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Original Paper

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

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A B S T R A C T

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 remain unclear. The Hetianhe gas field, as China's first supergiant He-rich gas field, provides a natural laboratory for studying the mechanisms of helium enrichment. By analyzing the primary gas components and noble gas data from natural gas wells in the Hetianhe gas field, and comparing these with geological data from known He-rich gas fields worldwide, a detailed anatomy of the Hetianhe helium-rich gas field is conducted from three aspects: generation, migration, and accumulation. The Hetianhe gas field is not only uniformly rich in helium 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 ^{4}He and ^{20}Ne in natural gas is positively correlated, which reflects the close relationship between He migration and groundwater. In addition, N_2 and He in natural gas in the Tarim Basin show a good positive correlation, which further indicates that ^{4}He dissolves into the groundwater system before degassing into a gas reservoir and that the variations in the ^{4}He 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.

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

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atmosphere is exceedingly low, at just 5.24 $\times$ 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 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 °C per 100 m and a pressure coefficient between 1.07 and 1.17 (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 (Xie et al., 2017; Ren et al., 2020). During the early to mid-Caledonian orogeny, a normal fault block belt formed along the northern edge of the gas field, marking the initial development of the regional uplift (Wang et al., 2000; Ren et al., 2021). During the early Hercynian orogeny, the northward subduction of the Paleo-Tethys Ocean resulted in the formation of a northward-tilted slope. Under compressional conditions, the previously formed normal faults were reactivated as reverse faults. During the late Hercynian orogeny, the continued northward subduction of the Paleo-Tethys Ocean led to further uplift of the study area (Wang et al., 2007; Song et al., 2015; Xie et al., 2017). During the Indosinian-Yanshanian orogeny, the Bachu Uplift experienced significant erosion. In the Himalayan orogeny, the Kunlun mountains underwent uplift. The early-formed northward-dipping slope in the study area experienced a reversal to a southward dip, resulting in the current southward-dipping slope and the final formation of the uplift (Wu et al., 2011).

3. Sampling and analysis

In this study, samples were collected from natural gas wells in the Hetianhe gas field of the Tarim Basin. During the collection process, high-pressure double-valve stainless steel bottles were used, connected to the wellhead via specialized pipelines. Additionally, to investigate the helium enrichment mechanisms in the Hetianhe gas field, this study collected 90 sets of geochemical data from other gas fields in the Tarim Basin and 38 sets of rare gas data from other typical He-rich gas fields.

The major gas compositions and He-Ne-Ar isotopes of the samples were analyzed immediately after collection at the Oil and Gas Research Center of the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. In the analysis of major gas components, CH_4 and non-hydrocarbon gases were determined using a MAT271 mass spectrometer,

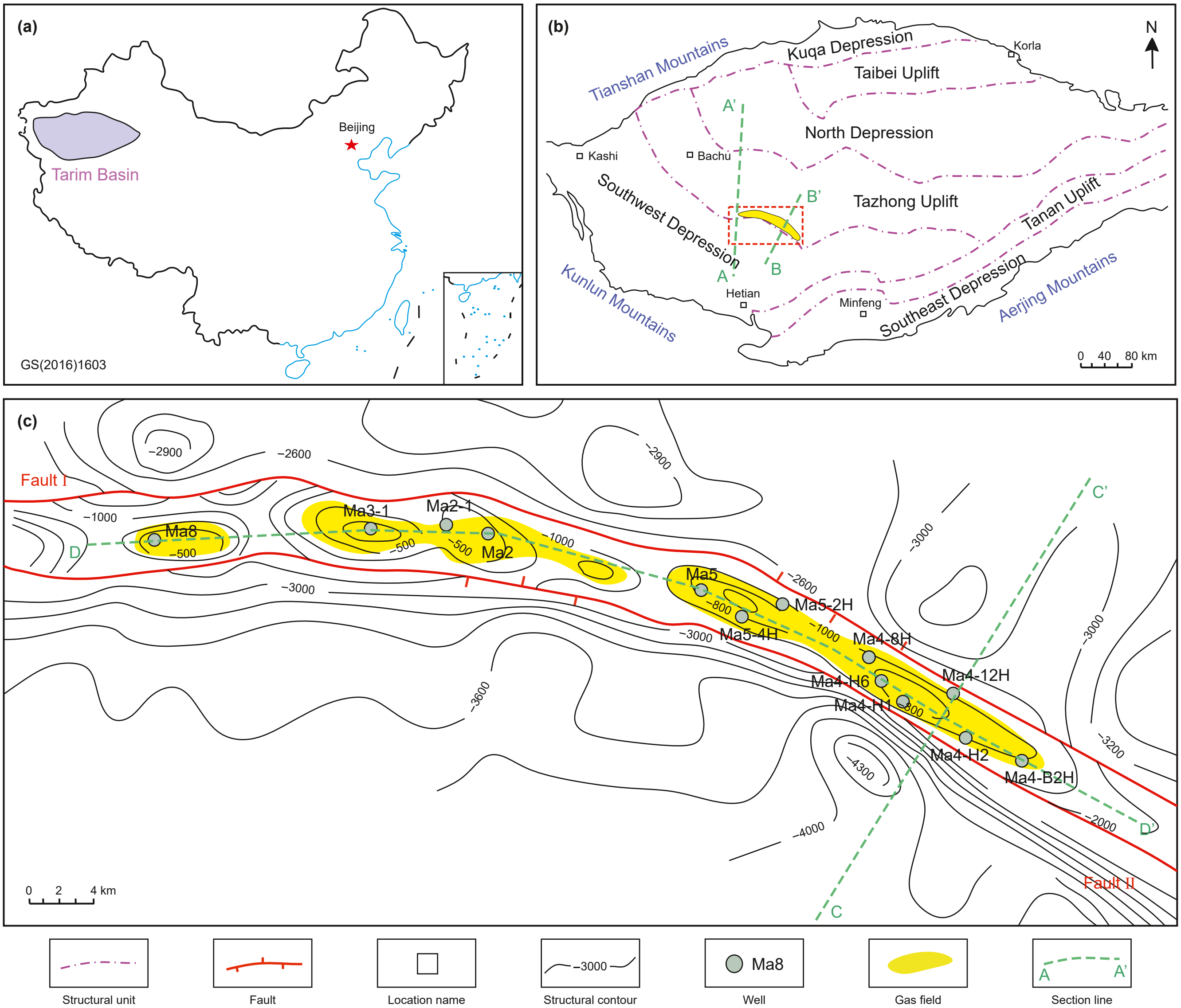

Fig. 1. **(a)** Geographical location of Tarim Basin. **(b)** Structural location of Hetianhe gas field. **(c)** Structure distribution of top surface of Ordovician in Hetianhe gas field (modified from Tao et al., 2019).

while individual hydrocarbon gases, including CH_4, were analyzed using a continuous flow gas chromatograph (Agilent 6980 GC). The final CH_4 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 Faraday collectors were used to measure ^{4}He, ^{20}Ne, ^{22}Ne, ^{40}Ar, and ^{36}Ar, while the electron multipliers were employed for the analysis of ^{3}He, ^{21}Ne, and ^{38}Ar. By calculating the voltage ratios of relevant ions in standard samples and test samples, the measurement data of the samples were obtained. The experimental uncertainty for the noble gas concentrations is less than 10%.

4. Results and discussion

4.1. Spatial distribution characteristics of helium

The major gas composition of the natural gas wells in the Hetianhe gas field is presented in Table 1. The helium concentration in the field ranges from 0.27% to 0.42%. According to the standard for He-rich gas reservoirs, which is set at 0.1% (Dai et al., 2017), the entire field is considered He-rich and holds significant exploration potential for helium resources. Spatially, the wells with high helium concentrations are primarily distributed in the western well area. By comparing the structural map of the Hetianhe gas field, it is evident that the eastern well area has relatively flat structures, with helium concentrations showing minimal variation with structural amplitude. However, overall, the structural amplitude in the western well area is higher than in the eastern area, and the helium concentration is significantly higher in the west. This indicates that helium is relatively enriched in the

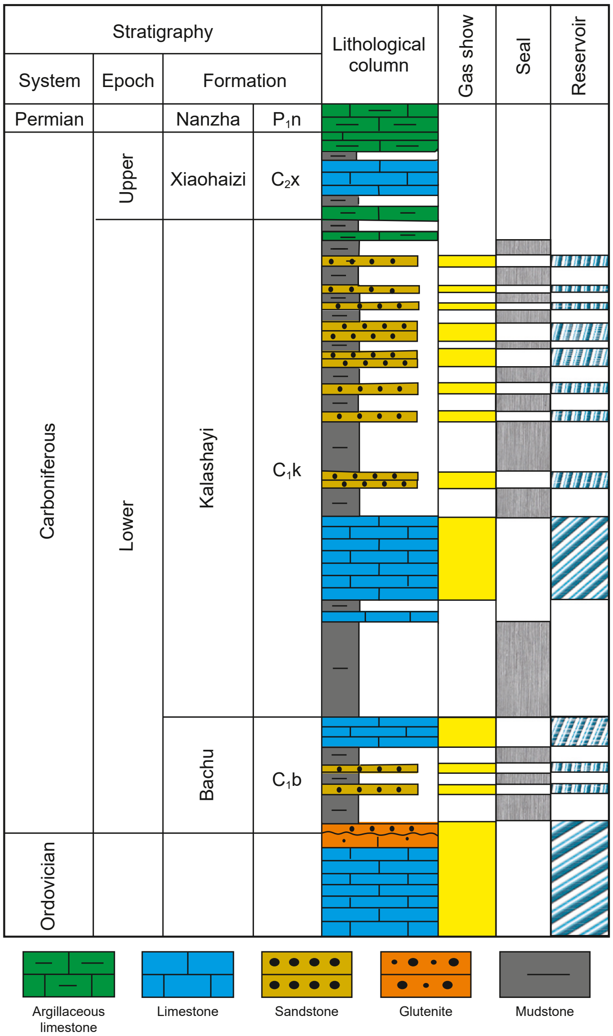

Fig. 2. Comprehensive stratigraphic column diagram of Hetianhe gas field (modified from Zhu et al., 2019).

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 $^4He/^{20}Ne$ 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, CO_2, N_2, and CH_4 (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

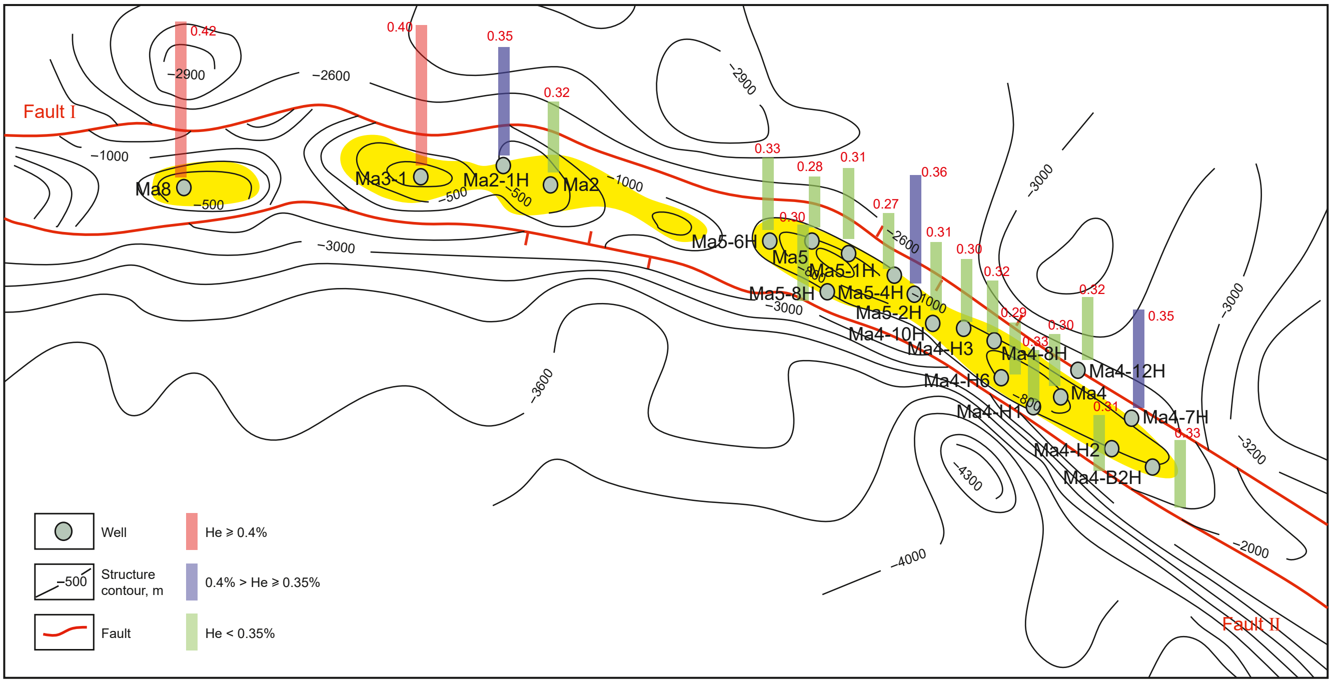

Fig. 3. Helium concentration distribution of natural gas in Hetianhe gas field.

Table 2
Isotopic characteristics of noble gases in natural gas from Hetianhe gas field (modified from Lv et al., 2025).

Well	^4He, $\times 10^{-4}$	^{20}Ne, $\times 10^{-7}$	^{40}Ar	$^3He/^4He$ (R/Ra)	$^{40}Ar/^{36}Ar$	$^{20}Ne/^{22}Ne$	$^{21}Ne/^{22}Ne$	$^4He/^{20}Ne$
	cm^3 STP/cm^3							
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

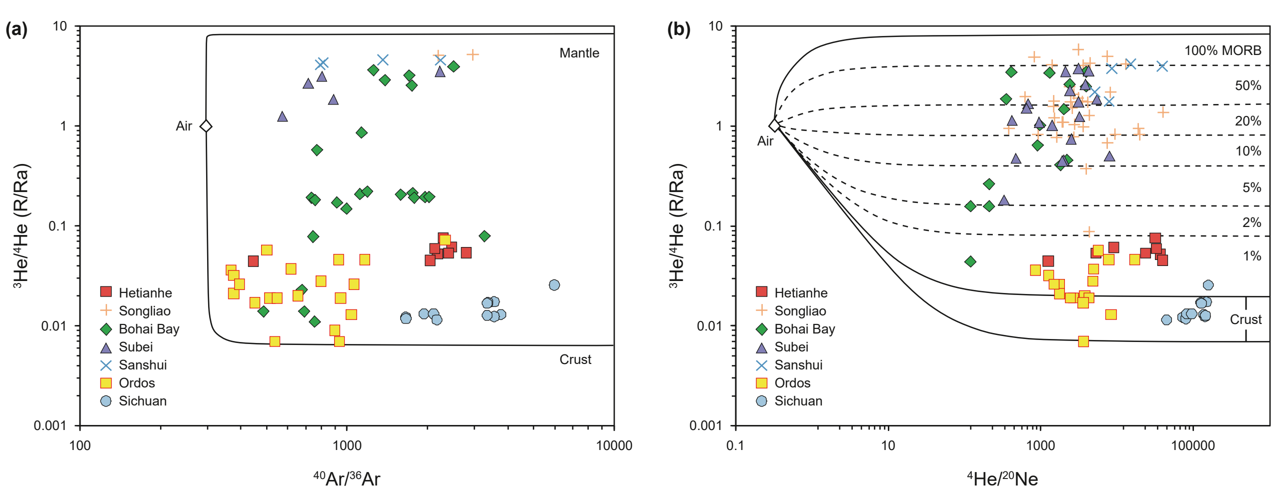

Fig. 4. Helium genesis identification in the Hetianhe gas field compared to typical oil and gas basins in China. The helium in the Hetianhe gas field is of typical crustal origin. The distribution of $^3He/^4He$ (R/Ra) is controlled by tectonic environment. The eastern coastal basin is dominated by mantle 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; Liu 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 ^{4}He in a natural gas reservoir can be expressed as:

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

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

$$^4\text{He} = \text{Q}_{(\text{gas})} \times \text{C}_{(\text{He})} \quad (2)$$

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

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

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

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, cm^3/(g*a). The helium production rate J_4 can be calculated as a function of U and Th concentrations in the crust, based on the theory proposed by Ballentine and Burnard (2002):

$$J_4 = 1.21 \times 10^{-13} \times \text{U} + 2.89 \times 10^{-14} \times \text{Th} \quad (4)$$

By integrating tectonic evolution and well logging data, we quantitatively evaluate the ^{4}He flux contributions from three sedimentary helium source rocks in the Hetianhe gas field. A crucial aspect of this calculation is the determination of the helium generation age parameter. Helium primarily originates from the radioactive decay of uranium (U) and thorium (Th) within crustal rocks. The helium generated in the crust is stored in various locations and requires underground fluids as carriers to transport the helium into gas reservoirs. Under favorable conditions, this leads to the accumulation of He-rich gas fields. The coupling relationship between helium and alkane gases determines the effective helium generation age of sedimentary helium source rocks. In He-rich natural gas reservoirs, the in-situ helium generation age of the reservoir refers to the time elapsed since the last helium loss event in geological history up to the present. The helium generation age of the underlying sedimentary strata of the reservoir refers to the time elapsed from the last helium loss event in geological history to the main period of helium accumulation. Therefore, the effective helium generation time for the in-situ Carboniferous and Ordovician systems extends from the Late Hercynian period (273 Ma) to the present. The effective helium generation age for the Cambrian source rocks ranges from the Late Hercynian period to the Late Himalayan period (250 Ma). Secondly, the U and Th concentrations of the three sets of sedimentary helium source rocks were determined using experimentally measured values. The final calculated results of the ^{4}He contribution flux for the three sets of sedimentary helium source rocks are presented in Table 3. The ^{4}He contribution fluxes for the in-situ Carboniferous, in-situ Ordovician, and Cambrian source rocks are 1156 $\times$ 10^4 m^3, 568 $\times$ 10^4 m^3, and 1144 $\times$ 10^4 m^3, respectively. The total ^{4}He contribution flux for the sedimentary helium source rocks amounts to 2868 $\times$ 10^4 m^3.

The proven geological natural gas reserves of the Hetianhe gas field total 228.75 $\times$ 10^8 m^3, with an average helium content of 0.33%. Based on Eq. (2), the cumulative ^{4}He volume in the gas field is estimated to reach 7548.75 $\times$ 10^4 m^3. It is noteworthy that the total ^{4}He contribution flux from sedimentary helium source rocks does not meet the current ^{4}He cumulative volume in the Hetianhe gas field, accounting for only 38% of the required amount. This indicates that the basement helium source rocks contribute significantly to the field's helium content. According to Eq. (1), the contribution from basement helium source rocks reaches 62%. In summary, the Hetianhe He-rich gas field is a typical crustal helium source genesis. The helium source is composed of 62% contribution from basement helium source rocks and 38% from sedimentary helium source rocks.

4.3. Evaluation of helium accumulation factors in Hetianhe gas field

Currently, helium extracted for industrial purposes is obtained through separation from natural gas reservoirs (Anderson, 2018; Liu et al., 2023). Although helium is frequently found in conjunction with hydrocarbons within specific traps, the geological processes governing the formation, migration, and accumulation of helium differ fundamentally from those of hydrocarbons (Wang, X. et al., 2023; Liu et al., 2024; Tao et al., 2024). The unique characteristics of helium accumulation are primarily manifested in the following aspects: (1) Helium is an inorganic gas, primarily generated through the physical decay of uranium and thorium-rich radioactive minerals; (2) the migration of helium involves a complex cross-layer transport system; (3) the accumulation of helium often requires a carrier phase.

4.3.1. Helium generation potential

Helium generation potential is the material basis for the formation of He-rich natural gas reservoirs and a prerequisite for accumulation (Brown, 2019; Wang et al., 2020). The presence of multiple magmatic and metamorphic rock bodies in the deep regions of the Tazhong Uplift in the Tarim Basin indicates active crustal magmatic activity (Cai et al., 2002; Li et al., 2011; Cheng et al., 2015). With the ongoing advancement of oil and gas exploration, increasing numbers of wells in the southwestern Tazhong Depression have progressively revealed varying degrees of the basin's basement. Well MT1, located southeast of the Hetianhe gas field, has drilled through the sedimentary cover and encountered a Precambrian granite basement, indicating the presence of a large-scale Precambrian granite basement near the Hetianhe gas field. Additionally, the electrical resistivity and seismic inversion profiles from the Awati Depression to the Maigaiti Slope reveal that the basement of the Hetianhe gas field predominantly exhibits high resistivity and strong magnetic properties (Fig. 5). This

Table 3
Contribution of helium flux from sedimentary helium source rocks in Hetianhe gas field.

Unit	U, ppm	Th, ppm	J_4, $\times 10^{-13}$ cm^3/g/a	Density, g/cm^3	Area, km^2	Thickness, m	Age, Ma	Porosity, %	Total ^{4}He flux, $\times 10^4$ m^3
In situ Carboniferous	1.3	5.2	3.07	2.6	76.6	760	273	8.7	1156
In situ Ordovician	0.83	1.1	1.32	2.6	76.6	900	273	12	568
Cambrian hydrocarbon source rock	58.6	10	73.8	2.8	76.6	30	250	3.6	1144

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

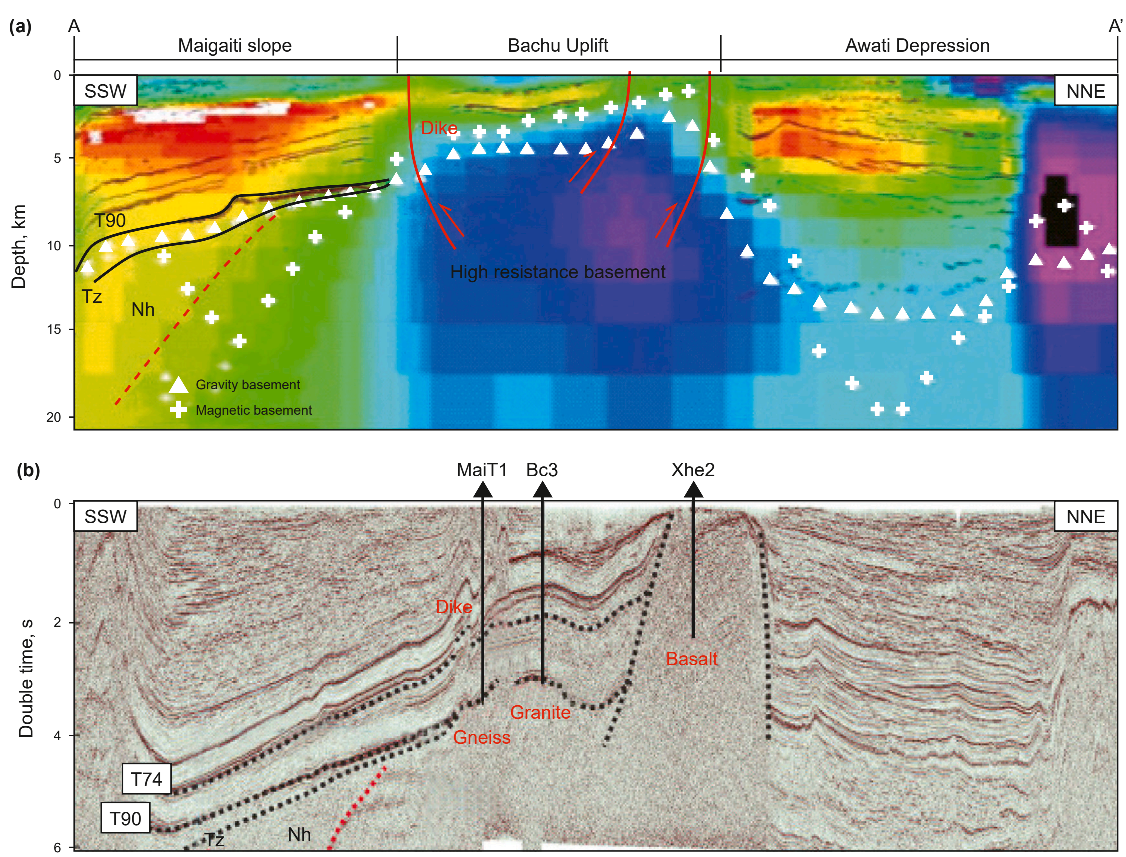

Fig. 5. Inversion section of electric sounding **(a)** and corresponding seismic section **(b)** of the traverse Awati Depression-Bachu Uplift and Maigaiti slope (modified from Cao et al., 2023). (T90 is the low interface of the Cambrian system; T74 is the top surface reflection of middle and lower Ordovician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

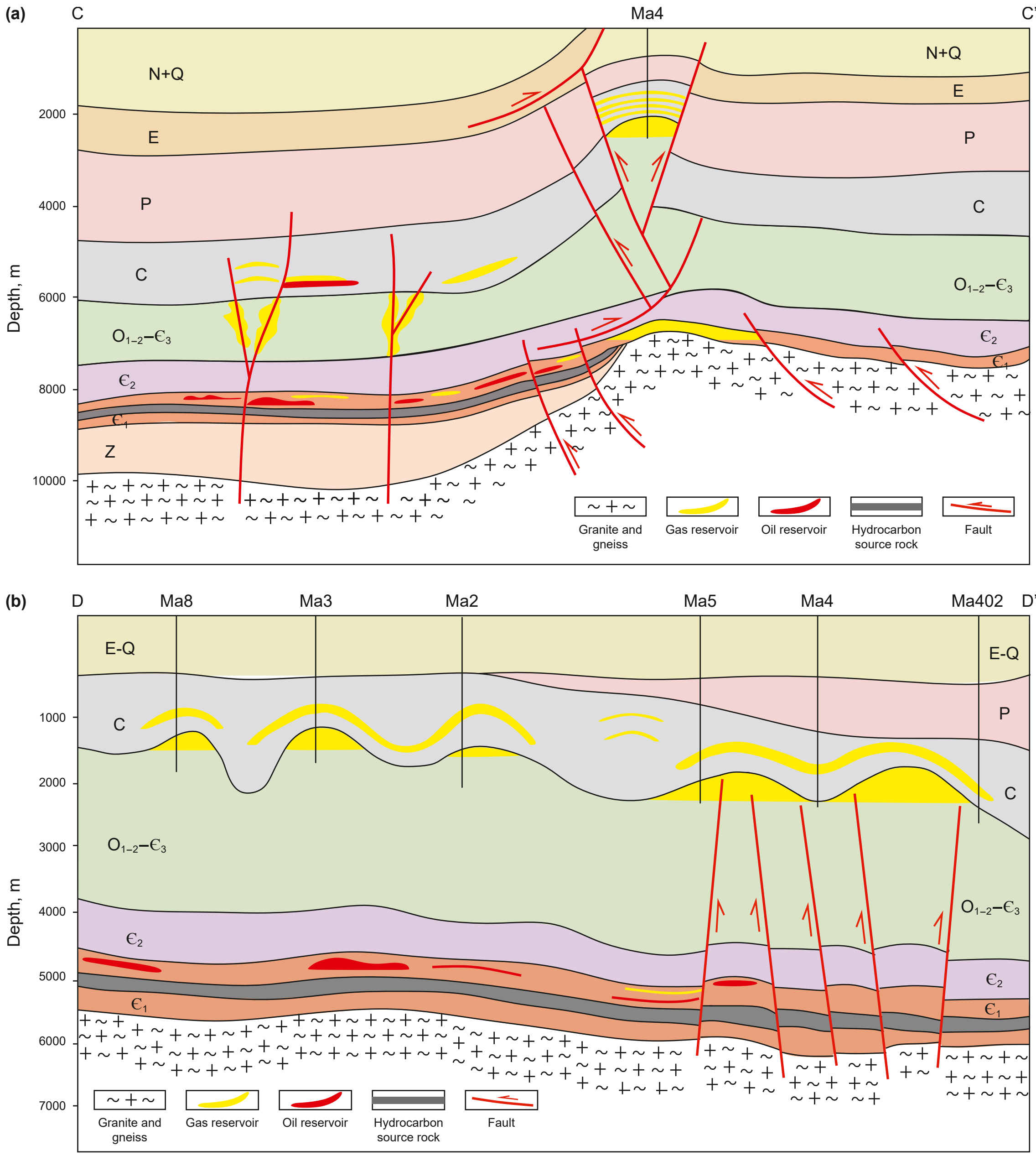

Fig. 6. Geological section of the North–South **(a)** and East–West **(b)** in the Hetianhe gas field (see Fig. 1(c) for the section location). The upward migration channels of deep helium are composed of multi-stage salt-penetrating strike-slip faults and deep-seated faults.

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., 2023). The source of ^{20}Ne in natural gas is quite singular, and its concentration can be used to reflect the total amount of groundwater (Zhang et al., 2019a). In the Hetianhe gas field samples, ^{4}He and ^{20}Ne exhibit a strong linear relationship (Fig. 7), indicating that both have undergone similar subsurface migration processes. This suggests that, prior to being extracted by natural gas, both He and Ne were dissolved in formation water and migrated along with the water. This phenomenon is also observed in the Panhandle-Hugoton gas field and along the northern margin of the Qaidam Basin, reflecting the close relationship between ^{4}He migration and groundwater movement (Brown, 2019; Zhang et al., 2019b). Additionally, in the Tarim Basin, there is a clear positive correlation between N_2 and ^{4}He concentrations in natural gas (Fig. 8). The $^{4}He/N_2$ ratio in the Hetianhe gas field ranges from 0.017 to 0.054, which is similar to the $^{4}He/N_2$ ratio of 0.028–0.078

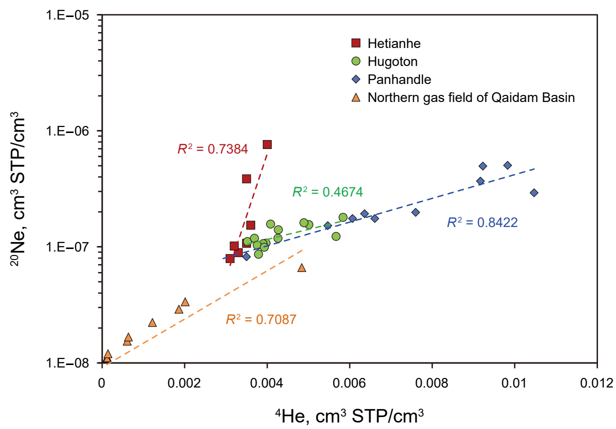

Fig. 7. Plot of ^{20}Ne vs ^{4}He in Hetianhe gas field and other typical He-rich fields. The source of ^{20}Ne in natural gas is very single, and the content of ^{20}Ne can reflect the total amount of groundwater. There is a good positive correlation between ^{4}He and ^{20}Ne in the samples of Hetianhe gas field, indicating that they have similar subsurface migration processes, and the migration of ^{4}He is closely related to groundwater (Gas data of the Hugoton–Panhandle gas field comes from Ballentine and Sherwood Lollar, 2002; Gas data of the northern Qaidam Basin comes from Zhang et al., 2019b).

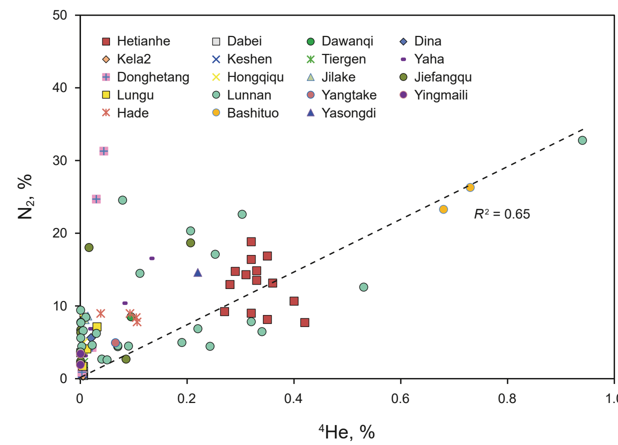

Fig. 8. Positive correlations between N_2 and ^{4}He concentrations in the Tarim Basin, data source (Liu et al., 2012; Xu et al., 2017; Wang et al., 2019).

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 ^{4}He 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 gas fields is closely linked to three key geological factors: "shallow depth, low pressure, and high structural uplift." These factors should be recognized as essential in guiding future helium exploration efforts. Additionally, a review of global He-rich gas fields supports the significance of these geological conditions in helium accumulation (Table 4), reinforcing their importance in the search for new helium resources.

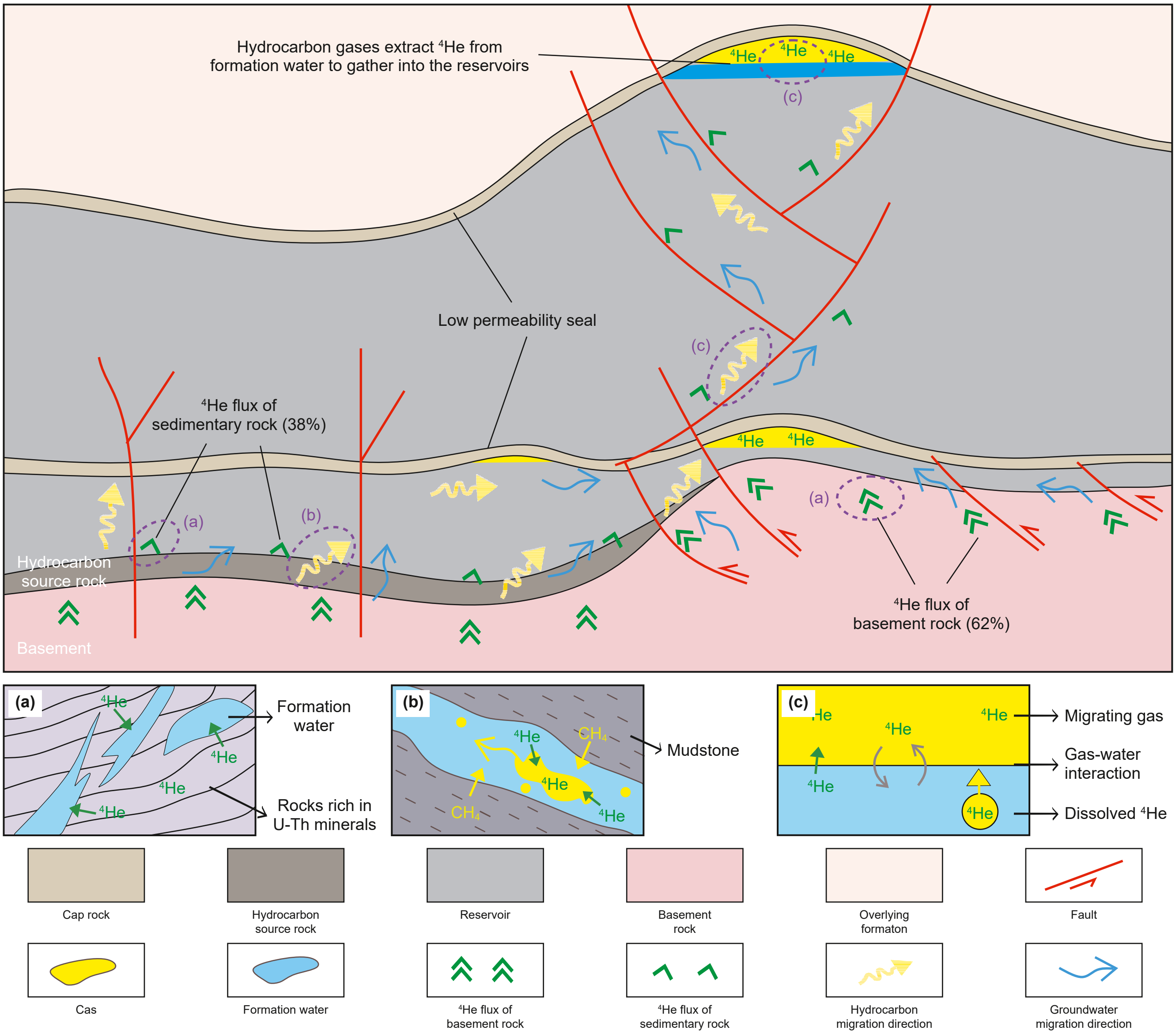

Fig. 9. Helium dynamic accumulation process in Hetianhe gas field.

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 ^{4}He and ^{20}Ne, indicating a close correlation between the migration of ^{4}He and groundwater. Additionally, the pronounced positive correlation between N_2 and ^{4}He 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 ^{4}He 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.

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