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The first extra-large helium-rich gas field identified in a tight sandstone of the Dongsheng Gas Field, Ordos Basin, China

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Abstract Helium gas is a scarce but important strategic resource, which is usually associated with natural gas. Presently, only one extra-large helium-rich gas field has been found in China: the Hetianhe Gas Field in the Tarim Basin. This paper reports a new example, the Dongsheng Gas Field (DGF) in the Ordos Basin. In this study, 92 natural gas samples from the DGF were analyzed for helium content and isotope composition using isotope mass spectrometry. The natural gas samples were found to have an average helium content of 0.133%, with 65 (70.7%) of the samples having a helium content of 0.1% or more. Based on the proven natural gas reserves of the DGF, the proven geological helium reserves were calculated to be 1.96×10^{8} m^3, suggesting that it represents the first extra-large helium-rich natural gas reservoir to be hosted in tight sandstone in China. The $^3He/^4He$ ratios of 5 natural gas samples from the DGF are within the range of 3.03×10^{-8}–3.44×10^{-8}. Therefore, the helium in the gas field is thought to be of typical crustal origin and to have formed in the granitic basement that is rich in uranium and thorium. The accumulation of helium-rich natural gas was controlled by regional tectonic activities. Activity along the fault connecting the reservoir with the basement caused release of the helium gas, which entered the overlying strata along the fault and accumulated with conventional hydrocarbon gas. Based on the structural background and the distribution of helium source rocks in the Ordos Basin, the main helium source rocks with high exploration potential are located in deep strata within the north and middle parts of the basin.

Keywords Helium gas, Granitic basement, Radiogenesis, Dongsheng Gas Field, Ordos Basin

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1. Introduction

Helium is not only the element with the lowest boiling point but also the most difficult to liquefy. It has unique properties such as low density, easy diffusion, chemical inertia, strong thermal conductivity, and extremely low viscosity. Therefore, it has irreplaceable applications in high-tech fields such as the military, aviation, medical treatments, semiconductors, and nuclear energy (Cai et al., 2010; Anderson, 2018). Although the helium content of the whole universe is second only to hydrogen, helium is scarce on the Earth. At present, industrial helium can only be extracted from natural gas. Natural gas is generally considered viable for helium production when it has a relative helium content of 0.05–0.1%, with 0.1% the minimum requirement for the industrial grade (Xu et al., 1997). According to estimations by the USGS, the

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total global helium resources have a volume of approximately 51.9×10^9 m^3 and are mainly distributed in the United States, Qatar, Russia, and Algeria. The United States has the highest helium resource, up to 20.6×10^9 m^3, accounting for 39.69% of the global total. China's helium resources are estimated to be only 1.1×10^9 m^3 (Peterson, 2021). However, with economic and social development, China's demand for helium gas increases at a rate of more than 10% per year (Zhao et al., 2012; Anderson, 2018), resulting in a severe situation for China's helium supply. At present, most helium originates from the decay of uranium and thorium in granitic rocks that are rich in radioactive elements, or from the volatilization of deep mantle-derived fluids (Xu et al., 1990; Ballentine and Sherwood Lollar, 2002; Dai et al., 2017; Li et al., 2017). The Panhandle-Hugoton Gas Field in the United States is a world-famous helium-rich gas field in the west of the Anadarko Basin, within reservoirs of Permian carbonate rock and sandstone. The large-scale granite underlying the gas field is considered to be the helium source rock (Ballentine and Sherwood Lollar, 2002). In recent years, several helium-related studies have been conducted in China (Zhang et al., 2015, 2019; Li et al., 2017, 2020; Wang et al., 2020a, 2020b). Tao et al. (2019) reported the discovery of China's first extra-large helium-rich natural gas reserves: the Hetianhe Gas Field, with proven geological helium reserves of 1.9591×10^8 m^3. The Hetianhe Gas Field is in the platform area of the Tarim Basin, and the helium has a typical crustal origin and is sourced mainly from the underlying bedrock. In recent years, breakthroughs have been achieved in natural gas exploration in Upper Paleozoic strata in the Hangjinqi area of the northern Ordos Basin, and the Dongsheng Gas Field (DGF) was discovered (Wu et al., 2017; Ni et al., 2018). Gas with a relatively high helium content (≥0.1%) was found in tight sandstones in several wells within the DGF, revealing the possible existence of tight sandstone type helium-rich natural gas. To clarify the geochemical characteristics of helium in the DGF, this study revealed its source and accumulation characteristics by analyzing the helium content and isotopic composition of tight sandstone gas in the DGF. This work not only provides a scientific basis for revealing the enrichment law of helium in the DGF, but also provides a reference for the subsequent general survey and exploration of helium resources in China.

2. Geological background

The Ordos Basin is a large petroliferous basin developed on the cratonic basement, which has great potential for natural gas resources. At present, a series of large gas fields have been discovered in the Ordos Basin, including the Sulige, Wushenqi, Daniudi, Mizhi, Zizhou, Shenmu, and Dongsheng Gas Fields in the Upper Paleozoic tight sandstone reservoir and the Jingbian Gas Field in the Lower Paleozoic marine carbonate reservoir (Liu et al., 2009; Dai, 2016). The structure of the Ordos Basin is relatively stable, and the fault system in the main area of the basin (i.e., the Yishan Slope) is relatively undeveloped; however, the fault system is more developed in the secondary structural units close to the basin margin, such as the Yimeng Uplift, Tianhuan Depression, and other structural units (Li et al., 2000; Wang et al., 2011; He et al., 2020).

The DGF is situated in the northern Ordos Basin, across three structural units of the Yishan Slope, Tianhuan Depression, and Yimeng Uplift, with its main body located on the Yimeng Uplift (Figure 1a). Several wells along the Sanyanjing, Wulanjilinmiao, and Borjianghaizi Faults have obtained high-yield industrial gas flow, leading to the discovery of the DGF (Figure 1b). On April 27, 2021, SINOPEC North China Branch deployed Well JPH-489, which is the key development well of the DGF along the northern margin of the Ordos Basin. This well achieved an open flow of 105×10^4 m^3 per day, which is the highest in the region. Thus, this well highlights the great potential of natural gas exploration in the northern uplift of the Ordos Basin. At present, the proven natural gas reserves of the DGF are 1474×10^8 m^3, with third-class gas reserves of 9777×10^8 m^3 reported at the end of 2019 (He et al., 2020). The studies indicate that natural gas in the DGF is mainly developed in Upper Paleozoic Carboniferous-Permian tight sandstone reservoirs (Figure 1c), which are characterized by low porosity and permeability (Wang et al., 2011; He et al., 2020). Natural gas in the DGF mainly originated in Carboniferous-Permian coal-measure source rocks (including coal and dark mudstone), displaying the characteristics of near-source accumulation (Peng et al., 2017; He et al., 2020). The side sealing and top sealing conditions of the DGF are the adjacent developed mudstone. The mudstone and sandy mudstone of the Permian Upper Shihezi and Shiqianfeng formations form regional caprocks on the tight sandstone gas in the Upper Paleozoic reservoirs of the basin (Wang et al., 2011; Peng et al., 2017; He et al., 2020).

3. Samples and experimental methods

In this study, 92 natural gas samples were collected from well block X and well block Y of the DGF, using stainless steel cylinders with double valves, for geochemical analysis. The relevant analysis was carried out in the Key Laboratory of Petroleum Resource Research, Chinese Academy of Sciences. A Noblesse SFT noble gas isotope mass spectrometer was used to determine the helium content and to analyze the isotopic compositions, while a Finnigan MAT-252 stable isotope mass spectrometer was used to analyze the carbon isotopic composition of alkane gas. Details of the specific

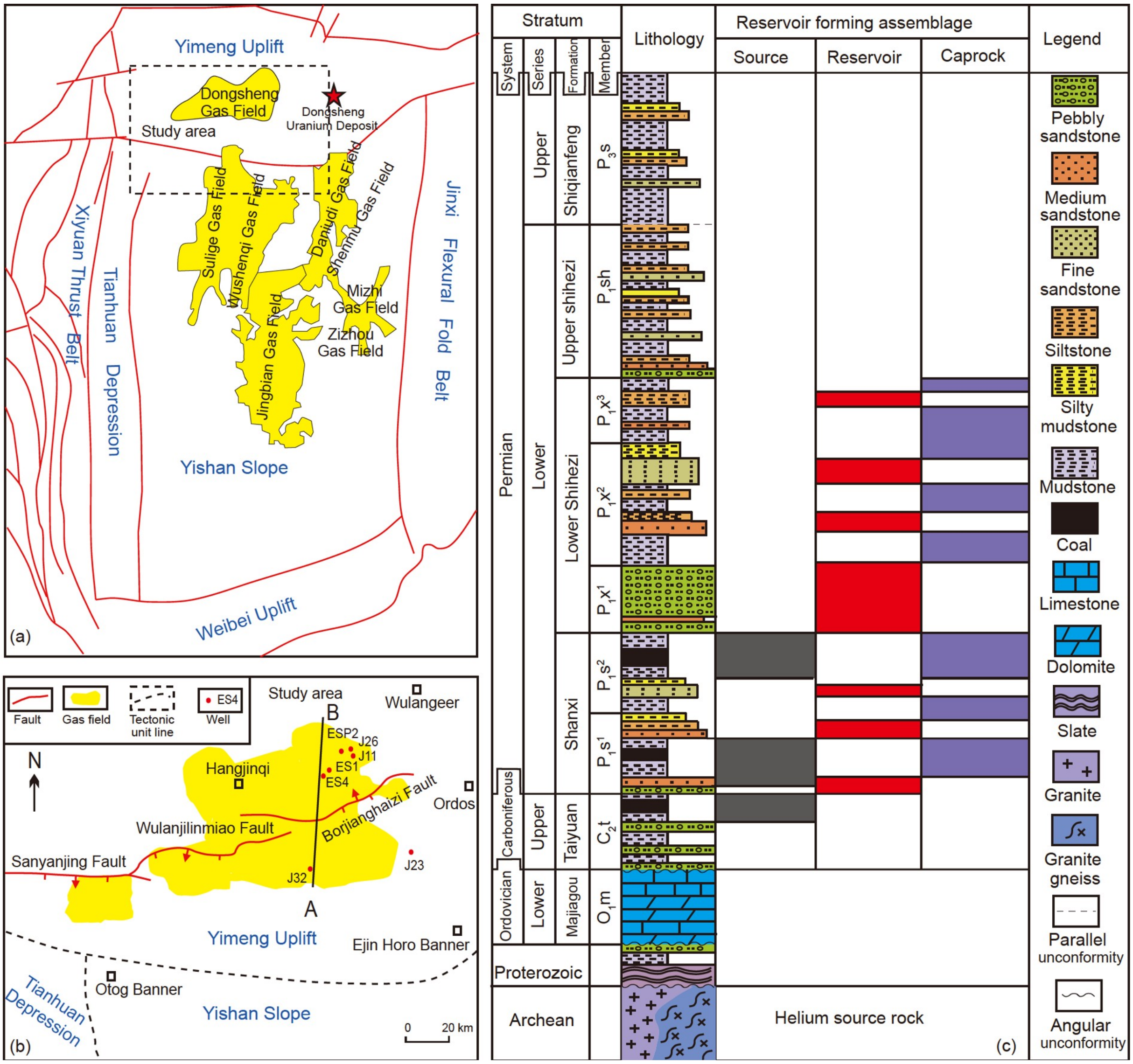

Figure 1 Location of Dongsheng Gas Field in the Ordos Basin (a), distribution of key wells (b), and comprehensive stratigraphic histogram (c).

analytical processes can be found in Cao et al. (2018) and Liu et al. (2014), respectively. In addition, data was also collected on the helium contents of 58 natural gas samples from the Sulige, Daniudi, Yulin, Mizhi, Wushenqi, Zizhou, and Jingbian Gas Fields in the Ordos Basin (Dai, 2016; Dai et al., 2017), for comparative analysis.

4. Geochemical characteristics of helium in the DGF

4.1 Helium content

Statistical analysis shows that 24 of the 37 gas samples from well block X of the DGF have relative helium contents exceeding 0.1% (Figure 2), accounting for 64.9%; in 39 of the 55 gas samples from well block Y, the helium content ranges from 0.1% to 0.3% (Figure 2), accounting for 70.9%, with the helium content of two samples exceeding 0.3%. 65 samples from the two well blocks of the DGF have helium contents greater than 0.1%, accounting for 70.7% of samples. The average helium content in the two well blocks is 0.133%, which reaches the industrial standard value. Dai et al. (2017) proposed the standard of helium enrichment degrees in natural gas, in which natural gas with 0.15%≤He% <0.50% is classified as helium-rich, while natural gas with a helium content of more than 0.5% is classified as extremely rich in helium. Of the samples from well block X and well block Y of the DGF, 6 and 22 samples respectively were found to have helium contents higher than 0.15%, which meets the standard of helium-rich natural gas. Analyzing the helium contents of other Paleozoic gas fields in the Ordos Basin indicates that the relative helium content is generally

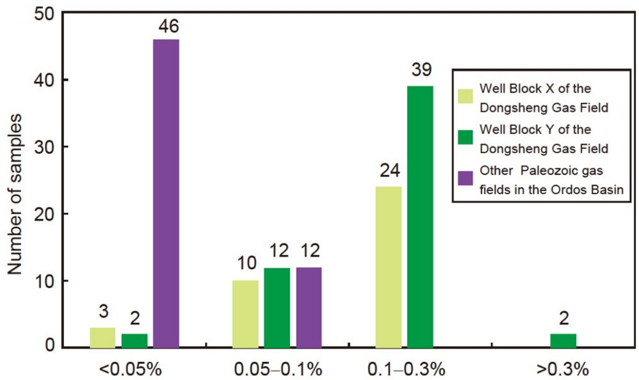

Figure 2 Helium content distribution in the DGF and other typical giant gas fields in the Ordos Basin, China.

low, and gas samples with He%<0.05% are dominant. Only 12 of the 58 samples have helium contents ranging from 0.05% to 0.1% (Figure 2). An analysis of helium content in giant gas fields of the Ordos Basin shows that the relative content of helium in the DGF in northern Ordos Basin is high, with the relative helium content reaching values suitable for industrial helium production. The relative helium content is also high in the Sulige and the Wushenqi Gas Fields, relatively close to the DGF field, indicating that the helium exploration potential is higher in the north of the Ordos Basin and exploration efforts should be focused in this area.

4.2 Helium isotopic composition and origin

Helium has two stable isotopes, i.e., ^{3}He and ^{4}He. ^{3}He is the original helium captured during the formation of the Earth, while ^{4}He is formed on the Earth from α decay of radioactive elements such as uranium and thorium (Oxburgh et al., 1986; Ballentine and Burnard, 2002). Helium is generally considered to originate from three sources, mantle-derived, crust-derived, and atmospheric-derived. Because the helium content in the air is very low (only 5.24 ppm, 1 ppm=1 μg g^{-1}), it is generally assumed that helium in a gas reservoir must be derived from the crust or the mantle (Zhang et al., 1992; Xu et al., 1997; Li et al., 2011; Tao et al., 2019). Crust-derived helium refers to the helium that comes from the α decay of uranium and thorium in minerals (Oxburgh et al., 1986; Ballentine and Burnard, 2002), whereas mantle-derived helium refers to the helium that has migrated from the mantle to a gas reservoir, through deep faults or major tectonic activities. Compared with crust-derived helium, mantle-derived helium is relatively enriched in ^{3}He (Oxburgh et al., 1986; Xu et al., 1990; Liu et al., 2016). Mantle-derived helium is generally found in tectonically active areas. For example, gas reservoirs of the rift basins distributed along the Tancheng-Lujiang Fault Zone in eastern China have a high proportion of mantle-derived helium (Xu et al., 1997; Tao et al., 2019).

There are significant differences in isotopic composition between crust-derived and mantle-derived helium, and the helium source can therefore be identified based on the difference in ^{3}He/^{4}He ratios. The ^{3}He/^{4}He value of crust-derived helium is generally in the order of 10^{-8}, and the commonly used crustal endmember value is 2×10^{-8}, whereas the ^{3}He/^{4}He value of the mantle-derived endmember is 1.1×10^{-5} (Lupton, 1983; Liu and Xu, 1993; Xu et al., 1997; Ballentine and Burnard, 2002; Kennedy and van Soest, 2007).

The ^{3}He/^{4}He values of the 58 natural gas samples from typical giant fields, such as the Sulige, Wushenqi, Zizhou, Daniudi, Mizhi, Yulin, and Jingbian Gas Fields in the Ordos Basin, are distributed in the range of 2.07×10^{-8}–13.64×10^{-8}, suggesting typical crust-derived helium. The calculation results show that the contribution of crust-derived helium exceeds 99%. The ^{3}He/^{4}He ratios of 5 gas samples from well block X of the DGF are in the range of 3.03×10^{-8}–3.44×10^{-8}, also suggesting crust-derived helium. The calculation shows that the contribution of crust-derived helium also exceeds 99%, i.e., the helium in natural gas from the DGF is of radioactive origin, derived from the radioactive decay of uranium and thorium. The relative lack of mantle-derived helium in the Ordos Basin is related to the overall stable structure of the basin and the relative absence of deep faults.

5. The source, enrichment model, and exploration potential of helium in the Dongsheng Gas Field

5.1 Helium source

The carbon isotopic composition of ethane in natural gas is mainly inherited from the parent material. Therefore, the $\delta^{13}C_2$ value is often used to identify the genetic type of natural gas, i.e., coal-derived gas has a $\delta^{13}C_2$ value higher than −28‰, whereas oil-associated gas has the opposite characteristic (Dai et al., 2005, 2009; Dai, 2016; Liu et al., 2019). The $\delta^{13}C_2$ value of natural gas in the DGF is higher than −28‰, suggesting typical coal-derived gas. However, the helium content in the DGF is relatively high, whereas the helium content in other coal-derived gas fields is relatively low. Moreover, the helium content of the Lower Paleozoic oil-associated gas in the Jingbian Gas Field coincides with that of the Upper Paleozoic coal-derived gas (Figure 3a). With the increase in helium content, $\delta^{13}C_2$ value does not show any regular variation, which suggests that there is no internal relationship between the origin of alkane gas and its helium content. The helium isotopic compositions of coal-derived gas and oil-associated gas have an obvious coincidence interval, which also indicates that there is no obvious relationship between helium isotopic composition and the origin of alkane gas (Figure 3b).

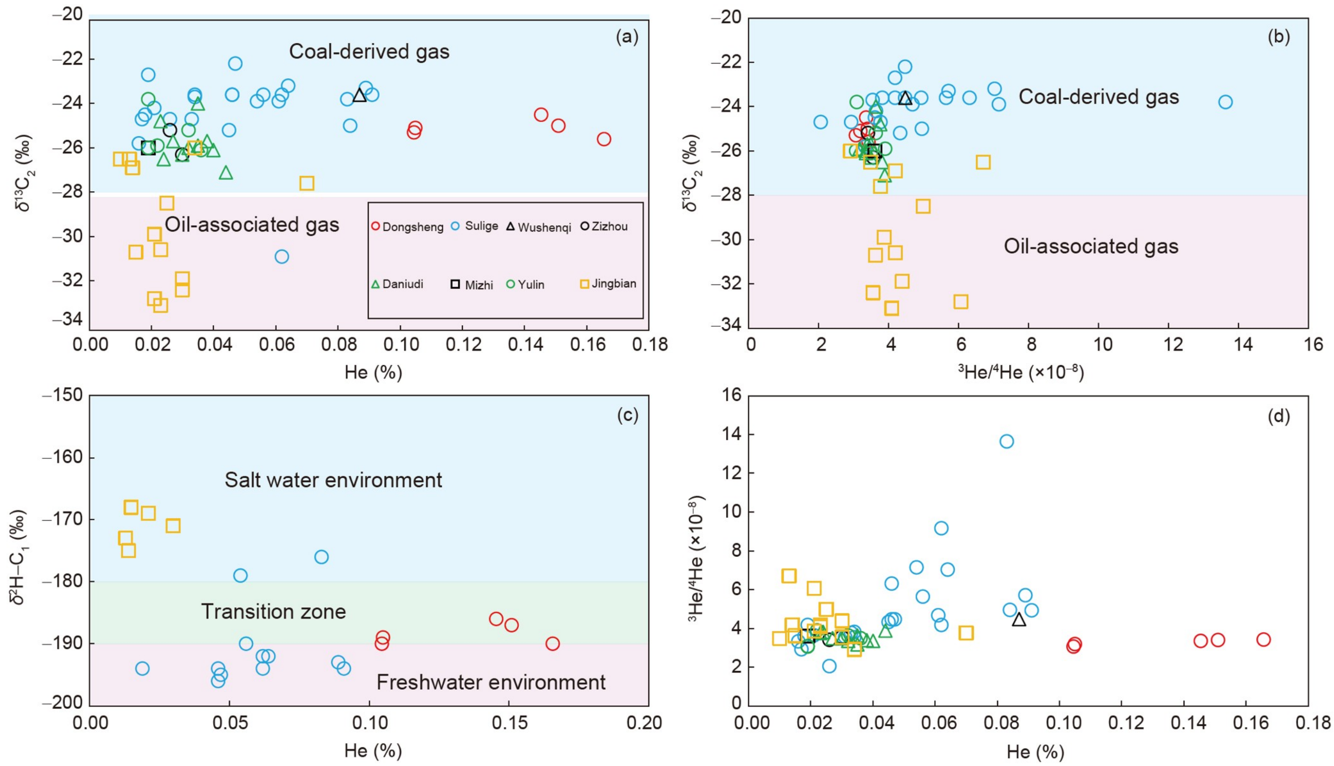

Figure 3 Plots of $\delta^{13}C_2$ vs. helium content (a), $\delta^{13}C_2$ vs. $^3He/^4He$ (b), helium content vs. δ^2H-C_1 (c), and helium content vs. $^3He/^4He$ (d) in natural gas from the Ordos Basin, China.

The hydrogen isotopic composition of alkane gas is mainly affected by the sedimentary environment and thermal maturity of the source rock. It is generally believed that when the hydrogen isotope value of methane (δ^2H-C_1) is higher than −180‰, the source rock is formed in a saltwater environment (Liu et al., 2008). When the hydrogen isotopic value of methane is lower than −190‰, the source rock is formed in a freshwater environment (Schoell, 1980). When the hydrogen isotope value of methane is between −190‰ and −180‰, the source rock is formed in a transitional sedimentary environment (Liu et al., 2008). There is no obvious correlation between δ^2H-C_1 and the helium content of natural gas from the DGF or other fields in the Ordos Basin (Figure 3c). On the one hand, this suggests that the helium content is unaffected by the salinity of the sedimentary water body; on the other hand, it shows that there is no obvious genetic correlation between helium and alkane gas. In natural gas from the Ordos Basin, there is no obvious relationship between $^3He/^4He$ ratio and helium content (Figure 3d). Although helium in natural gas is typically crust-derived, the helium content varies remarkably. The helium in natural gas is uncorrelated with either the organic type or sedimentary environment of source rocks in the Ordos Basin. Since the crust-derived helium mainly comes from the radioactive decay of uranium and thorium in minerals (Anderson, 2018), researchers have speculated that the high helium content of the DGF may be related to the relatively high uranium and thorium content of the basement rock, as well as the long-term radioactive decay. Helium in natural gas from the Hetianhe Gas Field in the Tarim Basin is also typically crust-derived (Tao et al., 2019). Therefore, the difference in helium content of natural gas from different gas fields is not only controlled by variations in the content and decay time of radioactive uranium and thorium in the helium source rock, but is also related to the accumulation process.

5.2 Helium enrichment model

The Yimeng Uplift in the northern Ordos Basin contains a large-scale uranium deposit (Figure 1a). Li et al. (2009), Li and Chen (2016), and Feng et al. (2017) believe that the Dongsheng Uranium Deposit is a syn-sedimentary uranium deposit, originating mainly from bedrock erosion in the source area in the northern Ordos Basin. The sedimentary uranium deposit in the Jurassic sandstone (Ren et al., 2006) overlies the DGF strata. Therefore, helium generated by radioactive decay of uranium and thorium is unlikely to pour downwards into the Lower Permian gas reservoir, and the helium in the DGF cannot have originated from the radioactive decay of the Jurassic sandstone uranium deposit. However, the development of sedimentary uranium deposits shows that the rocks in the denudation area on the northern margin of the basin are relatively rich in uranium. Many deep wells (e.g., J23, J32) in the DGF were drilled into the basement (Figure 1b) and revealed that the bedrock in this area is composed of granite or metamorphosed granite. These rocks are relatively rich in uranium and thorium elements (Li et al., 2011, 2017). Feng et al. (2017) dissected the uranium anomaly of the Dahuabei rock mass in the north of the Ordos Basin using gamma ray spectrometry and found that its average uranium content exceeded 5×10^{-6}. They also found that the uranium content of the clay deposit on the southern margin of the Dahuabei rock mass was as high as 170×10^{-6}, approximately 61 times the uranium abundance in the crust. Based on previous studies on the characteristics of the Dongsheng Uranium Deposit, granite enriched in uranium and thorium in the north basement of the Ordos Basin, and those of tight sandstone gas in the DGF (Ren et al., 2006; Li et al., 2009; Yang et al., 2010; Wang et al., 2011; Li and Chen, 2016; Peng et al., 2017; Feng et al., 2017; He et al., 2020), it is believed that the helium in natural gas from the DGF is mainly derived from the radioactive decay of uranium and thorium in the basement rocks.

Three EW-trending first-order faults connecting the basement and the surface, i.e., the Sanyanjing, Wulanjilinmiao, and Borjianghaizi Faults, are well developed in the area where the DGF is located (Figure 1b). These first-order faults were formed in the Caledonian period and were highly active in the Yanshanian and Himalayan periods. Many small-scale faults only extend from the basement to the Upper Paleozoic strata (He et al., 2020). The Sanyanjing Fault and Wulanjilinmiao Fault are south-dipping normal faults, while the Boerjianghaizi Fault is a north-dipping reverse fault (Figure 1b). Geochemical analysis of the Upper Paleozoic source rocks and natural gas from both sides of the Borjianghaizi Fault suggests that the source rocks to the north of the fault are relatively undeveloped. Hydrocarbon gas was mainly generated by source rocks to the south of the fault, migrated along the fault to the north, and accumulated in the reservoirs (Wu et al., 2017). It has also experienced obvious loss during migration (Ni et al., 2018). These three basement faults connect reservoirs to the helium source rock (granitic bedrock). In addition, the molecular diameter of helium is lower than that of methane, which makes it easier for helium to migrate and be lost from the system, compared with hydrocarbon gas. Therefore, these faults can provide a channel for helium release in geological history, leading inevitably to a certain degree of loss. The loss of hydrocarbon gas will cause obvious changes in the relative content and isotopic composition of both CH_4 and C_2H_6, i.e., compositional variation and isotopic fractionation. Therefore, the loss process of alkanes can be identified from relevant geochemical indicators (Ni et al., 2018). However, helium has only two stable isotopes of ^3He and ^4He, with ^4He in the majority, so there are no effective indicators relevant to helium content and isotopic composition that can be used to directly determine the helium loss process.

Previous studies have shown that the main accumulation period of the Upper Paleozoic tight sandstone gas in the Ordos Basin was from the Late Jurassic to Early Cretaceous (He et al., 2020). During this period, the Yanshan movement occurred, accompanied by hydrocarbon gas migration and accumulation and the continuous release of helium from the helium-source-rock (mainly granitic bedrock rich in uranium and thorium elements). Helium migrated upward through basement faults and mixed with hydrocarbon gases, and finally accumulated in tight sandstone reservoirs to form helium-rich gas pools. Because helium cannot form reservoirs independently (Li et al., 2011, 2017; Zhang et al., 2018), the migration and accumulation of helium may be synergistic with that of hydrocarbon gases. The main hydrocarbon gas accumulation period in the DGF was the Yanshanian period. Therefore, it is likely that the DGF also became enriched in helium during the Yanshanian period. As a regional caprock, the thick mudstone of the Upper Shihezi Formation plays a key role in preserving the helium-rich gas reservoir and limiting the loss of helium-rich gas (Figure 4).

5.3 Exploration potential

Dai et al. (2017) proposed the industrial classification standard of helium gas fields, in which a helium reserve of 1×10^8 m^3 or more is classified as an extra-large helium gas field, while a helium reserve of 0.5×10^8–1×10^8 m^3 is classified as large. Based on the average helium content of 92 gas samples from the DGF (0.133%) and the current proven geological reserves of natural gas, the proven helium reserves are approximately 1.96×10^8 m^3, reaching the standard of an extra-large helium gas field. Since 26 natural gas samples in the DGF meet the standard of helium-rich natural gas (helium content of more than 0.15%), the DGF is the first extra-large tight sandstone helium-rich gas field in China. The DGF has large helium reserves, and the average helium content meets the requirements of industrial helium production, displaying a high helium extraction value. The discovery of helium-rich reserves in tight sandstones in the northern Ordos Basin indicates that the northern Ordos Basin has favorable conditions for large-scale accumulation of helium-rich natural gas. Widely developed helium source rocks and relatively developed fault systems connecting source rocks and reservoirs are conducive to helium release and migration. Meanwhile, the favorable geological factors of natural gas accumulation in the northern Ordos Basin also provide conditions for helium enrichment. The average content of helium in the DGF is significantly higher than that in the Sulige, Wushenqi, Daniudi, and other gas fields to the south. The DGF is closer to the helium source area, as the basement in the northern Ordos Basin is shallower, with more intense tectonic activity. These factors are conducive to the migration of helium formed by the decay of radioactive

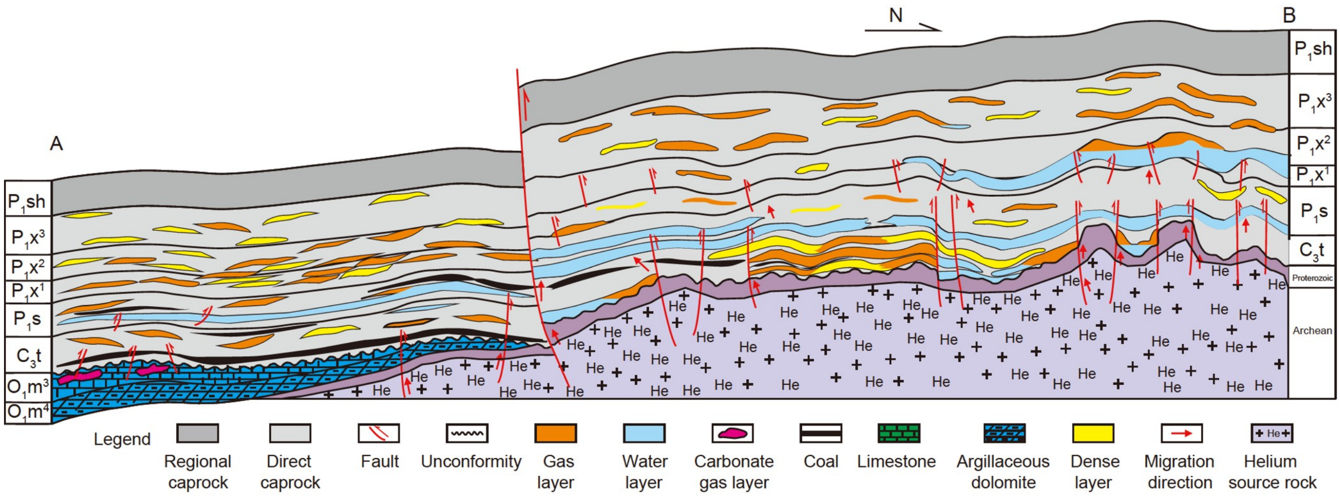

Figure 4 Accumulation model of helium-rich tight sandstone gas in the Dongsheng Gas Field, Ordos Basin, China (see Figure 1 for the position of section A-B).

elements in the basement to the gas reservoir for enrichment. Therefore, further surveys and exploration for helium in natural gas should be conducted in the north of the Ordos Basin. Moreover, attention should be paid to the real-time dynamic detection of helium content in natural gas over the whole basin, to broaden helium exploration in this region.

6. Conclusions

(1) The average content of helium in 92 gas samples from the Dongsheng Gas Field in the Ordos Basin is 0.133%, of which 65 samples exhibited a helium content higher than 0.1%, accounting for 70.7% of samples and meeting the industrial helium extraction standard. The proven geological reserves of helium in the Dongsheng Gas Field are approximately 1.96×10^8 m^3, making it the first extra-large tight sandstone helium-rich natural gas field in China. It is suggested to speed up the helium extraction from natural gas.

(2) Isotopic composition analysis shows that the helium in the Dongsheng Gas Field is typically crust-derived. The helium was mainly formed by the radioactive decay of uranium and thorium in basement rocks. The helium migrated upward along the basement faults into the overlying tight sandstone reservoirs and accumulated with hydrocarbon gas.

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