helium from the perspectives of “generation, migration, and accumulation”. The helium concentration in the Hetianhe gas field ranges from 0.27% to 0.42%, indicating that the entire field is He-rich with significant exploration potential. Helium is relatively concentrated in structural highs within the field. The helium in the Hetianhe gas field can be considered a mixture of mantle and crustal components, with R/Ra values quantifying it as a typical crustal-derived helium. To better constrain the contributions of sedimentary and basement helium source rocks, a quantitative calculation from the “source-reservoir dual control” perspective reveals that 62% of the helium originates from basement helium source rocks, while 38% comes from sedimentary helium source rocks.

Through the analysis of the He-rich gas reservoir in the Hetianhe gas field, it is evident that the Precambrian granite basement and uranium-thorium-rich sedimentary strata in the Hetianhe gas field serve as substantial helium source rocks. The multi-stage salt-cutting and deep large faults within the fracture system provide effective pathways for helium migration. In natural gas, ^{20}Ne can reflect the total volume of groundwater. In the Hetianhe gas field, there is a strong linear relationship between ^4He and ^{20}Ne , indicating a close correlation between the migration of ^4He and groundwater. Additionally, the pronounced positive correlation between N_2 and ^4He in the Tarim Basin further suggests that helium primarily resides in formation water before entering hydrocarbon gases. This demonstrates that both groundwater and natural gas serve as effective carriers for helium migration. It is noteworthy that natural gas carriers fulfill a dual function. Firstly, they act as transport media, facilitating the extraction of helium from formation waters. Secondly, the presence of substantial quantities of hydrocarbon gases can dilute the helium concentration, which adversely affects helium enrichment. The observed variations in the concentration of ^4He in the gas phase within the study area are caused by the difference of natural gas lateral migration and charging intensity.

The main controlling factors of helium enrichment in the Hetianhe gas field include the development of uranium- and thorium-rich basement rocks as the foundational source, an effective fracture system as the migration pathway, the synergy between groundwater and natural gas as the transport carriers, and the spatiotemporal alignment of these elements as the critical factor. In the Hetianhe gas field, the stable sub-salt structures within the Cambrian strata may harbor substantial hydrocarbon resources, with the hypothesis that Cambrian sub-salt primary oil and gas reservoirs are widely He-rich. Furthermore, an analysis of the accumulation characteristics of typical He-rich gas fields worldwide has highlighted that “shallow depth, low pressure, and high structural uplift” are critical geological factors for helium enrichment.

CRedit authorship contribution statement

Jia-Hao Lv: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Quan-You Liu:** Supervision, Resources, Project administration, Funding

acquisition. **Peng-Peng Li:** Visualization, Resources, Project administration, Methodology, Investigation. **Jia-Run Liu:** Visualization, Validation, Software, Investigation, Formal analysis. **Yu Gao:** Visualization, Validation, Investigation, Formal analysis. **Zheng Zhou:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research is funded by the National Helium Project (42141021), the Petrochemical Joint Fund (U20B6001), and the School-Enterprise Cooperation Project (041022070087). We thank Tarim Oilfield Company for providing samples and background geological information in this study.

References

- Anderson, S.T., 2018. Economics, helium, and the U.S. federal helium reserve: summary and outlook. *Nat. Resour. Res.* 27, 455–477. <https://doi.org/10.1007/S11053-017-9359-y>.
- Ballentine, C.J., Burnard, P.G., 2002. Production, release and transport of noble gases in the continental crust. *Rev. Mineral. Geochem.* 47, 481–538. <https://doi.org/10.2138/RMG.2002.47.12>.
- Ballentine, C.J., O'Nions, R.K., Oxburgh, E.R., Horvath, F., Deak, J., 1991. Rare gas constraints on hydrocarbon accumulation, crustal degassing and groundwater flow in the Pannonian Basin. *Earth Planet. Sci. Lett.* 105, 229–246. [https://doi.org/10.1016/0012-821X\(91\)90133-3](https://doi.org/10.1016/0012-821X(91)90133-3).
- Ballentine, C.J., Sherwood Lollar, B., 2002. Regional groundwater focusing of nitrogen and noble gases into the Hugoton-Panhandle giant gas field, USA. *Geochem. Cosmochim. Acta* 66, 2483–2497. [https://doi.org/10.1016/S0016-7037\(02\)00850-5](https://doi.org/10.1016/S0016-7037(02)00850-5).
- Barry, P.H., Lawson, M., Meurer, D., Danabalan, Mabry, J.C., Ballentine, C.J., 2017. Determining fluid migration and isolation times in multiphase crustal domains using noble gases. *Geology* 45 (9), 775–778. <https://doi.org/10.1130/G38900.1>.
- Bon, R.L., 1999. *Petroleum Geology of the Harley Dome Field, Grand County, Utah*. Geological Survey. OG-21, Utah.
- Brown, A., 2010. Formation of

- Danie, T.C., 1978. Dinah-Bi-Keyah. In: Fassett, J.E., Thomaidis, N.D., Matheny, M.L. (Eds.), *Oil and Gas Fields of the Four Corners Area*, vol. 1. Four Corners Geological Society., pp. 73–76
- Dubois, M.K., Byrnes, A.P., Bhattacharya, S., Bohling, G.C., Doveton, J.H., Barba, R.E., 2007. Hugoton Geomodel Final Report. Kansas Geological Survey 2007-06-1.
- Dunai, T.J., Porcelli, D., 2002. Storage and transport of noble gases in the subcontinental lithosphere. *Rev. Mineral. Geochem.* 47, 371–409. <https://doi.org/10.2138/rmg.2002.47.10>.
- Halford, D.T., Karolyt, R., Barry, P.H., Whyte, C.J., Darrah, T.H., Cuzella, J.J., 2022. High helium reservoirs in the four corners area of the Colorado Plateau, USA. *Chem. Geol.* 596, 120790. <https://doi.org/10.1016/j.chemgeo.2022.120790>.
- Halford, D.T., 2018. Isotopic analysis of Helium from wells located in the Four Corners Area, Southwestern US, vol 376. Colorado School of Mines PHD Dissertation.
- Johnson, E.G., 2012. Helium in northeastern British Columbia. In: *Geoscience Reports 2013*. British Columbia Ministry of Natural Gas Development, pp. 45–52.
- Kipfer, R., Aeschbach-Hertig, W., Peeters, F., Stute, M., 2002. Noble gases in lakes and ground waters. *Rev. Mineral. Geochem.* 47, 615–700. <https://doi.org/10.2138/RMG.2002.47.14>.
- Krivanek, C.M., 1978. Elmo field. In: *Oil and Gas Fields of the Four Corners are: Four Corners Geological Society*, pp. 148–1951.
- Li, X., Wang, Y., Li, H., Gao, S., Yang, W.,