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Research Article

Comparison on Rare Gas Geochemical Characteristics and Gas Originations of Kuche and Southwestern Depressions in Tarim Basin, China

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The Kuche Depression is considered as the most important gas resource potential and gas exploring area with great gas resource potential and prospect in the Tarim Basin. Based on geochemical experimental analyses and comprehensive geological studies, the general geochemical characteristics of molecular and isotope compositions of rare gases as well as hydrocarbon gases and nonhydrocarbon gases are comparatively studied in the Kuche and Southwestern Depressions. Then, their genetic types are separately identified and gas originations are comprehensively discussed. The main results are as follows. (1) Gas fields in the Kuche Depression have a higher methane abundance, accompanied with low N_2 and CO_2 abundances, but the Akemomu gas field in the Southwestern Depression has a relatively lower average methane abundance, accompanied with high average N_2 and CO_2 abundances. The helium abundance of natural gases in gas fields from the Kuche Depression general has 1 order of magnitude higher than the air value. Comparatively, it has more than 2 orders of magnitude higher than the atmospheric value in the Akemomu gas field from the Southwestern Depression. The neon, argon, krypton, and xenon abundances in both Kuche and Southwestern Depressions are lower than the corresponding air values. (2) Natural gases from gas fields in the Kuche Depression and the Southwestern Depressions are generally typical coal-formed gases. The rare gases in the Kuche Depression have typical crustal genesis, mainly deriving from the radioactive decay of elements in the crust, while in the Akemomu gas field from the Southwestern Depression, the rare gases have main crustal genesis with a proportion of 92.5%, probably accompanied with a little mantled genetic contribution. (3) Natural gases in the Kuche Depression are generally derived from coal measure source rocks of Jurassic and Triassic, which principally originated from Jurassic in strata period and coals in source rock types. The Jurassic source rocks account for 55%-75% and the Triassic source rocks account for 25%-45% approximately, while coals occupy 68% and mudstones occupy 32% separately. Natural gases from the Akemomu gas field in the Southwestern Depression mainly originated from humic mudstones of marine and continental transitional source rocks of Carboniferous to Permian.

1. Introduction

Rare gases mainly referring to helium, neon, argon, krypton, xenon, and radon are group zero elements with characteristics of inactive chemical properties, small resistance, heat conductivity coefficient, easy luminescence, and low melting, boiling, and solubility, and so on. Although rare gases have extremely low abundance in nature, their distinctive physical and chemical properties can be used for tracing formation and evaluation processes of geological bodies ([1]; Xu et al., 1994; [2–9]; Xu, 1996; [10–17]). It is considered as one of the most important hotspots and leading frontiers in

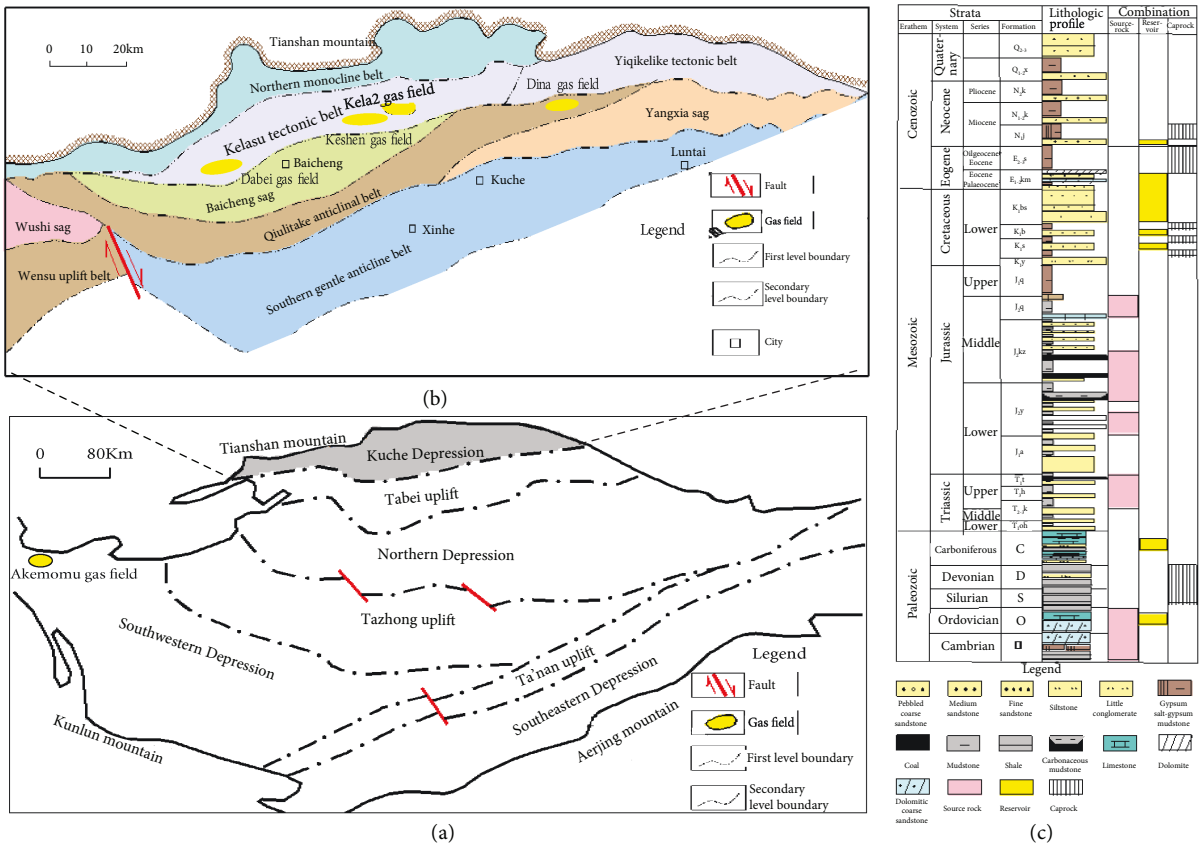


Figure 1: Gas field distribution and structural unit divisions of the Kuche and Southwestern Depressions, Tarim Basin (modified from [25]).

geosciences. The molecular and isotopic compositions of rare gases in natural gases can provide a lot of useful geochemical and geological information. They have extensive prospects on studies of gas genesis, migration, origination, deep mantled fluid action, volcanic moment, and earthquake activities ([1]; Xu et al., 1994; [5]; Liu and Xu, 1987; [18, 19]; Xu, 1996; [15–17, 20–24]). Because Rn is a radioactive element, the rare gas studies on oil and gas geology usually include helium, neon, argon, krypton, and xenon.

Sited in the north of the Tarim Basin, the Kuche Depression is one of the most important gas-bearing and exploration areas with the highest gas reserves. Many giant gas fields have been found in the Kulasu and Qiulitage tectonic belts such as the Kela2, Dina2, Dabei, Keshen2, and Keshen8 gas fields, showing huge gas resource potential and prospect for further exploration. Presently, many researchers in China have carried out a lot of studies and discussions on gas geochemical characteristics, genetic identifications, and gas originations, as well as mechanisms of gas reservoir forming and accumulation in the Kuche Depression ([25–33]; Li et al., 2018). However, geochemical characteristics of rare gases of the whole Kuche Depression have never been comprehensively and comparatively studied. By means of geochemical analyses and comprehensive geological studies, molecular and isotopic compositions of rare gases in the Kela2, Dabei, Dina2, and Keshen gas fields from the Kuche Depression as well as the Akemomu gas field from the Southwestern Depression are comparatively clarified firstly, then their genetic types are identified and finally gas originations are comprehensively discussed.

2. Geological Setting

The Tarim Basin is one of the three biggest cratonic and foreland superimposed basins and the largest petroliferous basin in China. It can be divided into Tabei, Tazhong, and Ta'nan uplifts, as well as Kuche, Northern, Southwestern, and Southeastern Depressions generally [34, 35]. The Kuche Depression is a Mesozoic and Cenozoic foreland basin, having northern monocline, southern gentle anticline, Qiulitake anticline, and Kelasu and Yiqikelike tectonic belts as well as Baicheng, Yangxia, and Wushi sags. The Kelasu tectonic belt is divided into Kela and Kelasu subsalt deep layers from north to south and 5 segments from west to east [26, 29]. The Kuche Depression has the most gas resource potential in the Tarim Basin, and many other large gas fields with gas reserve beyond 100 billion cubic meters have been found in recent two decades (Figure 1). Great breakthroughs have been achieved in the deep strata of the Kulasu and Qiulitage tectonic belts recently, showing great resource potential in the deep layer of the Kuche Depression.

The formation of the Kuche Depression from bottom to top mainly contains Triassic, Jurassic, and Shushanhe formation (K_1s), Baxigai formation (K_1b), and Bashijiqike formation (K1bs) of Lower Cretaceous, Kumugeliemu group ($E_{1\sim2}km$) and Suweiyi formation ($E_{2\text{-}3}s$) of Paleogene, and

Jidike formation (N_1j), Kangcun formation ($N_{1\text{-}2}k$), and Kuche formation (N_2k) of Neogene, Quaternary (Figure 1). The main gas-producing layers include the Kumugeliemu group ($E_{1\sim2}km$) in the Paleogene strata and the Bashijiqike formation (K_1bs) and the Baxigai formation (K_1b) in the Lower Cretaceous strata. The gypsum mudstone and gypsum salt layers of the Kumugeliemu group of the Paleogene and the Jidike formation of the Neogene in the Kuche Depression are two sets of important regional caprocks. The coal measure source rocks of Jurassic to Triassic are well developed in the Kuche Depression. The organic matter of Jurassic source rocks is mainly Type III, with the thickness of dark mudstones ranging around 100~600 m and coal seams distributing around 5~40 m [28, 30, 33]. The organic matter of Triassic source rocks is generally Type II_2 and Type II_1, with the thickness of dark mudstones ranging around 200~600 m and coal seams reaching 10 m separately [28, 30, 33].

For comparing these gas fields from the Kuche Depression, the Akemomu gas field and the Tazhong I oil and gas field in the Tarim Basin as well as the Xushen and Changshen gas fields in the Songliao Basin are adopted. The Tazhong I oil and gas field is in the Tazhong low uplift of central uplift and has nearly 300 million tons of proven oil and gas reserves equivalent in platform margin reef-bank complex carbonate of Ordovician (Wang et al., 2011; Yang et al., 2011). Natural gases in the Tazhong I oil and gas field are oil-typed gas and mainly originated from marine sapropelic source rocks of Cambrian-Ordovician. The Akemomu gas field is located in the Southwestern Depression and natural gases are typical coal-formed gas. The Songliao Basin is located in northeast China and has an area of about 26×10^4 km^2. It is a Mesozoic and Cenozoic sedimentary basin with fault and depression dual structures which was developed on late Paleozoic basement. The Xusheng gas field is located in the Xujiaweizi fault depression, and the main gas reservoir is volcanic rock of the Yingcheng formation in Cretaceous. The Changshen gas field is located in the Changling fault depression, and the main reservoir is volcanic rock of the Yingcheng formation and clastic rock of the Denglouku formation in Cretaceous. Natural gases in the Changshen and Xushen gas fields are mixed gases of organic coal-derived gas and deep inorganic gas [25].

3. Materials and Methods

A total of 21 gas samples including 19 from the Kela2, Dina2, Dabei, and Keshen gas fields in the Kuche Depression, as well as 2 from the Akemomu gas field in the Southwestern Depression, were specially selected and comprehensively studied, of which 8 were newly analyzed and 13 were collected from the author's previous researches. The relevant geochemical experimental analyses are completed in the Key Laboratory of Gas Reservoir Formation and Development of CNPC.

Conventional gas components were determined on an Agilent 6890N gas chromatograph (GC) equipped with a thermal conductivity detector (TCD), using helium as the carrier gas; a 30 m × 0.32 mm × 20 μm PLOT Q or a 30 m × 0.53 mm × 25 μm PLOT 5A MS column was used. The stable carbon isotopic compositions of natural gases were determined on a Delta plus isotopic mass spectrometer equipped with an Agilent 6890N GC. Gas components were separated by gas chromatography, converted to CO_2 in a combustion interface, and then injected into the mass spectrometer. Gas samples were analyzed and the stable carbon isotopic values are reported in conventional δ notation in per mil (‰) relative to Vienna Pee Dee Belemnite (VPDB) standards. The reproducibility and accuracy are estimated to be ±0.5‰ with respect to the VPDB standard.

Molecular composition abundances and isotopic compositions of rare gases were measured in the Key Laboratory of Gas Reservoir Formation and Development of CNPC. In order to reduce impacts of rare gases in the air on sampling and experimentation and obtain correct rare gas analyzed results, some special gas sample collecting methods were adopted [23]. The detailed analytic processes were listed as follows [15, 23]. (1) A natural gas cylinder was connected to the injection port of the device through a pressure relief valve, and a mechanical pump, a molecular pump, and an ion pump were utilized to obtain low, high, and ultrahigh vacuum for the stainless steel pipeline separately. (2) The amount of natural gases was controlled by the sample injection control valve and vacuum gauge. (3) The active gases such as hydrocarbon gases, nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and trace hydrogen gas (H_2) were purified by a zirconium base furnace, and an aspirator pump was used to enrich rare gases further. (4) The molecular composition abundances of rare gases were measured after purification. (5) Furthermore, a cryogenic pump, an activated carbon furnace, and liquid nitrogen were used to separate the components of helium (He), neon (Ne), argon (Ar), krypton (Kr), and xenon (Xe) according to different boiling points of different rare gases. (6) Finally, the separated rare gases were sent into rare gas isotope mass spectrometer to determine their isotopic compositions by method of peak height ratio on ion current signal intensity. The accuracies of molecular composition abundances of rare gases helium, neon, argon, krypton, and xenon were estimated to be ±3.36%, ±3.66%, ±1.32%, ±2.99%, and ±6.96% [23], and the accuracies of isotopic compositions of rare gases $^3He/^4He$, $^{20}Ne/^{22}Ne$, $^{40}Ar/^{36}Ar$, $^{38}Ar/^{36}Ar$, $^{129}Xe/^{130}Xe$, and $^{132}Xe/^{130}Xe$ were estimated to be ±4.50%, ±1.32%, ±1.27%, ±1.39%, ±1.63%, ±1.84%, and ±2.13%, respectively.

4. Results and Discussion

4.1. Molecular Compositions of Hydrocarbon, Nonhydrocarbon, and Rare Gases. Natural gases in the Kela2, Dabei, Dina2, and Keshen gas fields from the Kuche Depression have high and wide-ranging methane abundance, mainly ranging from 87.3% to 98.4% (average is 95.52%). The abundances of $C_{1\text{-}4}$ distribute around 97.03%~99.26% (average is 98.51%) and the drying coefficient (C_1/C_{1+}) is in the range of 0.892~0.995 (average is 0.972). The abundance of N_2 ranges from 0.36% to 1.67% (average is 0.74%), and CO_2 ranges around 0.05%~1.42% (average is 0.70%), excluding H_2S. On the contrary, natural gases in the Akemomu gas field from the Southwestern Depression have a relatively

low average methane abundance of 80.95% with high average carbon dioxide and nitrogen abundances of 10.75% and 8.11% separately and a high average drying coefficient of 0.997.

Compared to hydrocarbon and nonhydrocarbon gases, rare gas abundance in natural gases is extremely low. The general geochemical characteristics of each rare gas are as follows (Figures 2 and 3 and Table 1). (1) The helium abundance in gas fields from the Kuche Depression mainly distributes around $32\sim60\times10^{-6}$ (average is 49×10^{-6}), while it ranges around $1042\sim1062\times10^{-6}$ (average is 1054×10^{-6}) in the Akemomu gas field from the Southwestern Depression. (2) The neon abundance mainly distributes around $1.18\sim3.34\times10^{-6}$ (average is 1.76×10^{-6}) in the former and about $10.26\sim10.96\times10^{-6}$ (average is 10.608×10^{-6}) in the latter. (3) The argon abundance mainly distributes around $15\sim55\times10^{-6}$ (average is 27×10^{-6}) in the former. But it ranges around $342\sim394\times10^{-6}$ (average is 368×10^{-6}) in the latter. (4) The krypton abundance mainly distributes around $0.005\sim0.013\times10^{-6}$ (average is 0.008×10^{-6}) in the former. But it ranges around $0.042\sim0.056\times10^{-6}$ (average is 0.049×10^{-6}) in the latter. (5) The xenon abundance generally ranges $0.143\sim0.226\times10^{-8}$ (average is 0.174×10^{-8}) in the former. But it ranges around $1.081\sim1.402\times10^{-8}$ (average is 1.22×10^{-8}) in the latter.

Generally, the helium abundance in gas fields from the Kuche Depression is relatively 1 order of magnitude slightly higher than the air value, but it is more than 2 orders of magnitude in the Akemomu gas field from the Southwestern Depression. It is obviously not consistent with air from the distribution pattern of helium (Figure 3), obviously higher than the air value. The neon, argon, krypton, and xenon abundances in both areas are usually 1-3 orders lower than the corresponding air values. The distribution patterns of neon, argon, krypton, and xenon show that they are generally consistent with air (Figure 3). The relatively higher neon content indicates that neon in geological fluids of the gas field may be affected by air or air-saturated water before or during oil and gas reservoir forming.

4.2. Isotopic Compositions and Genetic Identification of Hydrocarbons and Rare Gases

4.2.1. Hydrocarbon Gases. The isotopic ratios of $\delta^{13}C_1$ and $\delta^{13}C_2$ in natural gases from the Kuche Depression generally range around -34.5‰~-26.4‰ (average value is -29.4‰) and -24.2‰~-16.1‰ (average value is 19.7‰) separately, while the average carbon isotopic values of $\delta^{13}C_1$ and $\delta^{13}C_2$ are -25.4‰ and -21.85‰ in the Akemomu gas field from the Kuche Depression correspondingly (Table 2).

According to the genetic identification index and charts provided by the former researchers [25, 36, 37], the $\delta^{13}C_2$ value of natural gases in the Kela2, Dabei, Dina2, and Keshen gas fields from the Kuche Depression mainly ranges from -24.2‰ to -16.1‰ with an average of -19.6‰, which is obviously heavier than that of typical oil-typed gas in the Tazhong oil and gas field and can be considered as typical coal-formed gas (Figure 4). The average isotopic value ethane value of (21.85‰) natural gases in the Akemomu gas field from the Southwestern Depression also shows the same characteristics of coal-formed gas as well.

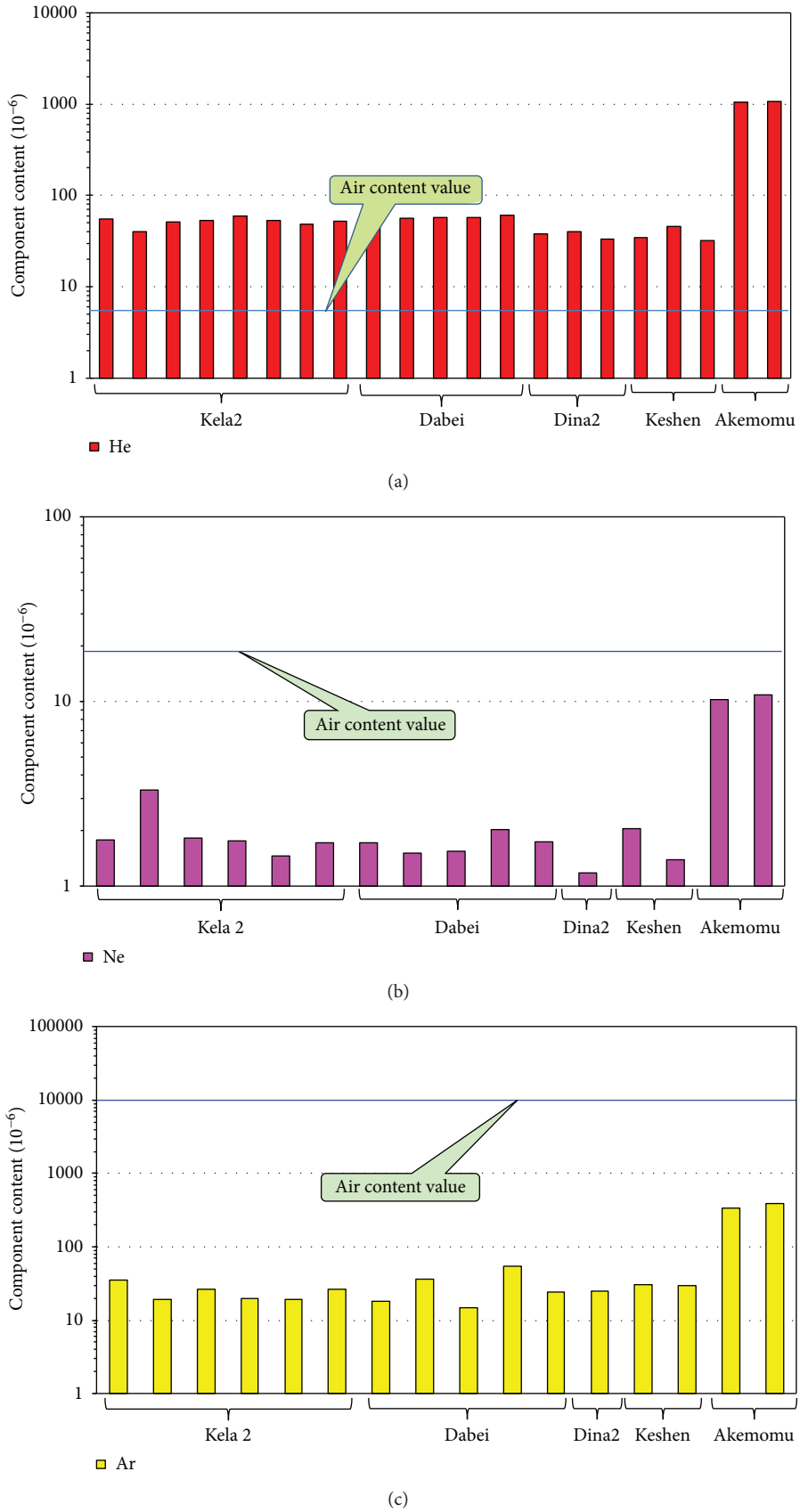
4.2.2. Helium. Helium has two stable isotopes: ^{3}He and ^{4}He. ^{3}He is a primordial nuclide, while ^{4}He is a radioactive nuclide which originated from radioactive elements [11, 38, 39]. The typical values of ^{3}He/^{4}He for air, mantle, and crust are 1.40×10^{-6}, 1.1×10^{-5}, and 2×10^{-8} separately [12, 14, 40, 41].

The ^{3}He/^{4}He value of natural gases in these gas fields from the Kuche Depression is generally distributed around $(3.33\sim11.24)\times10^{-8}$ $(0.024\sim0.080R_a)$ with an average of 6.04×10^{-8} $(0.043R_a)$, indicating a typical crustal genesis characteristics with crustal proportion more than 98.8% (Table 2 and Figure 5). It is primarily derived from the decay of crustal radioactive elements, such as uranium (U) and thorium (Th). The ^{3}He/^{4}He value of natural gases in the Akemomu gas field from the Southwestern Depression is chiefly distributed around $(83.1\sim83.6)\times10^{-8}$ $(0.0596\sim0.0597R_a)$ with an average of 83.35×10^{-8} $(0.05965R_a)$, showing main crustal genesis characteristics with crustal proportion around 92.5%, probably accompanied by a little mantled helium addition (Table 2 and Figure 5).

4.2.3. Neon. Neon has three stable isotopes, ^{20}Ne, ^{21}Ne, and ^{22}Ne, of which ^{20}Ne is a primordial nuclide, ^{21}Ne and ^{22}Ne are radioactive nuclides [42, 43]. The isotopic ratios of ^{20}Ne/^{22}Ne and ^{21}Ne/^{22}Ne in air usually keep stable, which are 9.800 and 0.0290 separately. The Mid Ocean Ridge Basalt (MORB) and Ocean Island Basalt (OIB) which originated from the mantle generally had an excessive primordial ^{20}Ne and then lead to a much higher ^{20}Ne/^{22}Ne value than that of air, while the radioactive elements in the crust such as uranium, thorium, oxygen, and fluorine (e.g., ^{18}O (n, a) ^{21}Ne and ^{19}F (n, a) ^{22}Ne) formed more enriched ^{21}Ne and ^{22}Ne and then caused a relatively lower ^{20}Ne/^{22}Ne value compared to that of the atmosphere.

The ^{20}Ne/^{22}Ne value of natural gases in gas fields from the Kuche Depression that ranged 9.50~9.74 with an average of 9.64 is generally lower than that of air, indicating that neon has crustal genesis and mainly originated from radioactive elements in the crust (Figures 6 and 7). In addition, the ^{20}Ne/^{22}Ne values of natural gases in gas fields from the Kuche Depression are positively correlated with ^{3}He/^{4}He values, indicating that ^{20}Ne possibly has the similar origination with ^{3}He and ^{22}Ne probably has the similar origination with ^{4}He (Figure 7). The ^{20}Ne/^{22}Ne value in the Akemomu gas field from the Southwestern Depression is about 9.71 and ^{20}Ne is relatively depleted, probably showing that neon has mainly crustal genesis (Figure 6). On the contrary, the ^{20}Ne/^{22}Ne value in the Changshen and Xushen gas fields is distributed around 9.88~10.07 and ^{20}Ne is relatively excessive compared with air, indicating that neon has an obvious mixture of mantle-derived genesis.

4.2.4. Argon. Argon generally has three stable isotopes, ^{36}Ar, ^{38}Ar, and ^{40}Ar, of which ^{36}Ar and ^{38}Ar are original nuclides, ^{40}Ar is a radioactive nuclide chiefly derived from the decay of ^{40}K ([5]; Liu and Xu, 1987; [7, 18]). The isotopic



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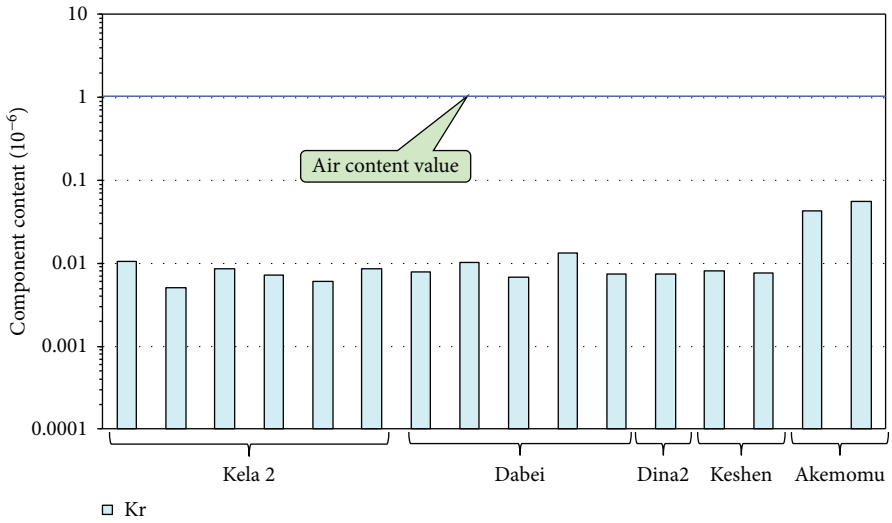

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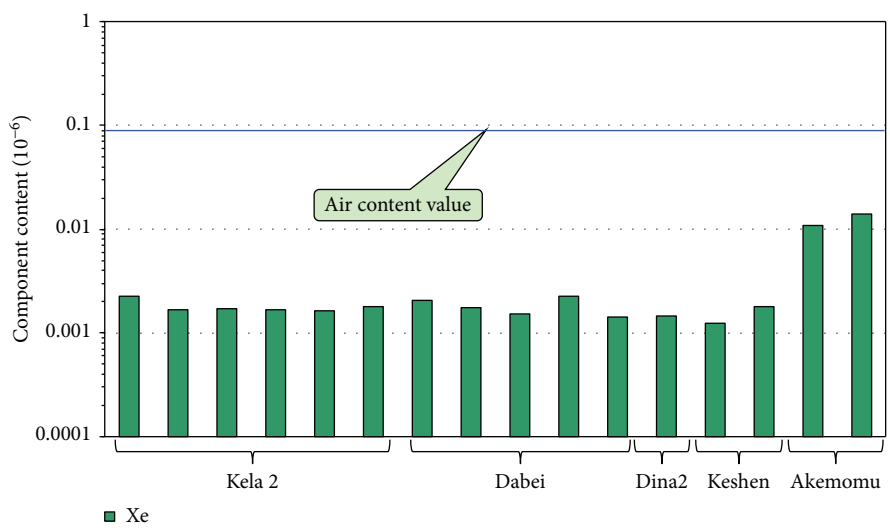

(e)

Figure 2: Histogram of helium, neon, argon, krypton, and xenon abundances in some gas fields from the Kuche and Southwestern Depressions, Tarim Basin.

compositions of argon in air are stable; the atmospheric $^{40}Ar/^{36}Ar$ and $^{38}Ar/^{36}Ar$ are 295.5 and 0.188 separately [5, 7, 20, 21]. Because of the uneven distribution of ^{40}K on the earth, the isotopic ratios of argon vary greatly in the crust and mantle.

The $^{40}Ar/^{36}Ar$ value of natural gases in gas fields from the Kuche Depression mainly distributes around 387~1323 (average of 659) and generally has a negative correlation with $^{3}He/^{4}He$ value, indicating that rare gas argon has typical crustal-derived genesis (Table 2 and Figure 8). The variation of argon isotope in the Kuche Depression is mainly caused by the uneven distribution of ^{40}K and possibly effected by different mixing ratios of air or air-saturated water during gas reservoir forming to some extent. In the Akemomu gas field from the Southern Depression, the $^{40}Ar/^{36}Ar$ value is relatively high and mainly distributed around 1653~1665 with an average of 1659, and the $^{3}He/^{4}He$ value is mainly distributed around $(8.31\sim8.36)\times10^{-7}$ with an average value of 8.34×10^{-7}, indicating that rare gases have main crustal genesis possibly with a few mantle-derived contribution (Figure 8). However, the isotopic ratio of $^{3}He/^{4}He$ of natural gases in the Changshen and Xushen gas fields is generally larger than that of atmospheric value and has an obvious positive relationship with $^{40}Ar/^{36}Ar$, indicating that rare gases are of obvious mantle genesis mixing.

4.2.5. Xenon. Xenon has nine stable isotopes, of which ^{129}Xe, ^{130}Xe, ^{131}Xe, ^{132}Xe, ^{134}Xe, and ^{136}Xe are relatively useful in gas genetic identification. ^{129}Xe in earth's materials principally originated from the radioactive decay of the extinct ^{129}I, and $^{131\sim136}Xe$ are usually derived from ^{238}U or extinct ^{244}Pu [17]. Because of short half-lives of ^{129}I (18 Ma) and ^{244}Pu (82 Ma), their decayed products ^{129}Xe and $^{131\sim136}Xe$ are totally trapped in the mantle [44]. So, the relative excess of ^{129}Xe and its positive correlation with $^{131\sim136}Xe$ in MORB show their origination of decay from ^{129}I and ^{244}Pu in the

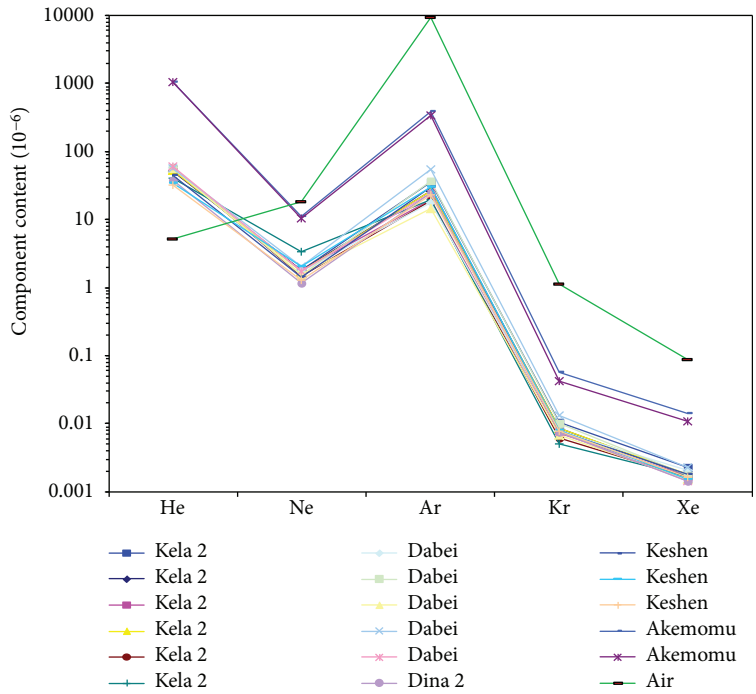

Figure 3: Broken line chart of helium, neon, argon, krypton, and xenon abundances in some gas fields from the Kuche and Southwestern Depressions, Tarim Basin.

Table 1: Molecular composition of hydrocarbon, nonhydrocarbon, and rare gases in some gas fields from the Kuche and Southwestern Depressions, Tarim Basin.

Tectonic unit	Gas field	Strata	CH_4 (%)	CO_2 (%)	N_2 (%)	$C_{1\text{-}4}$ (%)	C_1/C_{1+}	He (10^{-6})	Ne (10^{-6})	Ar (10^{-6})	Kr (10^{-6})	Xe (10^{-8})	References
Kuche Depression	Kela2	E	98.4	0.05	0.69	99.26	0.991	55	1.79	35	0.011	0.224	[15]
		K_1, E	97.5	0.60	0.37	99.03	0.985	41	3.34	19	0.005	0.167	
		K_1, E	93.7	0.53	0.36	99.11	0.995	52	1.82	26	0.009	0.172	
		K_1, E	98.1	0.70	0.56	98.74	0.994	53	1.77	20	0.007	0.166	
		K_1, E	97.4	0.69	0.38	98.93	0.985	59	1.46	19	0.006	0.162	
		K_1, E	98.3	0.69	0.58	98.73	0.994	53	1.73	27	0.009	0.180	
		K_1, E	97.7	0.43	0.36	99.2	0.985	48					This paper
		K_1, E	97.5	0.64	0.38	98.97	0.984	52					
	Dabei	K_1bs	95.8	1.42	0.44	98.15	0.976	59	1.73	18	0.008	0.204	[23]
		K_1bs	97.1	0.81	0.58	98.61	0.984	57	1.52	37	0.010	0.176	
		K_1bs	94.8	1.27	1.67	97.03	0.977	57	1.55	15	0.007	0.151	
		K_1bs	95.3	1.29	0.71	98.05	0.97	57	2.04	55	0.013	0.226	
		K_1bs	94.3	1.27	0.99	97.71	0.965	60	1.74	24	0.007	0.143	
	Dina	E	87.3	0.59	1.58	97.83	0.892	38	1.18	25	0.008	0.144	This paper
		E	88.5	0.33	1.11	97.95	0.904	40					
		E	89.1	0.36	1.08	98.34	0.906	33					
	Keshen	K_1bs	97.9	0.61	0.86	98.53	0.994	36	2.05	30	0.008	0.151	
		K_1bs	98.3	0.30	0.72	98.98	0.993	45	1.40	30	0.007	0.178	
		K_1bs	97.9	0.78	0.70	98.45	0.994	32	1.30	23	0.008	0.165	
Southwestern Depression	Akemomu	K	81.1	10.20	8.40	81.40	0.996	1046	10.26	342	0.042	1.081	
		K	80.8	11.30	7.80	80.89	0.997	1062	10.96	394	0.056	1.402	
Air								5.24	18.18	9340	1.140	8.7	

Table 2: Isotopic compositions for some hydrocarbon and rare gases in some gas fields from the Kuche and Southwestern Depressions, Tarim Basin.

Tectonic unit	Gas field	Strata	$\delta^{13}C_1$ (‰)	$\delta^{13}C_2$ (‰)	$^3He/^4He$ (10^{-8})	R/R_a	$^{20}Ne/^{22}Ne$	$^{21}Ne/^{22}Ne$	$^{40}Ar/^{36}Ar$	$^{38}Ar/^{36}Ar$	$^{129}Xe/^{130}Xe$	$^{132}Xe/^{130}Xe$	References
Kuche Depression	Kela2	E	-27.6	-18	3.93	0.028	9.70	0.0298	1211	0.195	6.301	6.663	[15]
		K_1, E	-26.4	-17.8	4.31	0.031	9.65	0.0305	1323	0.196	6.433	6.706	
		K_1, E	-26.8	-18.4	6.77	0.048	9.74	0.0299	589	0.196	6.434	6.745	
		K_1, E	-28.1	-19.1	8.58	0.061	9.69	0.0307	719	0.198	6.418	6.628	
		K_1, E	-28	-18.7	5.68	0.041	9.63	0.0301	720	0.197	6.452	6.685	
		K_1, E	-27.8	-19	7.24	0.052	9.68	0.0302	462	0.195	6.399	6.715	
		K_1, E	-27.3	-18.5	3.75	0.027							This paper
		K_1, E	-27.4	-18.3	4.12	0.029							
	Dabei	K_1bs	-30.9	-22.1	6.31	0.045	9.56	0.0291	858	0.201	6.446	6.689	[23]
		K_1bs	-29.4	-19.4	8.73	0.062	9.60	0.0303	504	0.197	6.436	6.653	
		K_1bs	-30.4	-21.8	7.14	0.051	9.62	0.0307	521	0.204	6.422	6.638	
		K_1bs	-30.7	-22.3	8.68	0.062			390	0.196			
		K_1bs	-31.9	-24.2	11.24	0.08	9.73	0.0299	485	0.199			
	Dina	E	-34.5	-21.3	3.33	0.024	9.50	0.0297	387	0.193	6.478	6.759	This paper
		E	-34.6	-22.4	3.56	0.025							
		E	-33.3	-22.5	3.82	0.027							
	Keshen	K_1bs	-27.8	-16.1	6.87	0.049	9.68	0.0304	841	0.194	6.381	6.809	
		K_1bs	-27.7	-16.3	4.58	0.033	9.54	0.0306	456	0.191	6.422	6.704	
		K_1bs	-27.6	-17.3	6.07	0.043	9.64	0.0302	412	0.187	6.471	6.775	
Southwestern Depression	Akemomu	K	-25.6	-21.9	83.10	0.596			1653	0.198	6.437	6.754	
		K	-25.2	-21.8	83.60	0.597	9.71		1665	0.202	6.389	6.828	
Air					140	1	9.8	0.029	295.5	0.188	6.496	6.607	

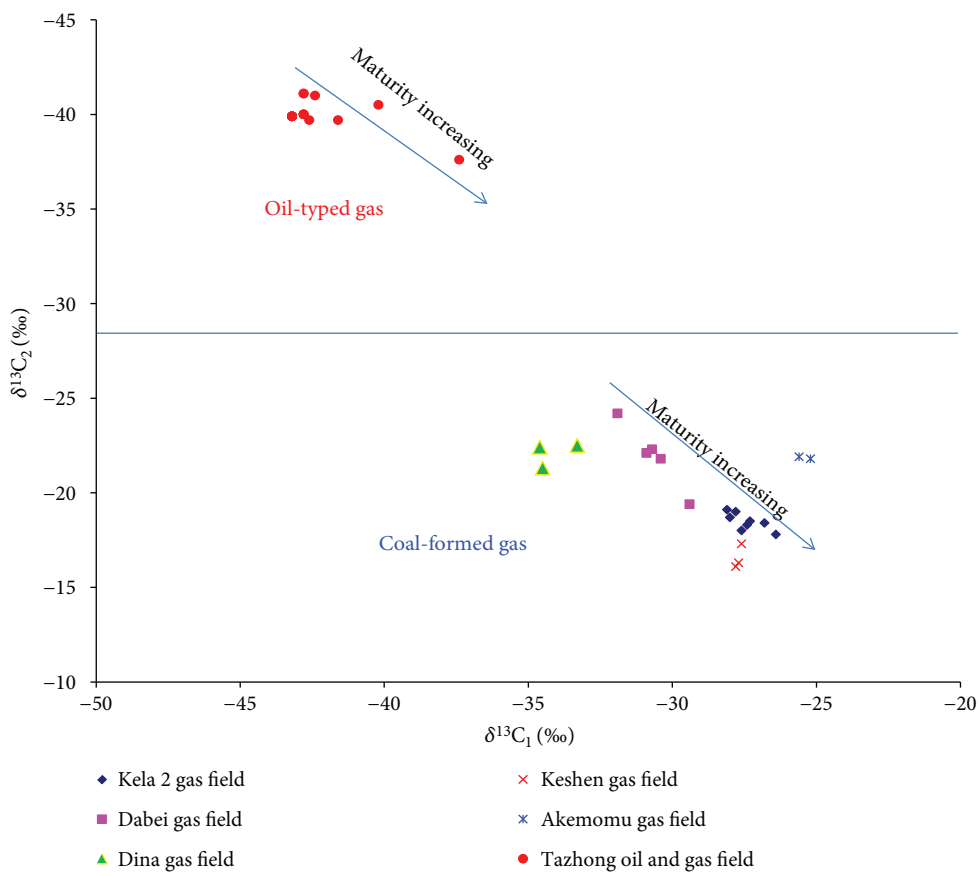

Figure 4: Genetic identification of $\delta^{13}C_1$ and $\delta^{13}C_2$ for natural gases of some gas fields from the Kuche and Southwestern Depressions, Tarim Basin (modified from [25, 36]).

mantle [11, 13, 17], while a relative excess of $^{131\sim136}Xe$ rather than ^{129}Xe generally reflects the origination of spontaneous fission from ^{238}U in the crust.

The $^{129}Xe/^{130}Xe$ value of natural gases in gas fields from the Kuche Depression ranges around 6.301~6.471 with an average of 6.422 and distributes around 6.389~6.437 with an average of 6.413 in the Akemomu gas field from the Southwest Depression (Table 2). The $^{132}Xe/^{130}Xe$ value of natural gases ranges around 6.628~6.809 with an average of 6.705 in the former and 6.754~6.828 with an average of 6.791 in the latter (Table 2). The relatively depleted ^{129}Xe and the excessive ^{132}Xe in gas fields from the Kuche Depression as well as the Akemomu gas field from the Southwestern Depression indicate that xenon has chiefly crustal-derived genesis (Figure 9), while the Changshen and Xushen gas fields in the Songliao Basin have a relatively excessive ^{129}Xe rather than ^{132}Xe, showing that xenon is obviously mixed with mantle-derived genesis [23].

4.3. Gas Source Correlation. Previous genetic identification of hydrocarbon gas isotopes shows that natural gases of the Kela2, Dina2, Dabei, and Keshen gas fields in the Kuche Depression are typical coal-formed gases (Figure 4), principally generated from coal measure source rocks in the Kuche Depression. According to the correlation between methane isotope ($\delta^{13}C_1$, ‰) of coal-formed gas and thermal evolution maturity (Ro, %) of coal measure source rocks [36, 37], $\delta^{13}C_1 = 14.131\lg(Ro) - 34.39$, the calculated maturity of coal-formed gases of these gas fields in the Kuche Depression is generally around 0.97%~3.68%. According to the relationship between coal-formed gas wetness (W, %) and maturity (Ro, %) (Dai et al., 2016), $Ro = -0.419\ln W + 1.908$, the calculated maturity of coal-formed gases of these gas fields in the Kuche Depression is about 0.96%~2.2%. From the comparison on the above calculated maturities, the former is more close to the actual thermal evolution of coal measure source rocks of Jurassic-Triassic in the Kuche Depression with maturity from mature to high mature even overmature. So, natural gases of these gas fields in the Kuche Depression generally originated from coal measure source rocks of Jurassic and Triassic with maturity from mature to high mature even overmature on conventional hydrocarbon gas source correlation.

Rare gases play a very important and useful role in identifying gas genesis and origination, enabling us to verify and deepen the understandings on conventional gas source correlation further. The average value of $^{3}He/^{4}He$ in gas fields from the Kuche Depression is about 6.04×10^{-8}, showing typical crustal-derived characteristics, so the chronological cumulative effect of argon isotopes can be adopted on gas

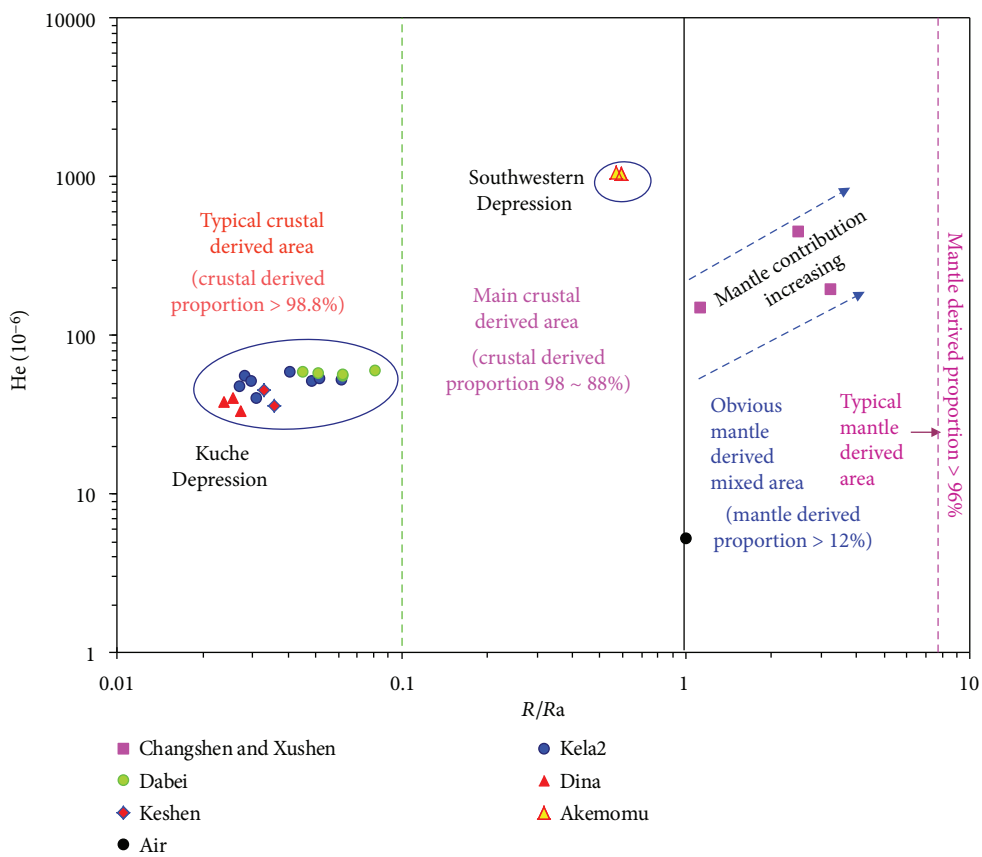

Figure 5: Genetic identification of He-R/R_a for some gas fields from the Kuche and Southwestern Depressions, Tarim Basin (chart modified from [23]).

source correlation in this area. Considering the carbonate source rocks having relatively old geologic age, the $^{40}Ar/^{36}Ar$ value of 387~1323 for natural gases in the Kuche Depression is obviously less than the calculated value of 2088~3686 from source rocks of Cambrian to Ordovician, so the carbonate source rocks of Cambrian to Ordovician can be excluded firstly. Coal measure source rocks of Triassic to Jurassic are greatly deposited in the Kuche Depression in the Mesozoic and Cenozoic periods. The average value of $^{40}Ar/^{36}Ar$ (659) in natural gases from the Kuche Depression mainly falls in the estimated range of gases generated from the Jurassic source rocks (571~767) and relatively deviates from the estimated range of gases generated from the Triassic source rocks (767~920). So, it can be concluded that natural gases of the Kuche Depression are probably derived from the coal measure source rocks of Jurassic and Triassic, principally from the Jurassic source rocks. According to obvious differences on $^{40}Ar/^{36}Ar$ value of natural gases that originated from different periods of source rocks, the calculated proportions of the Jurassic source rocks account for 55%-75% and the Triassic source rocks account for 25%-45%. As we know, the Jurassic source rocks are main coal measure source rocks and usually have a relatively higher gas potential, while the Triassic source rocks are main lake mudstone source rocks and generally have a relatively lower gas potential. The estimated proportion of the Jurassic and Triassic source rocks shows that the contribution of the Jurassic source rock is obviously higher than that of the Triassic source rock. The above evaluated result is generally according to the current mainstream viewpoints that the Jurassic source rock is the main source rocks for natural gases in the Kuche Depression when taking gas generation potential into account ([27, 28, 33–35, 45]; Li et al., 2005; [25, 46]).

Furthermore, because of great differences on kalium-bearing minerals in mudstones and coals, the $^{40}Ar/^{36}Ar$ values of natural gases that originated from mudstones and coals have obvious differences [18, 47]. Natural gases derived from mudstones usually have relatively higher $^{40}Ar/^{36}Ar$ values while natural gases derived from coal rocks generally have relatively lower $^{40}Ar/^{36}Ar$ values. It can be used to discuss the proportional contributions of mudstones and coals in coal measure source rocks. According to the above methods, assuming that the maximum $^{40}Ar/^{36}Ar$ value of natural gases in the Kuche Depression represented the maximum end-member value for gas that originated from mudstones and the minimum $^{40}Ar/^{36}Ar$ value of experimental thermal simulation gas on coals (341) represented the minimum end-member value for gas that originated from coals, the proportional contributions of coals and mudstones on coal measure source rocks of Jurassic and Triassic in the Kuche Depression are preliminarily evaluated. The results show that the contributed proportions of coals and

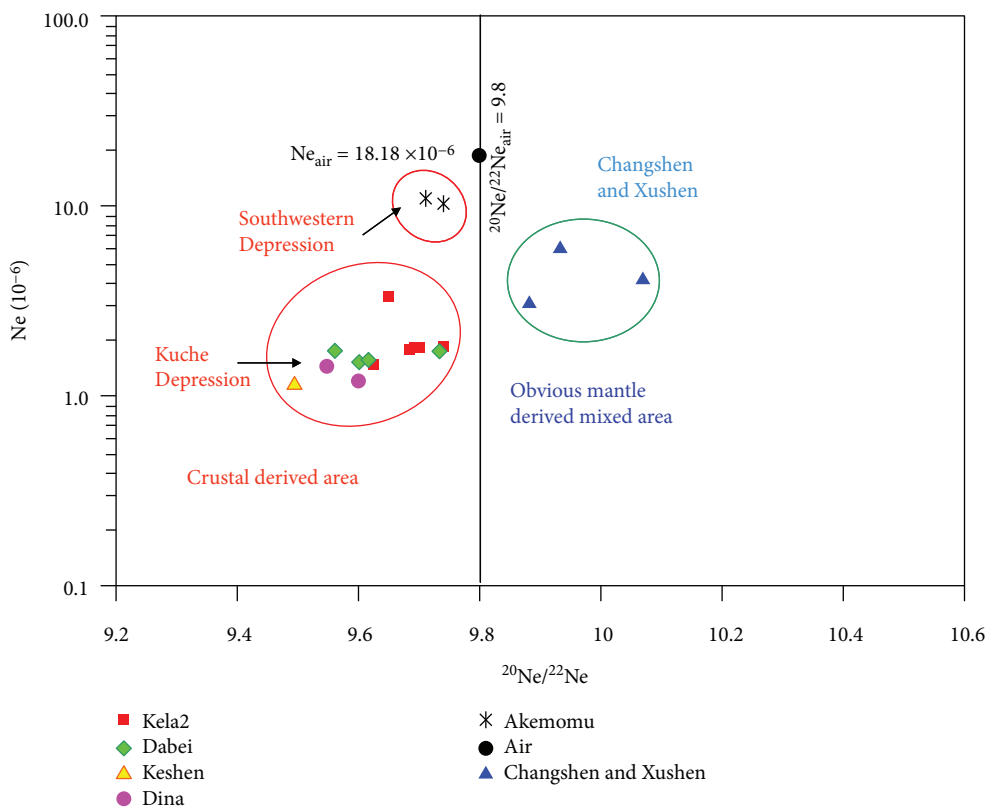

Figure 6: Genetic identification of Ne-$^{20}Ne/^{22}Ne$ for some gas fields from the Kuche and Southwestern Depressions, Tarim Basin.

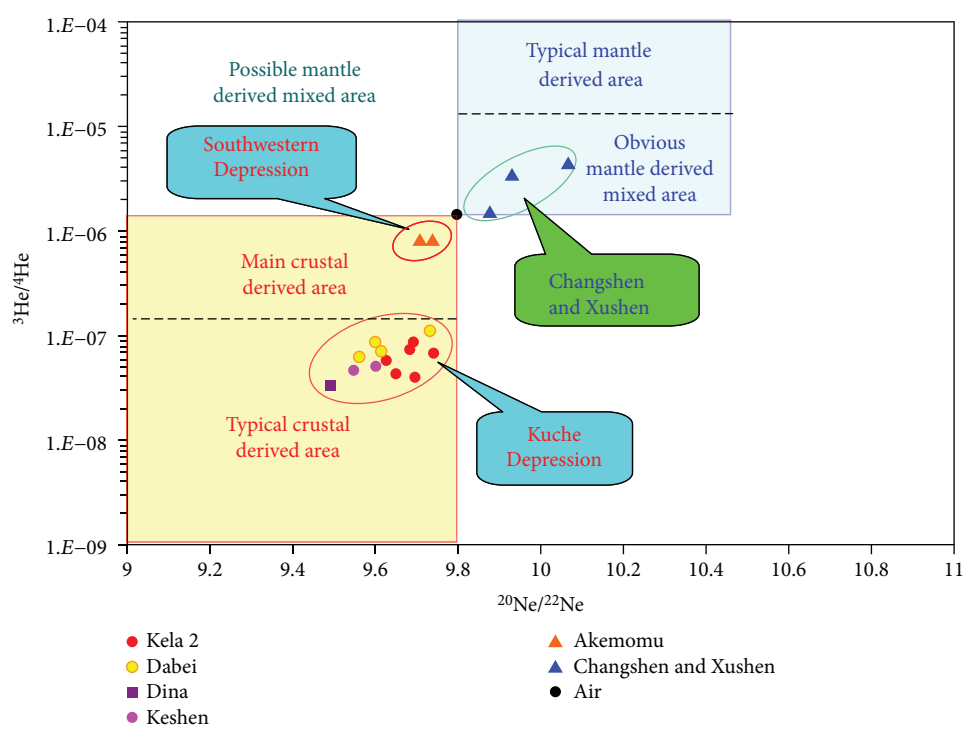

Figure 7: Genesis identification of $^{3}He/^{4}He$-$^{20}Ne/^{22}Ne$ for some gas fields from the Kuche and Southwestern Depressions, Tarim Basin (chart modified from [23]).

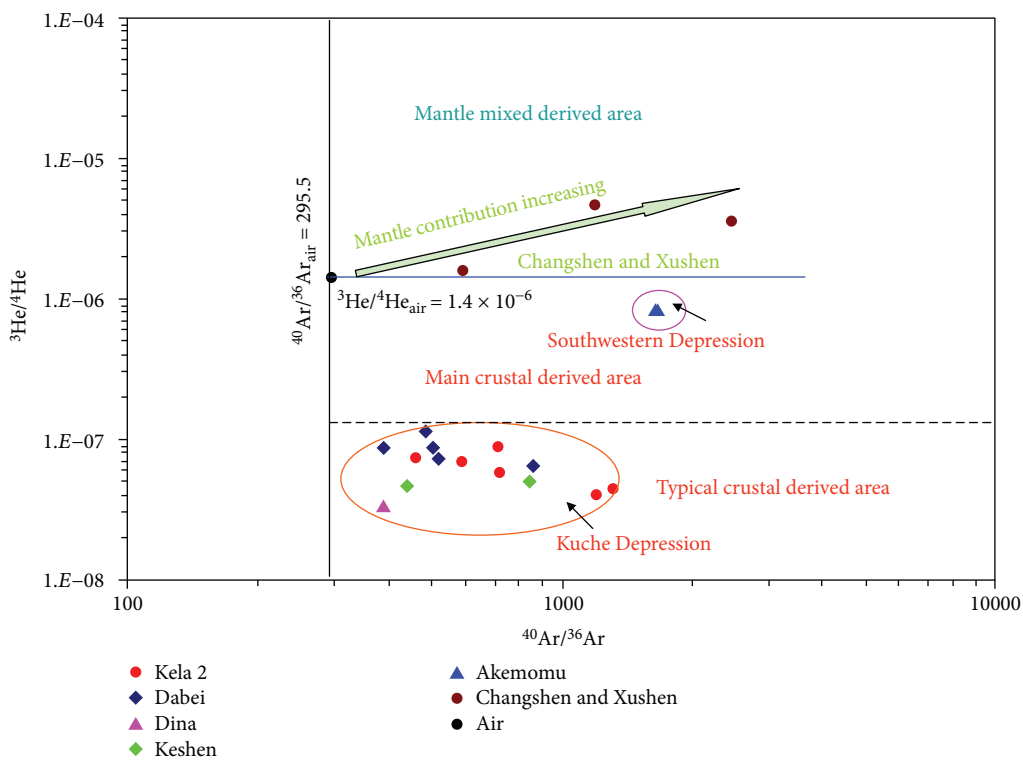

Figure 8: Genetic identification of ^{3}He/^{4}He-^{40}Ar/^{36}Ar for some gas fields from the Kuche and Southwestern Depressions, Tarim Basin (chart modified from [23]).

mudstones in coal measure source rocks of Jurassic and Triassic are 68% and 32%, respectively. In addition, adopting the average $\delta^{13}C_1$ of -29.38‰ of natural gases in the Kuche Depression and taking the reported heaviest $\delta^{13}C_1$ of -25.1‰ [48] and the lightest $\delta^{13}C_1$ of -36.9‰ [25] in the Kuche Depression as the end-member values of natural gases from coals and mudstones, the evaluated contributions of coals and mudstones from coal measure source rocks of Jurassic and Triassic in the Kuche Depression are around 64% and 36%, respectively. The two methods have nearly the same results which show that the evaluated result is correct and reliable.

Natural gases from the Akemomu gas field in the Southwestern Depressions are generally typical coal-formed gases (Figure 4). The drying coefficients of natural gas and carbon isotope ratios of methane indicate that Akemomu gas source rocks have high maturity. The natural gases in the Akemomu gas field have a relatively higher helium and argon contents and argon isotope than those of gas fields from the Kuche Depression, showings their obvious differences on gas geochemical characteristics and originations. Coal measure source rocks of Triassic to Jurassic and marine and continental transitional source rocks of Carboniferous to Permian are developed in the Southwestern Depression. The average value of ^{40}Ar/^{36}Ar (1659) of natural gases from the Akemomu gas field is obviously larger than the estimated value of gas generated from the source rocks of Jurassic to Triassic (571~920), and the higher argon isotope indicates that their source rock has a relatively longer accumulating time for gas accumulation, so the natural gases of the Akemomu gas field mainly originated from humic mudstones of marine and continental transitional source rocks of Carboniferous to Permian.

5. Conclusions

(1) Gas fields in the Kuche Depression have a higher methane abundance, accompanied with low N_2 and CO_2 abundances, but the Akemomu gas field in the Southwestern Depression has a relatively lower average methane abundance, accompanied with high average N_2 and CO_2 abundances. The helium abundance of natural gases in gas fields from the Kuche Depression general has 1 order of magnitude higher than the air value. Comparatively, it has more than 2 orders of magnitude higher than the atmospheric value in the Akemomu gas field from the Southwestern Depression. The neon, argon, krypton, and xenon abundances in both Kuche and Southwestern Depressions are generally lower than the corresponding air values.

(2) Natural gases from gas fields in the Kuche Depression and the Southwestern Depressions are generally typical coal-formed gases. The rare gases in the Kuche Depression have typical crustal genesis, mainly deriving from the radioactive decay of elements in the crust, while in the Akemomu gas field from the

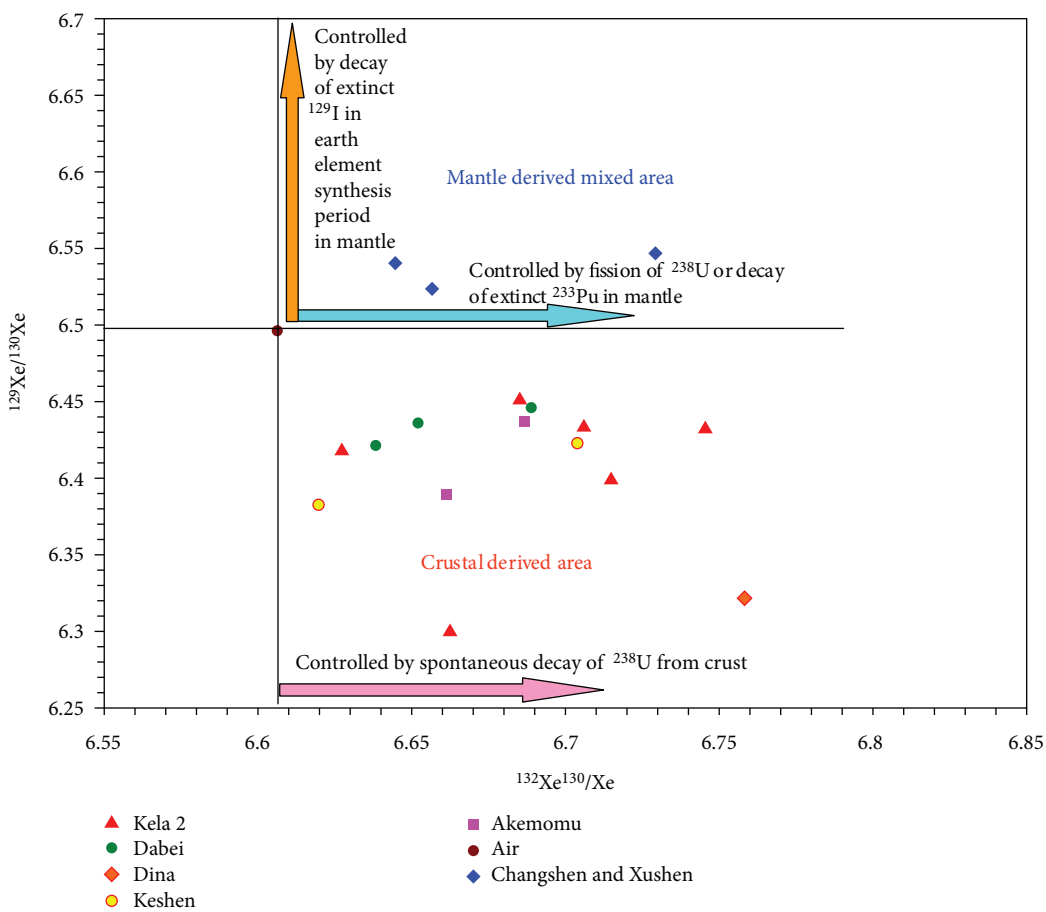

Figure 9: Genetic identification of $^{129}Xe/^{130}Xe$-$^{132}Xe/^{130}Xe$ for some gas fields from the Kuche and Southwestern Depressions, Tarim Basin (chart modified from [23]).

Southwestern Depression, the rare gases have main crustal genesis with a proportion of 92.5%, probably accompanied with a little mantled genetic contribution.

(3) Natural gases in the Kuche Depression are generally derived from coal measure source rocks of Jurassic and Triassic, which principally originated from Jurassic in strata period and coals in source rock types. The Jurassic source rocks account for 55%-75% and the Triassic source rocks account for 25%-45% approximately, while coals occupy 68% and mudstones occupy 32% separately. Natural gases from the Akemomu gas field in the Southwestern Depression mainly originated from humic mudstones of marine and continental transitional source rocks of Carboniferous to Permian.

Data Availability

The molecular and isotope composition geochemical data of natural gases used to support the findings of this study are included within the article. The experimental methods and processes are introduced in the manuscript. Some previously reported geochemical data are cited at relevant places within the text as references [15, 23] in the manuscript to support this study and are available at DOI: 10.1177/0144598715623673 and DOI: 10.1016/j.marpetgeo.2017.02.013.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] Y. C. Xu, X. B. Wang, R. M. Wu, P. Shen, Y. X. Wang, and Y. P. He, "Rare gas isotopic composition of natural gases," *Geochimica*, vol. 8, no. 9, pp. 271–282, 1979.

[2] C. J. Allegre, P. Sarda, and T. Staudacher, "Speculations about the cosmic origin of He and Ne in the interior of the Earth," *Earth and Planetary Science Letters*, vol. 117, no. 1-2, pp. 229–233, 1993.

[3] C. J. Allegre, T. Staudacher, P. Sarda, and M. Kurz, "Constraints on evolution of Earth's mantle from rare gas systematics," *Nature*, vol. 303, no. 5920, pp. 762–766, 1983.

[4] M. Honda, D. B. Patterson, I. McDougall, and T. J. Falloon, "Noble gases in submarine pillow basalt glasses from the Lau Basin: detection of a solar component in backarc basin basalts," *Earth and Planetary Science Letters*, vol. 120, no. 3-4, pp. 135–148, 1993.

[5] M. Ozima and F. A. Podesek, *Rare Gas Geochemistry*, Cambridge University Press, London, 1983.

[6] R. J. Poreda and K. A. Farley, "Rare gases in Samoan xenoliths," *Earth and Planetary Science Letters*, vol. 113, no. 1-2, pp. 129–144, 1992.

[7] X. B. Wang, *Rare Gas Isotope Geochemistry and Cosmochemistry*, Science Press, Beijing, 1989.

[8] J. A. Welhan and H. Craig, "Methane, hydrogen and helium in hydrothermal fluids at 21°N on the East Pacific Rise," in *Hydrothermal Processes at Seafloor Spreading Centers. NATO Conference Series (IV Marine Sciences), vol 12*, P. A. Rona, K. Bostrom, and L. Laubier, Eds., pp. 391–410, Plenum Press, Boston, MA, USA, 1983.

[9] J. A. Welhan, R. J. Poreda, W. Rison, R. Poreda, and P. Craig, "Geothermal gases of the Mud Volcano Area, Yellowstone Park," *Eos(Transactions, American Geophysical Union)*, vol. 64, p. 882, 1983.

[10] A. Battani, P. Sarda, and A. Prinzhofer, "Basin scale natural gas source, migration and trapping traced by noble gases and major elements: the Pakistan Indus basin," *Earth and Planetary Science Letters*, vol. 181, no. 1-2, pp. 229–249, 2000.

[11] P. Burnard, L. Zimmermann, and Y. Sano, "The noble gases as geochemical tracers: history and background," in *The Noble Gases as Geochemical Tracers. Advances in Isotope Geochemistry*, P. Burnard, Ed., pp. 1–16, Springer, Berlin, Heidelberg, 2013.

[12] J. Lupton and L. Evans, "The atmospheric helium isotope ratio: is it changing?," *Geophysical Research Letters*, vol. 31, no. 13, pp. 482–485, 2004.

[13] A. Prinzhofer, "Noble gas in oil and gas accumulations," in *The noble Gases as Geochemical Tracers. Advances in Isotope Geochemistry*, P. Burnard, Ed., pp. 225–247, Springer, Berlin, Heidelberg, 2013.

[14] Y. Sano, T. Tokutake, and N. Takahata, "Accurate measurement of atmospheric helium isotopes," *Analytical Sciences*, vol. 24, no. 4, pp. 521–525, 2008.

[15] X. Wang, G. Wei, J. Li et al., "Geochemical characteristics and origins of noble gases of the Kela 2 gas field in the Tarim Basin, China," *Marine and Petroleum Geology*, vol. 89, pp. 155–163, 2018.

[16] S. Xu, Y. C. Xu, P. Shen et al., "The isotopic composition and its geological significance of neon in natural gas of eastern basin in China," *Chinese Science Bulletin*, vol. 41, no. 21, pp. 970–l972, 1996.

[17] S. Xu, Y. Xu, P. Shen, S.'. Nakal, and H. Wakita, "Noble gas isotopes in natural gases from Central and Northwest China," *Chinese Science Bulletin*, vol. 42, no. 10, pp. 838–841, 1997.

[18] W. H. Liu and Y. C. Xu, "The significance of helium and argon isotopic composition in natural gases," *Chinese Science Bulletin*, vol. 38, no. 9, pp. 818–821, 1993.

[19] M. L. Sun, Y. C. Xu, and X. B. Wang, "Mass spectrometer analysis for He isotope in natural gases," *Journal of Instrumental Analysis*, vol. 10, no. 5, pp. 50–55, 1991.

[20] J. Y. Lee, K. Marti, J. P. Severinghaus et al., "A redetermination of the isotopic abundances of atmospheric Ar," *Geochimica et Cosmochimica Acta*, vol. 70, no. 17, pp. 4507–4512, 2006.

[21] D. F. Mark, F. M. Stuart, and M. de Podesta, "New high-precision measurements of the isotopic composition of atmospheric argon," *Geochimica et Cosmochimica Acta*, vol. 75, no. 23, pp. 7494–7501, 2011.

[22] X. Wang, Z. Li, J. Li et al., "Technique for total composition and isotope analyses of rare gases," *Acta Petrolei Sinica*, vol. 34, pp. 70–77, 2013.

[23] X. Wang, J. Chen, Z. Li et al., "Rare gases geochemical characteristics and gas source correlation for Dabei gas field in Kuche depression, Tarim Basin," *Energy Exploration & Exploitation*, vol. 34, no. 1, pp. 113–128, 2016.

[24] G. Wei, D. Wang, X. Wang et al., "Characteristics of noble gases in the large Gaoshiti-Moxi gas field in Sichuan Basin, SW China," *Petroleum Exploration and Development*, vol. 41, no. 5, pp. 585–590, 2014.

[25] J. X. Dai, *Coal-Derived Large Gas Fields and Their Gas Sources in China*, Science Press, Beijing, 2014.

[26] G. L. Lei, H. W. Xie, J. Z. Zhang et al., "Stuctural features and natural gas exploration in the Kelasu structural belt, Kuqa Depression," *Oil & Gas Geology*, vol. 28, no. 6, pp. 816–820, 2007.

[27] J. Li, Z. Y. Xie, Z. S. Li, X. Luo, G. Y. Hu, and S. Gong, "Gas-source correlation of natural gas in Kuqa Depression, Tarim Basin," *Petroleum Exploration and Development*, vol. 28, no. 5, pp. 29–32, 2001.

[28] D. Liang, S. Zhang, J. Chen, F. Wang, and P. Wang, "Organic geochemistry of oil and gas in the Kuqa Depression, Tarim Basin, NW China," *Organic Geochemistry*, vol. 34, no. 7, pp. 873–888, 2003.

[29] Y. Neng, J. F. Qi, H. W. Xie, Y. Li, G. L. Lei, and C. Wu, "Structural characteristics of northern margin of Kuqa depression, Tarim Basin," *Geological Bulletin of China*, vol. 31, no. 9, pp. 1510–1519, 2012.

[30] Y. Song, F. Hong, X. Y. Xia, G. Gao, and Y. G. Fu, "Syngenesis relationship between abnormal overpressure and gas pool formation-with Kuqa Depression as an example," *Petroleum Exploration and Development*, vol. 33, no. 3, pp. 303–308, 2006.

[31] N. Zhang, H. L. Guo, and Z. Y. Gao, "The characteristics of fluid inclusions and pool forming process of oil and gas reservoirs in the Kela 2 giant gas field, Tarim Basin," *Acta Petrologica Sinica*, vol. 16, no. 4, pp. 665–669, 2000.

[32] S. Zhang, B. Zhang, G. Zhu, H. Wang, and Z. Li, "Geochemical evidence for coal-derived hydrocarbons and their charge history in the Dabei Gas Field, Kuqa Thrust Belt, Tarim Basin, NW China," *Marine and Petroleum Geology*, vol. 28, no. 7, pp. 1364–1375, 2011.

[33] W. Zhao, S. Zhang, F. Wang et al., "Gas systems in the Kuche Depression of the Tarim Basin: source rock distributions, generation kinetics and gas accumulation history," *Organic Geochemistry*, vol. 36, no. 12, pp. 1583–1601, 2005.

[34] C. Z. Jia, Y. Y. Hu, and Z. J. Tian, "The large gas fields exploration of Kuqa Depression in Tarim Basin," in *The Frontier Petroleum Exploration in China (Vol.1)*, G. Ruiqi and Z. Zhengzhang, Eds., pp. 254–268, Petroleum Industry Publish, Beijing, 2001.

[35] C. Jia and G. Wei, "Structural characteristics and petroliferous features of Tarim Basin," *Chinese Science Bulletin*, vol. 47, no. S1, pp. 1–11, 2002.

[36] J. X. Dai, "Identification and distinction of various alkenes gases," *Science in China Series B-Chemistry*, vol. 35, no. 10, pp. 1246–1257, 1992.

[37] J. X. Dai and H. F. Qi, "The relationship between δ^{13}C and Ro in coal derived hydrocarbon in China," *Chinese Science Bulletin*, vol. 34, no. 9, pp. 690–692, 1989.

[38] W. B. Clarke, W. J. Jenkins, and Z. Top, "Determination of tritium by mass spectrometric measurement of ^{3}He," *The International Journal of Applied Radiation and Isotopes*, vol. 27, no. 9, pp. 515–522, 1976.

[39] B. A. Mamyrin, G. S. Anufrriev, I. L. Kamenskii, and I. N. Tolstikhin, "Determination of the isotopic composition of air helium," *Geochemistry International*, vol. 7, pp. 498–505, 1970.

[40] J. E. Lupton, "Terrestrial inert gases: isotope tracer studies and clues to primordial components in the mantle," *Annual Review of Earth and Planetary Sciences*, vol. 11, no. 1, pp. 371–414, 1983.

[41] R. J. Poreda, P. D. Jenden, I. R. Kaplan, and H. Craig, "Mantle helium in Sacramento basin natural gas wells," *Geochimica et Cosmochimica Acta*, vol. 50, no. 12, pp. 2847–2853, 1986.

[42] J. G. Du, "The geochemistry of light rare gases," *Geology Geochemistry*, vol. 17, no. 4, pp. 56–59, 1989.

[43] B. A. Mamyrin and I. N. Tolstikhin, "Helium isotopes in nature," in *Developments in Geochemistry 3*, p. 287, Elsevier, Amsterdam, 1984.

[44] H. Hiyagon, M. Ozima, B. Marty, S. Zashu, and H. Sakai, "Noble gases in submarine glasses from mid-oceanic ridges and Loihi seamount: constraints on the early history of the Earth," *Geochimica et Cosmochimica Acta*, vol. 56, no. 3, pp. 1301–1316, 1992.

[45] J. X. Dai, J. Li, W. W. Ding et al., "Geochemical characters of the giants gas accumulations with over one hundred billion cubic meters reserves in China," *Petroleum Exploration and Development*, vol. 32, no. 4, pp. 16–23, 2005.

[46] S. Qin, J. Dai, and X. Liu, "The controlling factors of oil and gas generation from coal in the Kuqa Depression of Tarim Basin, China," *International Journal of Coal Geology*, vol. 70, no. 1-3, pp. 255–263, 2007.

[47] D. W. Zhang, W. H. Liu, J. J. Zheng, X. F. Wang, and Q. Y. Nan, "Identification of main gas source in Kuqa Depression using argon isotope ratios," *Geochimica*, vol. 34, no. 4, pp. 405–409, 2005.

[48] Z. Wang, T. Wang, Z. Xiao, Z. Xu, M. Li, and F. Lin, "Migration and accumulation of natural gas in Kela-2 gas field," *Chinese Science Bulletin*, vol. 47, Supplement 1, pp. 107–112, 2002.