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The characteristics and helium generation potential of helium source rocks in the northern Ordos Basin, China

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The origin of helium is predominantly governed by helium source rocks, which encompass a spectrum of lithologies, including metamorphic rocks within the basin's basement, and mudstones, coal, and other rocks in the overlying sedimentary formations. This study investigated four distinct types of potential helium source rocks and their associated helium generation potential within the northern Ordos Basin. Employing methodologies such as geological field surveys, interpretation of gravity and magnetic data, core descriptions, and analytical assays of major and trace elements, the study revealed the following: The Archean continental block in the northern Ordos Basin is overlain by a Paleoproterozoic metamorphosed volcano-sedimentary sequence, predominantly consisting of high-grade metamorphic gneisses, granulites, marbles, migmatites, and granitic gneisses. These rocks exhibit average uranium (U) and thorium (Th) abundances of 2.59 μg/g and 15.20 μg/g, respectively, and a helium generation intensity of 0.750×10^{-6} $cm^3/(Ma{\cdot}g)$. The Mesoproterozoic Changcheng Series of metasedimentary rocks, distributed in parts of the central and northern basin, displays average abundances of U and Th at 2.66 μg/g and 8.36 μg/g, respectively, with a helium generation intensity of 0.562×10^{-6} $cm^3/(Ma{\cdot}g)$. Widespread Upper Paleozoic Carboniferous-Permian mudstones and coal across the northern basin exhibit higher helium generation intensities. The mudstones of Taiyuan Formation have average U and Th abundances of 6.43 μg/g and 20.32 μg/g, respectively, and a helium generation intensity of 1.361×10^{-6} $cm^3/(Ma{\cdot}g)$. In contrast, the coal from the Taiyuan Formation has average U and Th abundances of 5.61 μg/g and 13.09 μg/g, respectively, with a helium generation intensity of 1.054×10^{-6} $cm^3/(Ma{\cdot}g)$. The research has established a classification criterion for crustal helium source rocks. According to the helium generation potential evaluation and identification chart for helium source rocks, Type I helium source rocks are mainly granites and metamorphic rocks in the basement of the northern Ordos Basin and the Lvliang Mountains area on the eastern margin. The Hangjingi area in the northern Ordos Basin exhibits dual development of Archean-Paleoproterozoic basement-type and Upper Paleozoic sedimentary-type helium source rocks, characterized by a "multi-source helium supply" system, demonstrating significant helium source rock potential.

KEYWORDS

helium generation potential, helium source rocks, helium, natural gas, ordos basin

1 Introduction

As an irreplaceable key element in modern high-tech industries, helium is an important strategic resource, with global helium resources mainly concentrated in a few countries such as the United States, Algeria, and Russia. China's helium resources are highly dependent on foreign sources, and the channels and sources of imported helium are extremely concentrated and limited, which seriously restricts the development of China's high-tech industries and national security (Bradshaw and Hamacher, 2013; Wang et al., 2019; Zhang et al., 2022). Scholars have researched the formation conditions of helium-rich conventional gas, tight gas, and water-dissolved gas reservoirs. Therefore, the progress and understanding achieved have laid the foundation for this study (Dai et al., 2005; Du and Liu, 1991; Liu et al., 2009; Liu and Xu, 1992; Liu and Xu, 1994; Wang, 1988; Xu, 1997; Xu et al., 1996; Xu, 1997; Xu, 1998; Xu et al., 1990). China has discovered helium-rich and high-helium natural gas reservoirs in several basins, including central Sichuan, Ordos, western Tarim, Qaidam, eastern Songliao, Hailar, Subei, Bohai Bay, and southern Sanshui (Cao et al., 2001; Chang, 1997; Chen et al., 2021; Peng et al., 2022; Wang et al., 2002; Wu et al., 2017; Yu et al., 2013; Zhang et al., 2020). Helium has also been found in some areas of geothermal wells and hot springs (Li et al., 2017; Zhang et al., 2018).

Helium in natural gas mainly comes from the atmosphere, the crust (formed by the decay of radioactive U and Th in rocks), and the mantle (primordial helium that was present in the Earth's deep interior at the time of its formation), with most commercially valuable helium resources being crustal helium. Crustal helium source rocks are mainly divided into: crustal far-source type and crustal near-source type (Chen et al., 2023). Crustal far-source type rocks mainly include high-grade metamorphic gneisses, granulites, marbles, migmatites, and granitic gneisses. For example, the main helium source rock for the helium-rich natural gas reservoir in the Weihe Basin is the U-rich granite widely developed in the Northern Qinling Mountains; the helium in the Dongsheng gas field mainly comes from the decay of U and Th elements in the metamorphic rocks and granites of the Archean-Proterozoic basement (Peng et al., 2022). Crustal near-source type rocks are mainly sedimentary rocks rich in U and Th, especially organic-rich shale. Among crustal rocks, organic-rich shale, which adsorbs a large amount of uranium and thorium elements, has the highest content of U and Th and the largest helium generation, with the amount of helium generated by organic-rich shale per unit of time being 9 to 10 times that of granite. For example, the Wufeng-Longmaxi Formations in the Sichuan Basin, which are rich in organic shale, have high U and Th content, large thickness, and wide distribution, indicating a great potential for helium resources (Ballentine and Burnard, 2002; Brown, 2019; Lowenstern et al., 2014; Meng et al., 2021; Nie et al., 2023; Rufer et al., 2017). Besides, recent advancements in analytical geochemistry, including high-resolution ICP-MS and LA-ICP-MS, have enabled precise quantification of U/Th concentrations in basement lithologies and refining estimates of helium generation potential (Chajduk et al., 2013; Zhang et al., 2023).

The formation and evolution of crust-derived helium exhibit two distinctive characteristics: Firstly, its generation follows a continuous accumulation mechanism over prolonged geological timescales ($>10^8$ years), lacking evident episodic enrichment features. Secondly, its resource potential is fundamentally controlled by the abundance of parent elements (U and Th series) and their decay dynamics. The unique dual attributes of this gas–chemical inertness coupled with strong diffusivity–further complicate reservoir formation studies. Although preliminary investigations have been conducted on helium gas and source rocks in the northern Ordos Basin, there remains an absence of systematic evaluation index systems for assessing helium source rock effectiveness. Traditional hydrocarbon source rock evaluation methodologies encounter theoretical limitations when applied to helium source rock studies, which directly constrain the assessment of helium resource potential and the optimization of exploration targets (Liu et al., 2022; Wang et al., 2023; Wu et al., 2025). Helium sources are essential for the formation of helium resources, and the spatial distribution of helium source rocks and the evaluation of their potential are key issues in the exploration of helium resources. After conducting geological field surveys, describing cores, and analyzing major and trace elements in the laboratory, a systematic analysis was done to investigate the potential of rocks to generate helium based on their varying uranium (U) and thorium (Th) contents. A quantitative evaluation was conducted for the potential helium sources in the northern Ordos Basin, using numerical simulation to identify the main sources of helium and to analyze the abundance and intensity of helium production in various rock formations within the basin and its underlying basement.

2 Geological background

The Ordos Basin is a multi-cycle superimposed basin developed on the metamorphic crystalline basement of the western North China Craton. The basin can be divided into six first-order structural units based on its evolutionary history, differences in structural characteristics, and basement properties. These units are the Yimeng Uplift, the Jinxi Fold and Thrust Belt, the Yishan Slope, the Weinan Uplift, the Tianhuan Depression, and the Western Margin Thrust Belt (Jiang et al., 2023; Liu et al., 2022; Su et al., 2021; Yang, 2002).

The basin is rich in natural gas resources, with multiple gas fields such as the Qingyang, Sulige, and Yulin fields discovered to date (Wang et al., 2024). Among them, the Dongsheng gas field has an average helium content of 0.133%, the East, Central, West, and South areas of the Sulige gas field range from 0.042% to 0.108%, the Yulin gas field is 0.320%, the Shenmu gas field is 0.052%, the Zizhou-Mizhi gas field is 0.041%, the Dniudi gas field is 0.043%, the Yichuan gas field is 0.041%, the Huanglong gas field is 0.233%, the Gaoqiao gas field is 0.052%, and the Qingyang gas field is 0.068%. The Dongsheng gas field, Shenmu gas field, and Sulige gas field located in the northern part of the basin have a large number of natural gas reserves, with an average helium content ranging from 0.052% to 0.133%, indicating that some natural gas in the Ordos Basin has a relatively high helium content (Figure 1) (Ding et al., 2024; Gao et al., 2024; Liu et al., 2023; Liu et al., 2024).

At present, the main exploration horizons of natural gas in the Ordos Basin are the Carboniferous-Permian of the Upper Paleozoic and the Ordovician of the Lower Paleozoic. The Upper Paleozoic, the target horizon of this study, is mainly composed of Carboniferous-Permian terrigenous clastic rocks and coal-measure strata. The coal-measure strata of the Upper Paleozoic, from old to new, are the

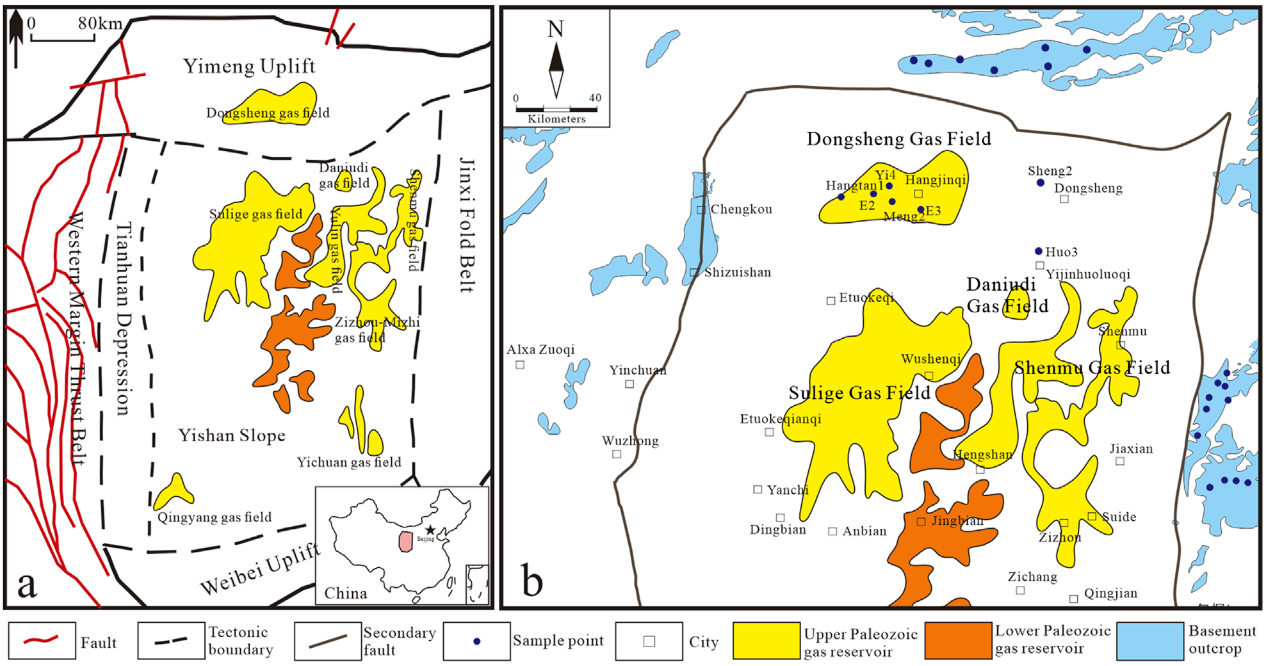

FIGURE 1
(a) Location map of major natural gas fields in the Ordos Basin; **(b)** Distribution of helium abundance and sampling points in discovered helium-bearing gas fields, northern Ordos Basin.

Benxi Formation (C_2b), the Taiyuan Formation (P_1t), and the Shanxi Formation (P_1s). The main source rocks are coal, dark mudstone, and carbonaceous mudstone, whose organic matter type is mainly humic, making them high-quality source rock combinations. The natural gas of the Upper Paleozoic accumulates in the sandstone reservoirs of the Taiyuan Formation of the Upper Carboniferous, the Shanxi Formation of the Lower Carboniferous, and the Lower Shihezi Formation, and originates from the coal-measure source rocks of the Taiyuan Formation - Shanxi Formation (Han et al., 2017; Jiang et al., 2023; Yang et al., 2012; Zhao et al., 2005).

The potential helium source rocks in the Ordos Basin encompass a diverse range of lithologies, such as Archean-Paleoproterozoic granites and granitic gneisses rich in U and Th elements, as well as Mesoproterozoic Changcheng Series of black slates, Upper Carboniferous Benxi Formation and Lower Permian Taiyuan Formation and Shanxi Formation shales and coals (Figure 2).

3 Samples and methods

3.1 Sample description

The helium source rock samples selected for this study encompass basement granites and metamorphic rocks from the Hangjinqi area of the Ordos Basin, Upper Paleozoic Carboniferous-Permian coal and dark mudstone, as well as outcrop granites and metamorphic rocks from the Daqing Mountains area on the northern margin and the Lvliang Mountains area on the eastern margin of the Ordos Basin. To achieve the research objectives, the petrological characteristics, uranium-thorium element contents, and helium generation potential of these granite, metamorphic rock, and dark mudstone samples were systematically analyzed. This chapter will comprehensively classify and summarize the experimental methods employed in this study.

3.2 Petrographic thin-section analysis

The petrographic thin-section identification was performed at the State Key Laboratory of Oil and Gas Resources and Prospecting, China University of Petroleum (Beijing), using a LinKam-350 Leica polarizing microscope as the experimental instrument. First, select a representative rock sample and cut it into a thin section approximately 0.03 mm thick using a slicing machine. After coarse grinding, fine grinding, and polishing to achieve optical transparency, the thin section is mounted on a glass slide using epoxy resin. Observations are conducted under a polarizing microscope to examine mineral optical properties (e.g., color, cleavage, interference colors), combined with rotating the stage to analyze extinction characteristics. Gypsum or mica test plates are employed to determine elongation and optical sign. Finally, the rock type and mineral composition are determined by integrating mineral morphology, content, and structural features.

3.3 Scanning electron microscope observation

Scanning electron microscope (SEM) thin-section observation was performed at the State Key Laboratory of Oil and Gas Resources

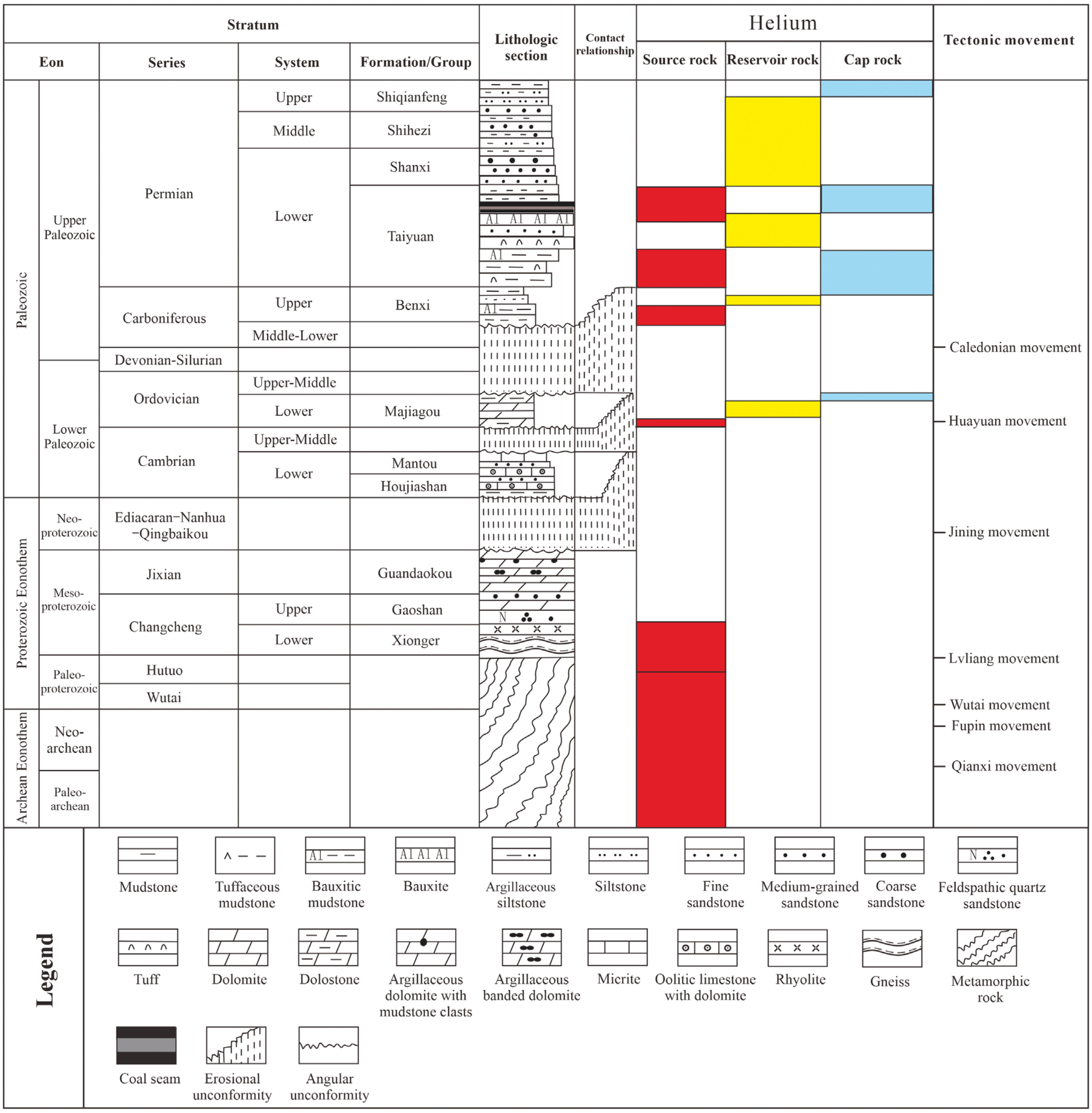

FIGURE 2
Stratigraphic column of potential helium source rocks in the Ordos Basin.

and Prospecting, China University of Petroleum (Beijing), using a Zeiss Merlin field-emission scanning electron microscope as the analytical instrument. The operating procedure for the scanning electron microscope (SEM) is as follows: Firstly, the sample is cut, polished, and conductively treated (e.g., sputter coating) to ensure a flat and conductive surface. Then, the prepared sample is mounted on the sample stage, ensuring correct positioning and alignment with the microscope. The SEM is started, and the vacuum system is checked for normal operation. Suitable parameters are set, including acceleration voltage (typically 5–30 kV), working distance (usually 5–15 mm), and beam current (generally 1–10 nA), to optimize imaging. The secondary electron detector (SE) is used for topographic information, the backscattered electron detector (BSE) for compositional contrast, and energy-dispersive X-ray spectroscopy (EDS) for elemental analysis. High-resolution images and data are recorded, after which the SEM is shut down, and the sample is stored properly. Throughout the process, sample cleanliness and parameter adjustments are ensured for high-quality images and data.

3.4 Uranium and thorium element determination

Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) was conducted at Beijing Craton Analytical Testing Company, a method used for elemental analysis of solid samples that avoids the cumbersome wet chemical digestion process and features low background, low oxide, and hydroxide interference. A total of 25 dark mudstone samples from the Dongsheng and Shenmu gas fields were analyzed for trace elements. In geological sample analysis, the LA-ICP-MS technique, by integrating a laser ablation system with ICP-MS, can directly analyze the elemental content in solid samples, including trace elements. The core component of ICP-MS is the inductively coupled plasma, which ionizes the working gas (such as argon) into a high-temperature, highly ionized plasma under the influence of a high-frequency electromagnetic field. This plasma is a high-temperature ionized gas environment that can ionize the elements in the sample. The sample (such as rock powder) is introduced into the ICP through an appropriate sample introduction system (such as a pneumatic nebulizer). In the high-temperature, highly ionized environment of the ICP, the sample is rapidly evaporated, dissociated, and atomized, and then ionized into ions. The ions are sent to the mass spectrometer for analysis. In the mass spectrometer, ions are separated based on their mass-to-charge ratio (m/z) under the influence of electric and magnetic fields. Since ions of different elements have different m/z values, specific ion peaks can be formed on the mass spectrometer, thereby enabling the identification and quantitative analysis of elements. After mass spectrometric analysis, the instrument outputs the detection results of the elements, including information on the types and amounts of elements. These results can be processed and interpreted through software to obtain the final sample analysis report.

3.5 Principles of helium formation

Based on the principle of radioactive decay, the generation process of helium is an inorganic process, which is not affected by external conditions such as temperature and pressure, but is only related to the half-life of the elements. Over the long geological history, the U and Th elements contained in the helium source rock minerals decay at a constant rate, releasing a continuous stream of helium. Therefore, we can derive a calculation formula for the generation of helium according to the principles of radioactive decay of U and Th elements. This formula can be used to assess the intensity of helium generation in potential helium source rocks (Meng et al., 2021).

$$R_{He} = 1.207 \times 10^{-13}[U] + 2.868 \times 10^{-14}[Th] \tag{1}$$

In the formula, the unit of R_{He} is cm^3/(year Gram of rock), which represents the helium generation intensity of the rock [U] and [Th] are in ppm, representing the content of trace elements U and Th in the rock, respectively. According to this formula, we can understand that the amount of helium generated within a unit volume of rock is jointly affected by time and the abundance of radioactive elements U and Th. Therefore, the accumulation of helium is mainly controlled by the U-Th abundance in the source rock, the decay time, and the scale of the helium source rock.

The amount of helium generated by the genetic method is calculated according to the following formula (He et al., 2023a; He et al., 2023b):

$$N_{He} = A \times H \times \rho \times (1 - \emptyset) \times R_{He} \tag{2}$$

In the formula:

N_{He}—the amount of helium generated by the rock, in billion cubic meters;

A—the exposed area of the rock, in square meters (m^2);

H—the average thickness of the rock, in meters (m);

ρ—the average density of the rock, in kilograms per cubic meter (kg/m^3);

$\emptyset$ — the average porosity of the rock, in percent (%);

R_{He}—the helium generation intensity of the rock, in cubic centimeters per year per Gram of rock (cm^3/(year Gram of rock)).

4 Results and discussion

4.1 Helium source rock characteristics

Helium source rocks are diverse, and it is generally believed that granites, granodiorites, coal, mudstone, and shale are all good sources of helium. Potential helium source rocks in the northern part of the Ordos Basin mainly include Archean to Paleoproterozoic metamorphic rocks such as granite and granodiorite that are rich in U-Th elements, Mesoproterozoic to Neoproterozoic metasedimentary rocks such as quartzite, quartz sandstone, crystalline limestone, marble, and schist, as well as Paleozoic mudstones and coal from the upper Paleozoic era (Figure 3).

The role of magnetic characteristics in helium exploration is primarily manifested in the processing and interpretation of gravity and magnetic data, which allows for the inference of the locations of major faults and potential helium source rocks. In the northern part of the Ordos Basin, the sedimentary rocks are virtually non-magnetic, and magnetic anomalies mainly originate from the igneous and metamorphic rock series of the crystalline basement. Within the crystalline basement, metamorphic rocks such as migmatites, marbles, phyllites, and quartzites are non-magnetic or weakly magnetic, while the deeply metamorphosed gneisses, granulites, basic volcanic rocks, and contemporaneous granites of the Archean to Lower Proterozoic are strongly magnetic. The magnetic anomaly map of the Ordos Basin reflects the zonal characteristics of the basin's basement structure, where the northernmost part is dominated by the Wulashan Group, generally trending east-west; the central and eastern parts are composed of the Jinning Group, Lvliang Group, and Jiehekou Group (Fan et al., 2023; Li and Gao, 2010; Tian et al., 2024) (Figure 4).

4.2 Uranium and thorium elemental content

The crystalline basement of the Hangjinqi area, where the Dongsheng Gas Field is located, is primarily composed of rocks

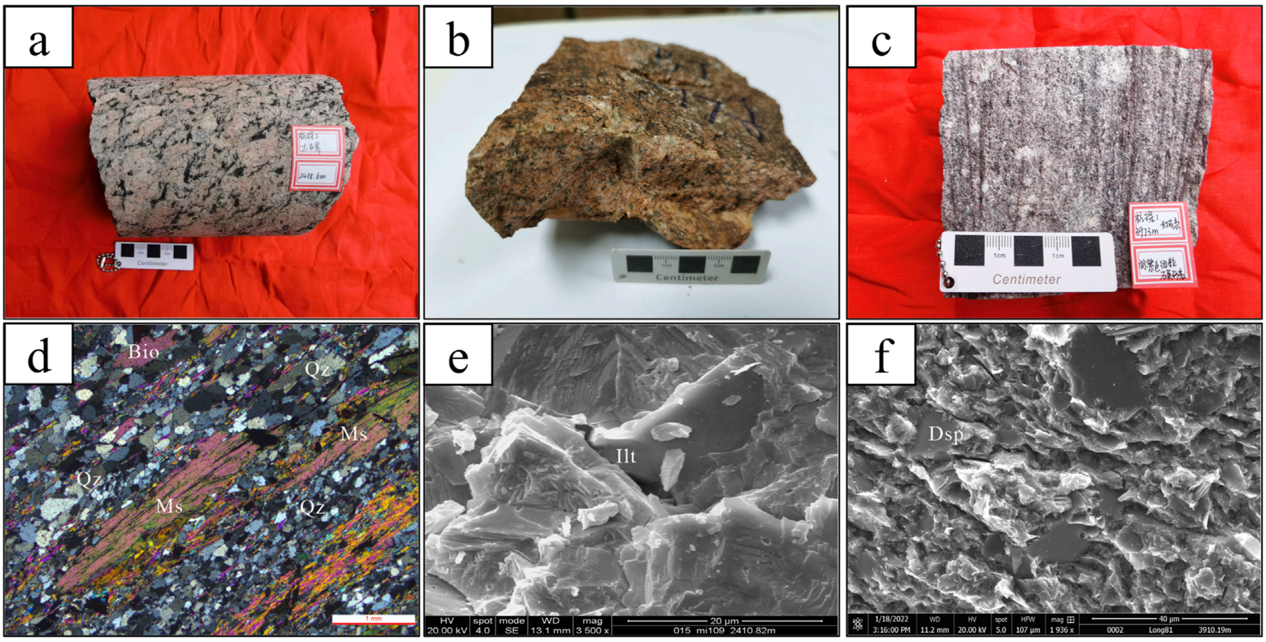

FIGURE 3
Field outcrop samples, core samples, thin sections, and scanning electron microscope images of potential helium source rocks in the Ordos Basin **(a)**. Drill core sample photograph of gray granodiorite gneiss, Sheng-2 Well, Archean, depth 2,354 m **(b)**. Field outcrop photograph of thulite granodiorite gneiss, Wula Mountains-Daqing Mountains area, Proterozoic **(c)**. Drill core sample photograph of quartz sandstone, Hangtan-1 Well, Changcheng Series, depth 3,973.0 m **(d)**. Photomicrograph under polarized light of two-mica quartz schist (+, indicating preferred orientation), Wula Mountains-Daqing Mountains area, Proterozoic **(e)**. SEM image showing illite (Ilt) in sandstone, Mi-109 Well, Taiyuan Formation, depth 2,348.60 m **(f)**. SEM image illustrating pisolitic distribution of diaspore (Dsp) in bauxite, Long-81 Well, Taiyuan Formation, depth 3,910.19 m.

from the Archean and Paleoproterozoic eons. Gneisses and granitic gneisses are the dominant components of the Archean and Paleoproterozoic rocks, while the Mesoproterozoic sections are mainly characterized by quartzites and quartz sandstones. Data presented in Table 1 reveal that the concentration of U in the gneissic and granitic gneissic basement of the Hangjinqi area varies from 0.88 to 2.89 μg/g, with a mean concentration of 1.49 μg/g. Conversely, the concentration of Th markedly exceeds that of uranium, with values ranging from 3.47 to 8.94 μg/g and an average of 5.44 μg/g. In comparison, the U content in the quartz sandstone and quartzite basement ranges from 0.81 to 7.31 μg/g, averaging 3.07 μg/g. In contrast the Th content, which is again higher than uranium, spans from 3.42 to 28.93 μg/g with a mean of 13.77 μg/g (Figure 5). It is noteworthy that the concentrations of U and Th in quartz sandstones and quartzites are considerably higher than those in gneisses and granitic gneisses, with Th concentrations being particularly elevated relative to uranium. Within the Paleozoic coal-measure source rocks, U concentrations vary from 1.27 to 9.27 μg/g, averaging 5.61 μg/g, and Th concentrations range from 3.62 to 18.94 μg/g, with an average of 13.09 μg/g. Collectively, the concentrations of U and Th in mudstone surpass those in the basement rocks. Additionally, it is observed that in the northern Ordos Basin, the concentrations of U and Th in the basement-type helium source rocks of the Hangjinqi area and the Lvliang Mountains area are significantly higher than those in the Daqing Mountains area (Figure 6).

4.3 Intensity of helium generation in various types of helium source rocks

4.3.1 Basement-type potential helium source rocks

The basement has undergone Archean to Paleoproterozoic tectonic movements, forming a set of stable crystalline basements with strong overall magnetism, mainly composed of high-grade metamorphic gneisses and granulites of the Archean age, and another set with weaker overall magnetism, primarily comprised of marbles, migmatites, and granitic gneisses of the Paleoproterozoic age. On the Archean landmass, a volcano-sedimentary sequence of the Paleoproterozoic is superimposed, which from north to south are the Wulashan Group, Shangjining Group, Helanshan Group, Hengshan-Lvliang Group, Jiehekou Group, and Suishui-Zhongtiao Group, and in the northern Ordos Basin, mainly the Wulashan Group, Jining Group, and Hengshan-Lvliang Group. The Wula Mountains-Daqing Mountains area, located on the northern edge of the Ordos Basin, is composed of dioritic and alkaline rocks, whereas the Lang Mountains area is predominantly composed of dioritic rocks. By interpreting gravity and magnetic data, it can be inferred that the Archean and Paleoproterozoic strata are roughly distributed in an alternating pattern, approximately in a northeast-southwest direction (Figure 4).

By conducting SHRIMP zircon U-Pb dating analysis on drill core samples from the western basement garnet-biotite-plagioclase

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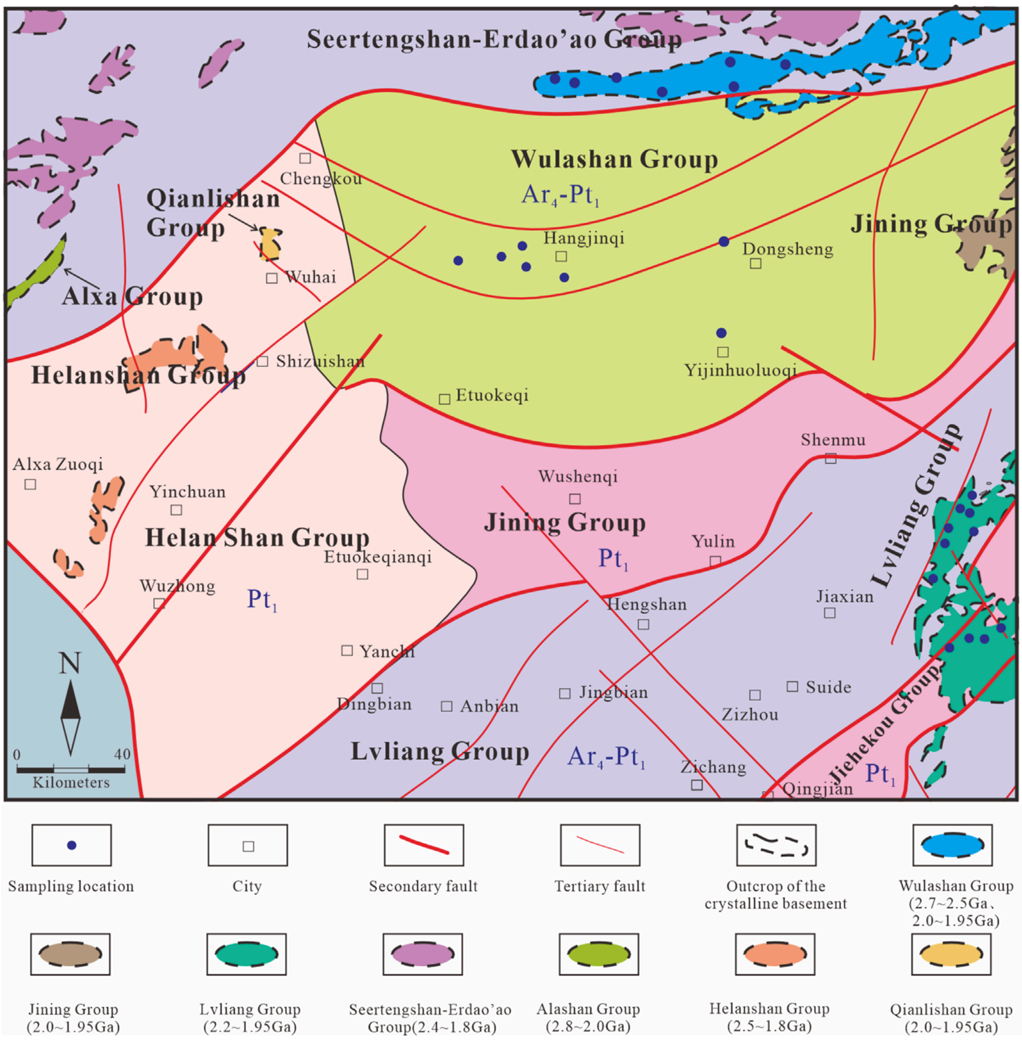

FIGURE 4
Basement structure and age attribute zonation map of the northern Ordos Basin (modified after (Hu et al., 2013; Tian et al., 2024; Zou et al., 2023)).

gneiss and the eastern gneissic two-mica granite, we obtained age data of 2031 ± 10 Ma and 2035 ± 10 Ma, respectively (Gou et al., 2016; Hu et al., 2012). Using the principles of radioactivity and the decay equations of U and Th (see Equation 1) we can calculate the helium generation intensity of the helium source rock. The average abundance of U and Th in the basin's basement rocks is 2.59 μg/g and 15.20 μg/g, respectively, with a helium generation intensity of 0.750×10^{-6} $cm^3/(Ma{\cdot}g)$ (Table 1). The basement thickness in the northern Ordos region is much greater than the overlying sedimentary layers, indicating a high potential for helium generation.

4.3.2 Sedimentary potential helium source rocks

After the formation of the basement, the basin experienced multiple tectonic movements, including the Jinning, Caledonian, Hercynian, Indosinian, Yanshan, and Himalayan periods, resulting in a sedimentary cover layer dominated by carbonate rocks and terrestrial clastic rocks, with a thickness of approximately 3,000 to 8,000 m (Bao et al., 2019; He et al., 2023; Zhang et al., 2023).

4.3.2.1 The Changcheng Series

The Middle Proterozoic Changcheng Series exhibits distinct rift basin (aulacogen) sedimentary characteristics, with the western and southern margins of the basin being the main rift zones, possibly representing the earliest sedimentary records of the Qinling Mountains, Qilian Mountains, and Helan Mountains triple rift system. The thickness is mostly over a thousand meters, and there is a clear trend of thickening towards the deep depressional area on the western margin of the basin, where the sedimentary thickness can locally reach more than 2,000 to 3,000 m. Except for the eastern part of the basin, the Changcheng Series is distributed throughout the basin, with the maximum thickness reaching 1,000 m. The lithology mainly consists of quartz sandstone (Figure 3D), feldspathic (lithic) quartz sandstone, carbonaceous slate, and crystalline limestone (marble). The black slate of the Changcheng Series is a potential helium source rock, mainly distributed in the northern and southwestern parts of the basin. The initial age of the Middle Proterozoic is taken as 1,717 Ma, with average abundances of U and Th being 2.66 μg/g and 8.36 μg/g, respectively, and the helium

TABLE 1 Statistics of potential helium source rock parameters in the Northern Ordos Basin (abundance: minimum-maximum/mean number of samples).

Helium source rock formation	Age	Lithology	Average abundance of U	Average abundance of Th	Helium intensity
	(Ma)		(μg/g)	(μg/g)	(10^{-6} cm^3/(Ma·g))
Archean Eon - Paleoproterozoic Era	2,300–2,500	Black mica schist, granitic gneiss	(0.34~8.55)/2.59 (33)	(1.45~67.05)/15.20 (33)	0.750
Middle Proterozoic	1,535–1785	Quartz rock, phyllite	(0.27~5.15)/2.66 (5)	(1.70~18.07)/8.36 (5)	0.562
Paleozoic Carboniferous-Permian	285 ± 50	Mudstone	(2.07~27.51)/6.43 (55)	(7.82~62.92)/20.32 (55)	1.361
		Coal	(1.27~9.27)/5.61 (5)	(3.62~18.94)/13.09 (5)	1.054

Note: Average abundance is the minimum-maximum/mean (number of samples).

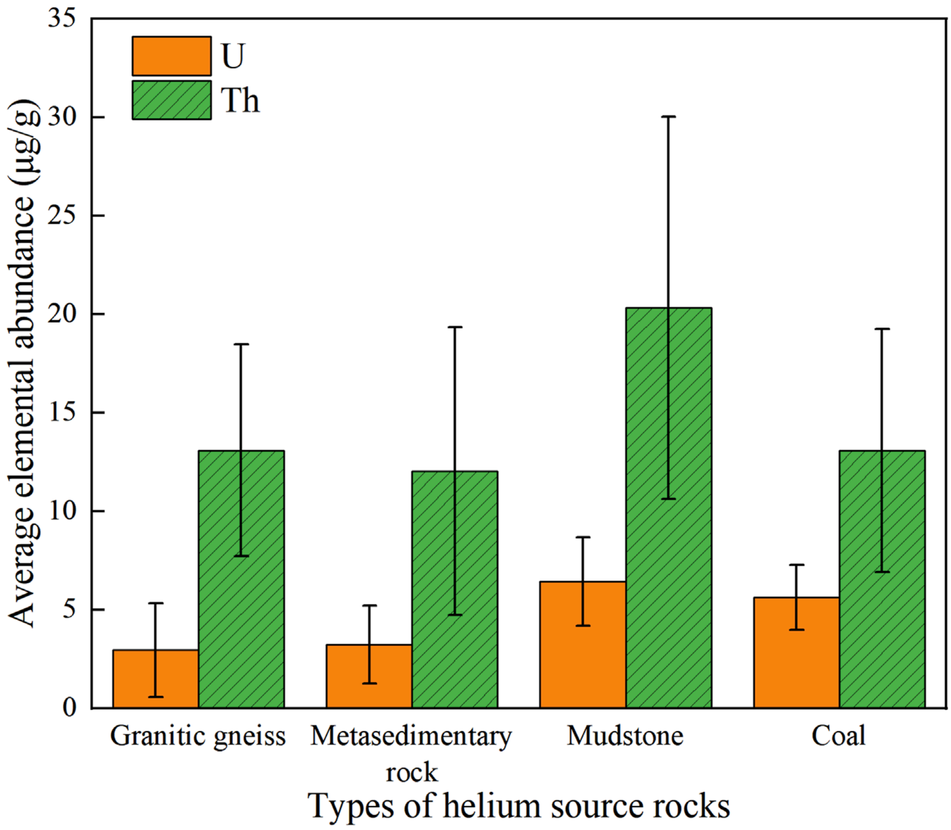

FIGURE 5
Bar chart showing the uranium and thorium content in different types of helium-source rocks in the northern Ordos Basin and its surrounding basement.

generation intensity is 0.562 × 10^{-6} cm^3/(Ma·g). Given the older age of the Middle Proterozoic Changcheng Series, potential helium source rocks and their higher abundance of U and Th elements. They have a large development scale both laterally and in-depth, indicating a high potential for helium generation.

4.3.2.2 Carboniferous-Permian

The mudstone, carbonaceous shale, and coal of the Carboniferous-Permian age serve as source rocks for hydrocarbons, while sandstone and bauxite act as reservoir rocks for natural gas (Figures 3E, F). Mudstone, shale, and coal are widely distributed throughout the basin, with an average age of 292 Ma. The average U and Th abundances in the Upper Paleozoic mudstone are 6.43 μg/g and 20.32 μg/g, respectively, with an average mudstone thickness of about 30 m and a helium generation intensity of 1.361 × 10^{-6} cm^3/(Ma·g). The average U and Th abundances in the Permian Taiyuan Formation coal are 5.61 μg/g and 13.09 μg/g, respectively, with a maximum thickness of 14 m and a helium

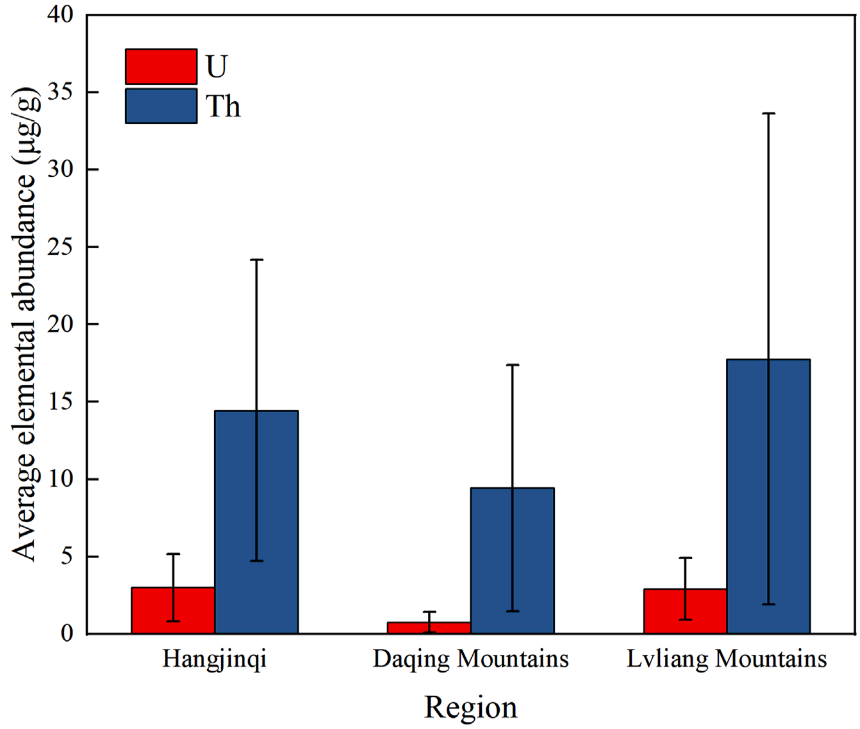

FIGURE 6
Bar chart showing the uranium and thorium content of helium-source rock in the northern Ordos Basin and its surrounding basement.

generation intensity of 1.054×10^{-6} cm^3/(Ma·g). Due to the relatively small thickness of the Carboniferous-Permian mudstone and coal compared to the basement helium source rocks, the helium generation potential of this stratigraphic series is significantly constrained.

4.4 Tectonic evolution and its impact on helium source rocks

During the tectonic evolution of the North China Craton, the northern part of the Ordos Basin has experienced pivotal geological events that have profoundly influenced the formation and development of helium source rocks. Specifically, during the period from the Archean to the Paleoproterozoic Era, the prototype of the North China Craton was formed through the amalgamation of multiple ancient continental nuclei (Hu et al., 2013; Zhai et al., 2021). The four major tectonic movements in the northern Ordos Basin—Qianxi, Fuping, Wutai, and Lvliang—have shaped the basement structural characteristics (Figure 2).

During the Fuping Movement, the formation of ancient continental nuclei marked the initial phase of regional tectonic activity, while the Wutai Movement led to the transition of these nuclei from plastic to rigid states. Approximately 1.8 billion years ago, the Lvliang Movement formed a stable crystalline basement. Throughout this process, the basement rock series in the northern Ordos Basin underwent metamorphism, magmatism, and folding, resulting in distinctive magnetic anomalies that are distributed in an east-west direction across the Wushenqi and Qingshuihe regions, manifesting as alternating positive and negative magnetic anomaly zones. The northern positive anomaly zone, represented by the Jinling Group, Wulashan Group, and Erdaoao Group, displays a rock assemblage from granulite to amphibolite facies, with local areas of greenstone facies, primarily composed of the Archean continental nuclei. The interior part of the basement is characterized by a broad, northeast-trending strip, mainly consisting of the Proterozoic Wutai Group and Hutuo Group, with rock types including metamorphic gneiss, schist, and marble. The southeastern region, represented by the Lvliang Group, Jiehekou Group, and Yejishan Group, comprises a rock assemblage of greenstone, phyllite, marble, and metamorphosed volcanic rocks, predominantly constituting the Proterozoic folded metamorphic rock series (Du et al., 2013; Liu et al., 2006; Tang et al., 2017).

The tectonic evolution of the northern Ordos Basin has significantly impacted the formation of helium source rocks. The metamorphic and granitic rock series in this region is enriched in radioactive elements such as uranium and thorium, whose decay processes are the primary sources of helium generation. Consequently, the geological background of the northern Ordos Basin provides an abundant material basis for helium generation and also controls the spatial distribution and abundance of helium source rocks. The metamorphism and magmatism of these rocks have created favorable conditions for the long-term stable supply of helium, thus forming helium source rocks of significant potential in the northern Ordos Basin.

TABLE 2 Evaluation parameter standards for helium source rocks.

Symbol	Zonation categories of helium-generative potential in source rocks	Age (Ma)	U (μg/g)	Th (μg/g)	Unit mass-specific helium production rate (10^{-6} cm^3/(Ma·g))
I	High Age-High U-Th abundance	>251	>2.7	>10.5	>0.63
II_1	Low Age-High U-Th abundance	<251	>2.7	>10.5	>0.63
II_2	High Age-Low U-Th abundance	>251	<2.7	<10.5	<0.63
III	Low Age-Low U-Th abundance	<251	<2.7	<10.5	<0.63

4.5 Helium generation potential and prospective area prediction

The enrichment of crust-derived helium in natural gas reservoirs is controlled by the coupled effect of uranium or thorium abundance in source rocks and diagenetic age. Due to the extremely long half-lives of parent isotopes (e.g., ^{232}Th at 1.4×10^{10}a) and the inherent low average abundance of U-Th in the crust (μg/g level), conventional geological bodies are all weak helium sources. Therefore, the volume-time integral effect of source rocks is the key to determining economically viable helium abundance. This study establishes a four-quadrant evaluation system: Type I (old age-high U-Th abundance), Type II_1 (young age-high U-Th abundance), Type II_2 (old age-low U-Th abundance), and Type III (young age-low U-Th abundance). Only Type I has industrial exploitation potential (Table 2).

Research indicates that the northern Ordos Basin hosts typical Type I helium source rocks, including Archaean–Proterozoic granites in the basement of the Hangjinqi area, Carboniferous–Permian coal and mudstone from the Upper Paleozoic strata, and Archaean–Proterozoic granitic gneiss in the Lvliang Orogenic Belt along the eastern margin (Figure 7). The significant helium generation potential of these rocks is attributed to their high U and Th concentrations and ancient geological ages. Notably, the Archaean–Proterozoic granites (Hangjinqi basement) and granitic gneiss (Lvliang Orogenic Belt) exhibit exceptional U-Th enrichment (exceeding upper crustal averages), large-scale rock thickness (far surpassing other helium source layers), and ages exceeding 1.8 Ga, which are markedly superior to Carboniferous–Permian mudstone and coal (ages <350 Ma). Consequently, the Archaean–Proterozoic granites and granitic gneiss, characterized by higher U-Th abundance, broader spatial distribution, and prolonged geological evolution, demonstrate significantly enhanced helium generation capacity, thereby providing substantial helium resources for natural gas fields in the northern Ordos Basin.

Based on the analysis above, it has been identified that the potential helium source rocks in the northern Ordos Basin are primarily metamorphic. These include Archean-Proterozoic granitic gneisses rich in U and Th elements, as well as metasedimentary rocks like quartzites, crystalline limestones, marbles, and schists, and Upper Paleozoic mudstones and coal. A comprehensive analysis indicates that the helium generation intensity decreases in the following order: Upper Paleozoic mudstones, Upper Paleozoic coal, metamorphic rocks, and metasedimentary rocks. However, considering the age of the rocks and other parameters for evaluating the potential of helium source rocks, such as the volume scale of the helium source rocks, a more in-depth discussion is still needed to determine their contribution to helium generation. For instance, the Archean-Proterozoic granitic-metasedimentary rock series is considerably thick, while the sedimentary series, such as the Carboniferous-Permian coal-measures, have a thickness of 30–50 m. Although the Carboniferous-Permian coal-measures have a higher helium generation intensity, the total amount of helium generated per unit time is significantly less than that of the Archean-Proterozoic granitic-metasedimentary rock series. Taking the Dongsheng Gas Field in the Hangjinqi area of the northern Ordos Basin as an example, calculations based on Equation 2 reveal that the cumulative helium generation from Archean-Paleoproterozoic crystalline basement-type source rocks reaches 1588.98×10^8 m^3, whereas that from Carboniferous-Permian sedimentary-type source rocks is merely 2.56×10^8 m^3, substantially lower than the former.

Compared to other areas in the northern Ordos Basin, the Hangjinqi region is notably developed with Neoarchean to Proterozoic basement-type helium source rocks and Upper Paleozoic sedimentary-type helium source rocks, exhibiting characteristics of "multi-source helium supply". The burial depth of the basement rocks in the Hangjinqi area generally ranges from 974 to 4,202 m, which is relatively shallow compared to other regions. The U content in the Proterozoic Dahuaibei Rock Body and Wuhai Zhuozishan Granite of the northern Ordos Basin varies from 5.16 μg/g to 25.7 μg/g. Meanwhile, the Th content ranges from 24 μg/g to 47.5 μg/g. These variations indirectly confirms that the Archean to Proterozoic metamorphic rocks and granitic series in this area are rich in radioactive elements such as U and Th (He et al., 2021; Wang et al., 2015). Given the high abundance of uranium (U) and thorium (Th) elements, greater geological age, and enormous volumetric scale of potential helium source rocks such as basement granitic rock masses and metamorphic rocks, the Hangjinqi area in the northern Ordos Basin demonstrates the optimal potential for helium generation. Notably, although the superimposed helium generation intensity of various helium source rock formations in the Hangjinqi area, where the Dongsheng Gas Field is located, is lower than that of other regions in the northern Ordos Basin, this area has developed a multi-level fault system. This system comprises major basement-connected faults and an interlayer secondary fault network that links Carboniferous-Permian reservoirs (Peng et al., 2022). This structural framework provides efficient vertical migration pathways for helium generated from basement source rocks, facilitating helium accumulation in

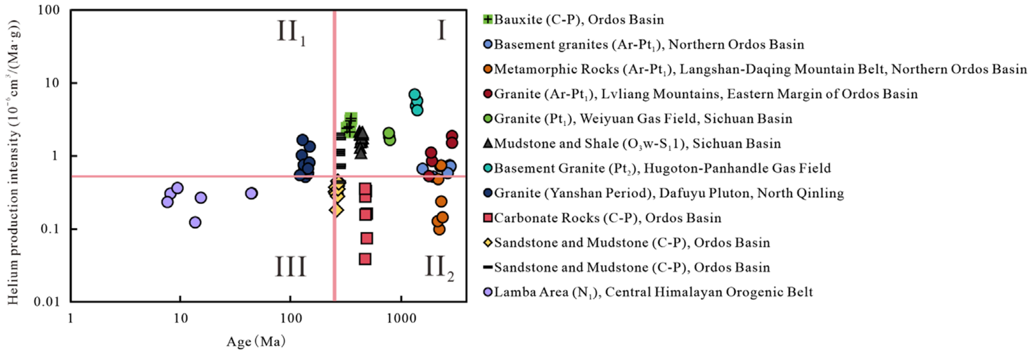

FIGURE 7
Relationship between helium generation intensity and rock age of potential helium source rocks.

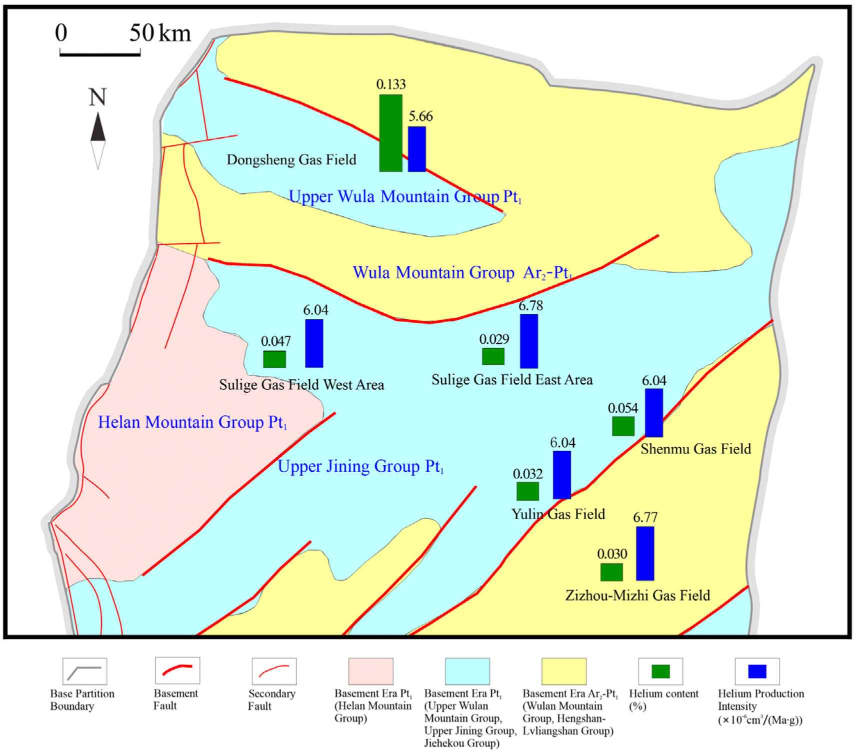

FIGURE 8
Distribution map of potential helium source rocks and helium generation intensity in the northern Ordos Basin.

reservoirs. Through a comprehensive evaluation of helium source rock potential and helium enrichment controls, this study concludes that the Hangjinqi area possesses superior helium accumulation conditions, representing the most prospective helium enrichment zone in the northern Ordos Basin (Figure 8).

5 Conclusion

(1) The potential helium source rocks in the northern Ordos Basin are of crustal type, including basement and sedimentary rock series. The main rocks are Archean-Paleoproterozoic granites and metamorphic rocks such as schists and granitic gneisses rich in U and Th elements, the Mesoproterozoic Changcheng Series of metasedimentary rocks, and Upper Paleozoic mudstones and coal.

(2) The helium generation intensity of the Archean and Paleoproterozoic basement rock series is 0.750 × 10^{-6} $cm^3/(Ma \cdot g)$, while that of the Changcheng Series slates, Carboniferous-Permian mudstone, and coal are 0.562 × 10^{-6} $cm^3/(Ma \cdot g)$, 1.361 × 10^{-6} $cm^3/(Ma \cdot g)$, and 1.054 × 10^{-6} $cm^3/(Ma \cdot g)$, respectively.

(3) Based on differences in helium source evaluation parameters such as uranium and thorium abundance and rock age, helium source evaluation standards can be preliminarily categorized into four types: old age rock with high uranium and

thorium abundance (Type I), young age rock with high uranium and thorium (Type II_1), old age rock with low uranium and thorium (Type II_2), and young age rock with very low uranium and thorium abundance (Type III). The Type I potential helium source rocks, primarily composed of basement granite and granitic gneiss in the northern part of the Ordos Basin, as well as Archean–Paleoproterozoic granite and gneiss in the Lvliang Mountains on the eastern margin, can be considered high-quality helium source rocks.

(4) Archean-Paleoproterozoic basement-type helium source rocks and Upper Paleozoic sedimentary-type helium source rocks are both developed in the Hangjinqi area of the northern Ordos Basin, featuring a "multi-source helium supply" characteristic. Combined with the well-developed fault network distribution in the region, these geological conditions suggest that this area represents a favorable zone for the distribution of helium-rich natural gas.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZD: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review and editing, Data curation, Formal Analysis. CL: Conceptualization, Formal Analysis, Writing – review and editing, Data curation, Resources. JC: Writing – review and editing, Supervision. HW: Writing – review and editing, Conceptualization, Methodology, Visualization, Investigation. MK: Writing – review and editing, Formal Analysis, Conceptualization. AT: Conceptualization, Methodology, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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