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Original research paper

The Late Paleozoic relative gas fields of coal measure in China and their significances on the natural gas industry☆

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Abstract

The coal measure gas sources of coal-derived gas fields in the Late Paleozoic China are the Lower Carboniferous Dishuiquan Formation, the Upper Carboniferous Batamayineishan Formation and Benxi Formation, the Lower Permian Taiyuan Formation and Shanxi Formation, and the Upper Permian Longtan Formation. The coal-derived gas accumulates in Ordovician, Carboniferous, Permian, and Paleocene reservoirs and are distributed in Ordos Basin, Bohai Bay Basin, Junggar Basin, and Sichuan Basin. There are 16 gas fields and 12 of them are large gas fields such as the Sulige large gas field which is China's largest reserve with the highest annual output. According to component and alkane carbon isotope data of 99 gas samples, they are distinguished to be coal-derived gas from coal-derived gas with $\delta^{13}C_2 > -28.5‰$ and $\delta^{13}C_1$ -$\delta^{13}C_2$ -$\delta^{13}C_3$ identification chart. The Late Paleozoic relative gas fields of coal measure are significant for the Chinese natural gas industry: proven natural gas geological reserves and annual output of them account for 1/3 in China, and the gas source of three significant large gas fields is coal-derived, which of five significant large gas fields supporting China to be a great gas producing country. The average reserves of the gas fields and the large gas fields formed from the late Paleozoic coal measure are 5.3 and 1.7 times that of the gas fields and the large gas fields in China.

Keywords: China; The Late Paleozoic; Coal-derived gas; Natural gas industry

1. Introduction

Coal is mainly composed of humic coal and sapropelic coal. Sapropelic coal is formed from shallow sea algae, mainly in the lower organisms. The Cambrian, Ordovician, and Silurian had coal measures appeared. At present, the coal in China are anthracite in places where the proportion of coal is very small and the geographical distribution is limited. Humic coal is formed from swamps and onshore higher plants and is a major component of coal measures. The earliest known terrestrial flora in the world evolved in the Late Silurian to Early Devonian period. On such flora in Altay in Xinjiang, Shanglin in Guangxi, Fengkai in Guangdong, Luquan in Yunnan formed Early and Middle Devonian coal line or thin coal seam. Early Devonian flora has begun to appear on the earth, but the distribution is sparse and have not discovered valuable coal seam yet [1]. Due to the early Paleozoic sapropel and Devonian system's humic coal restricted distribution area's inability to form scale coal measures, so far it has not been found in the world of coal-derived gas field.

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2. The coal measures associated with coal-derived gas in the Late Paleozoic

There are eight main coal accumulating periods in China from Early Cambrian to Tertiary. The Late Paleozoic, the Late Carboniferous to the Early Permian, and Late Permian, are two of China's four biggest coal accumulating effect phase [1]. The Late Paleozoic coal-bearing strata is distributed widely in China and developed well. Associated with the currently known coal-derived gas field of coal-bearing strata, it is mainly distributed in the Upper Carboniferous Benxi Formation, the Lower Permian Taiyuan Formation and Shanxi Formation of the Eastern North and Northwest of China, the Lower Carboniferous Dishuiquan Formation and the Upper Carboniferous Batamayineishan Formation in Junggar Basin of Xinjiang, and the Upper Permian Longtan Formation of south China.

2.1. The coal measures associated with coal-derived gas in north China coal basin

Late Paleozoic coal accumulating basin of North China, or North China coal basin, is an important coal-bearing area in China. The original scope of the coal basin, north from south of Yinshan Mountain, south to north of Qinling Mountain and Dabie Mountain, west to the east of Helan Mountain, east facing Japan sea, an area of 120×10^4 km^2, is a very large coal-bearing basin. Basin, in the main part of the formation from bottom to top are: Hutian Formation (Tielvyan Formation), Benxi Formation, Taiyuan Formation, Shanxi Formation, Shihezi Formation, and Shiqianfeng Formation [2]. The Benxi Formation, Taiyuan Formation and Shanxi Formation are coal-bearing strata in the north. The Shihezi Formation in southern basin, the south of the north latitude 35° of Pingdingshan and Huainan regions, has coal and buried shallow. It is now an important coal mining area, in addition to the coal bed methane, not found coal-derived gas field.

North China coal basin, which is suffering the influence of the Cenozoic tectonic movement, has significant changes. It formed an uplift tectonic belt of the NNE trend Taihang Mountain−Lvliang Mountain in the middle. The rise of the late Paleozoic coal, with shallow buried depth, becomes China's major coal-producing area. And Qinshui area in its south became the coal bed of gas production area in China. However, coal-derived gas field in the uplift belt hasn't been found so far. In the Bohai Bay Basin of the eastern uplift belt, Mesozoic−Cenozoic tectonic is strongly active, and is becoming a rift type with many fractures. It makes many areas in the original coal continuous distribution by denudation because of the rising, coal measures just to be saved in deep sag, and found the relevant coal-derived gas field. In the west of Taihang Mountain−Lvliang Mountain uplift belt area mainly is Ordos Basin and is a craton-type structure region [3], the continuous Late Paleozoic coal measures preserved well in the interior.

2.1.1. The accumulation conditions of Late Paleozoic coal into gas in Ordos Basin

Ordos Basin is the earliest basin (in 1907) in mainland China to use mechanic well drilling (Well Yan 1) to explore oil and gas. But since then, because of the traditional industry thinking coal measures is not hydrocarbon source rock, it doesn't put the Carboniferous-Permian coal as exploration targets. Until 1978 it has no progress for natural gas exploration. In 1979, after the birth of the theory of coal-derived gas [4], many scholars have pointed out that coal-bearing strata of Benxi Formation, Taiyuan Formation, and Shanxi Formation in the basin are good gas source rocks since 1980, and should strengthen the coal-derived gas exploration [5−10].

Coal and mudstone of late Paleozoic in Ordos Basin are all kerogen III. Coal seams are mainly distributed in Taiyuan Formation and Shanxi Formation, the thickness 2−20 m in general, dark mudstone in the western basin generally 140−150 m, 70−140 m for east, and 20−50 m for north and

Table 1
Geochemical parameters of Upper Paleozoic source rocks in Ordos Basin [12,13].

Type		Organic carbon /%	Chloroform bitumen A/%	Total hydrocarbon /ppm	Maceral/%		
					Vitrinite	Fusinoid	Inertinite
		Maximum/minimum Average					
Shanxi Formation	Coal	*89.17/49.28* 73.6	*2.45/0.1* 0.8	*6699.93/519.9* 2539.8	*90.2/43.8* 73.6	*54/6.3* 24	*12.3/0* 4.6
	Mudstone	*19.29/0.07* 2.25	*0.5/0.0024* 0.04	*524.96/519.85* 163.8	*47/8* 20.5	*87/51.8* 72	*20.3/0* 7.4
Taiyuan Formation	Coal	*83.2/3.83* 74.7	*1.96/0.03* 0.61	*4463/222* 1757.1	*98.8/21.2* 64.2	*63.7/1.3* 32.1	*15.1/0* 3.7
	Mudstone	*23.38/0.1* 3.33	*2.95/0.003* 0.12	*1904.64/15* 361.6	*82/8.3* 38	*89.3/15.3* 53.3	*34.5/0.3* 8.4
	Limestone	*6.29/0.11* 1.41	*0.43/0.0026* 0.08	*2194.53/88.92* 493.2			
Benxi Formation	Coal	*80.26/55.38* 70.8	*0.97/0.41* 0.77		*93.3/72* 87.2	*25.2/6.7* 16	*2.8/0* 1.4
	Mudstone	*11.71/0.05* 2.54	*0.44/0.0024* 0.065	*1466.34/12.51* 322.73	*47.8/12.3* 24.5	*59.8/12.3* 44	*39.5/0.3* 18.2

south [11]. The geochemical parameters of the coal and dark mudstone in Benxi Formation, Taiyuan Formation, and Shanxi Formation [12,13] are shown in Table 1. Three sets of coal in basin can be seen in Table 1 as good gas source rock.

Shanxi Formation and Xiashihezi Formation in basin-developed sandstone reservoir, with sandstone porosity less than 8% accounted for 63.71%, 8%–12% accounted for 28.58%, larger than 12% accounted for only 7.70%. With permeability less than 1×10^{-3} μm^2 accounted for 86.38%, it is a typical tight sandstone reservoir. The reservoir continuous plane distribution, distribution range is extensive. Vertically superimposed layers sand body, the sand layer thickness generally 30–100 m, the main reservoir sand mud ratio greater than 60%, provides good reservoir space for the large area of tight sandstone gas [14,15].

The stable lateral distribution of lacustrine mudstones of the Upper Paleozoic Shangshihezi Formation and Shiqianfeng Formation are important regional cap rocks. Shangshihezi Formation lacustrine argillaceous rocks are mainly sandy mudstone and silty mudstone, with thickness generally 150–200 m, mudstone gas absolute permeability commonly $(10^{-4}–10^{-5}) \times 10^3$ μm^2, gas breakthrough pressure 1.5–2.0 MPa, and have a strong ability to block.

Ordos Basin's Late Paleozoic large area has continuous stable distribution of coal-derived gas source rock at the bottom, middle plane shape wide distribution, vertically multilayer sand body overlaying large thickness tight sandstone, Shangshihezi Formation and Shiqianfeng Formation stable lateral distribution above, large thickness, and good lake mudstone seal forming good vertical source-reservoir-cap combinations, so it is good for large coal-derived gas accumulated in Xiashihezi Formation, Shanxi Formation, and Taiyuan Formation. Thus, many coal-derived gas fields have been found (Sulige, Daniudi, Yulin, Shenmu, Wushenqi, Zizhou, Mizhi, Liuyangbao, Dongsheng,

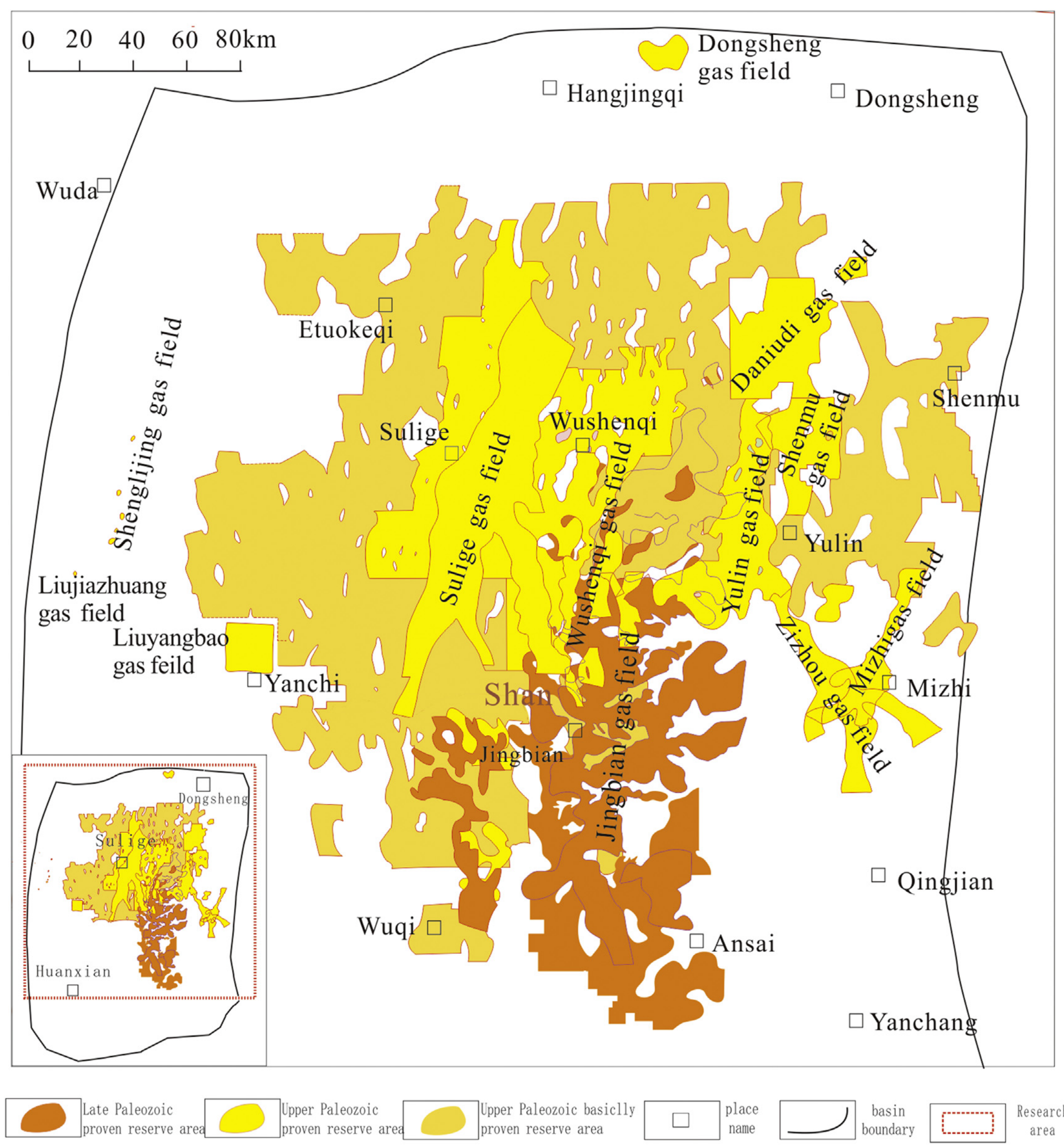

Fig. 1. Continuous distribution of Late Paleozoic coal measure relative gas fields.

Shenglijing) (Fig. 1). In addition, there is the Jingbian gas field with the coal-derived gas and oil-type gas gathered in the Ordovician Majiagou Formation carbonate rocks karst weathering crust. Many scholars agree about coal-derived gas in Jingbian gas field generated by late Paleozoic coal measures and migrated by Majiagou Formation channeling [16–19]. But there are two views for the gas source rocks of the oil-type gas in the gas field. Some of them thought they are from limestone interlayer with gas generation condition in Taiyuan Formation and Shanxi Formation (Table 1) [11,17–19], and others considered gas source rock as the Ordovician Majiagou Formation carbonate rocks [20–22].

2.1.2. The accumulation conditions of late Paleozoic coal into gas in Bohai Bay Basin

Bohai Bay Basin is a part of north China coal basin, Late Paleozoic coal measures forming environment, strata group, sedimentary condition, tectonic setting, superior gas generation condition, basically consistent with Ordos Basin. But due to the Cenozoic tectonic movement to be reformed to rift basin, the original contiguous wide distribution coal measure of Upper Paleozoic Benxi, Taiyuan and Shanxi Formation are lifted by strong reform, and most of the coal measure were eroded and preserved only in depression (fault). For example, coal measure of the Jidong Depression only distributed in southeast depression, the distribution area is less than 1/3 of the depression. So the coal accumulation region is much less, leading to accumulation scale small and scattered [23], and gas reservoir closely related to fracture (Fig. 2). Now discovered production gas reservoir are Suqiao condensate gas field, Wenliu gas field, Hubuzhai gas field, and many small gas fields, such as Chenghai, Wangguantun, Gubei, and so on [24–26].

2.2. The accumulation of Carboniferous coal into gas in Junggar Basin

Carboniferous tectonic activity in Junggar Basin is strong, and because of the frequent volcanic eruptions resulting in the same period stratigraphic lithology changing considerably and district named differently. Just analyze gas generation and accumulation function of the Dishuiquan Formation (C_1d) and Batamayineishan Formation in Zhundong area with which the Kelameili large gas field is in. Many scholars have pointed out that the Carboniferous coal measures are effective hydrocarbon source rocks [27–32]: the main hydrocarbon source rocks are the middle of Batamayineishan Formation, followed by the

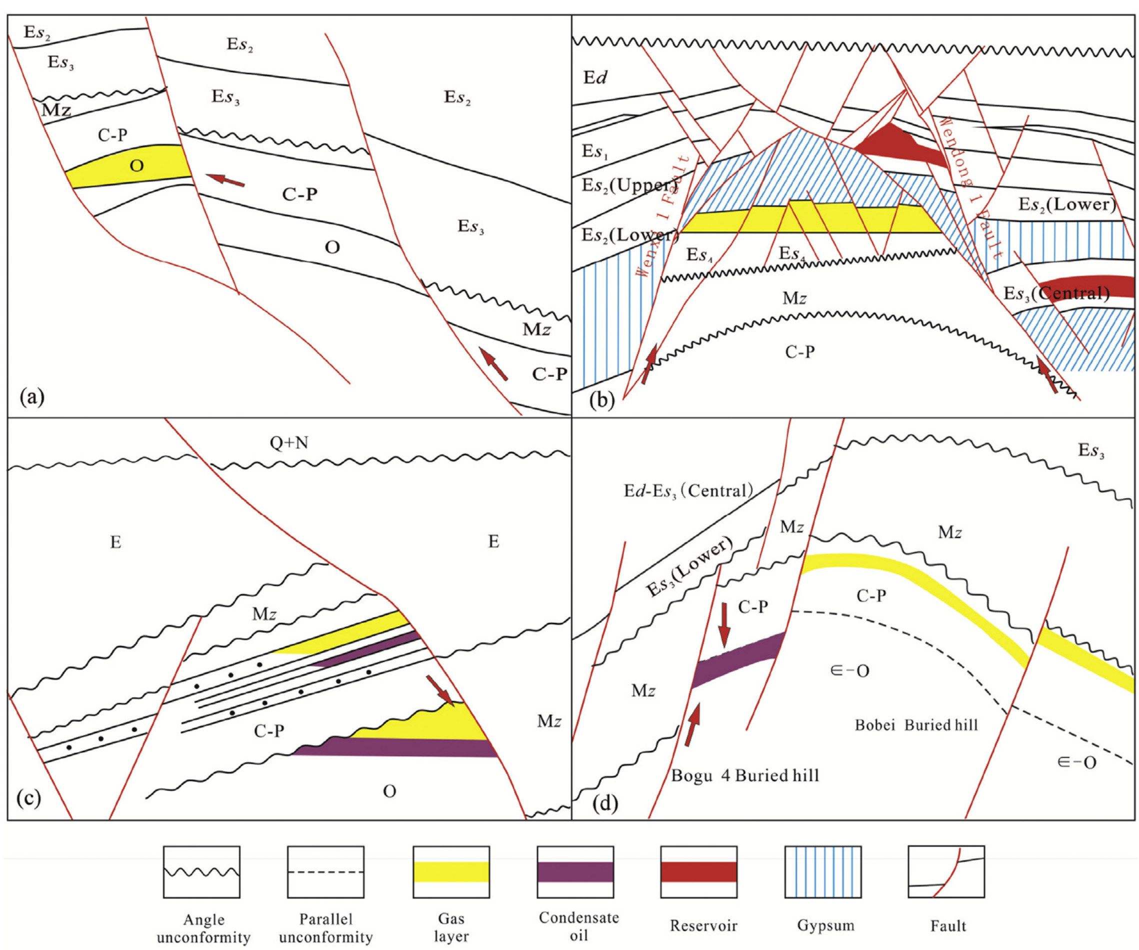

Fig. 2. Relationship between coal measure derived gas reservoir of Late Paleozoic and fracture in Bohai Bay Basin. (a) Chenghai; (b) Wen23; (c) Suqiao; (d) Bogu 4 buried hill.

Table 2
Organic matter abundance of Carboniferous source rocks in Ludong-Wucaiwan Area [33].

Stratum	Lithology	TOC/%	$S_1 + S_2$/ (mg/g)
Batamayineishan Formation C_2b	Tuff and tuffite	0.4−8.36, average 1.75	0.2−49.12, average 4.27
	Mudstone and carbonaceous mudstone	0.46−19.26, average 4.07	0.05−27.2, average 3.56
	Coal	15.95−37.59, average 21.96	0.55−53.27, average 18.5
Dishuiquan Formation C_1d	Tuff and tuffite	0.46−2.43, average 1.01	0.1−0.74, average 0.34
	Mudstone and carbonaceous mudstone	0.4−2.51, average 1.06	0.07−10.71, average 0.65

Dishuiquan Formation, and both of them are the coal-bearing strata. Dishuiquan Formation are coastal − shoreland transitional facies sedimentary environment, mainly terrigenous clastic and volcanic debris, development in Dishuiquan fault and Dongdaohaizi−Wucaiwan fault of north and south Kelameili gas field in the central basin, with thickness 49−623 m in Well Caican 1, hydrocarbon source rock 49−291 m, mainly dark mudstone, and a small amount of carbonaceous mudstone and coal. In Ludong-Wucaiwan area, Batamayineishan Formation is 124−3060 m thick, hydrocarbon source rocks 200−520 m, mainly dark mudstone, secondly carbonaceous mudstone and coal, then tuffite. In the Well Zhang 3, source rocks are 140.5 m thick, dark mudstone 106 m, carbonaceous mudstone 21.5 m, coal seam 13 m. Organic matter types of two formations are II_2 and III, and the organic matter abundance [33] are shown in Table 2.

Batamayineishan Formation is the main hydrocarbon source rocks, the volcanic rock the main reservoir. Batamayineishan Formation volcanic rocks can be divided into two segments, the middle for sedimentary space, upper segment volcanic rocks with serious erosion later and limited distribution, lower segment volcanic rocks as the products of the volcanic strong eruption, intermediate-acid volcanic rocks mainly of eruption facies and flooding facies, reservoir space dominated by secondary dissolution pores and fractures. In the Kelameili gas field, the porosity is 0.80%−28.80% with an average of 8.85%, the permeability (0.01−522.00) $\times$ 10^{-3} μm^2 with an average of 0.618 $\times$ 10^{-3} μm^2. Regional cap rock is Permian mudstone. The Kelameili large gas filed is found in this source reservoir cap rock assemblage above. Due to changeable facies and bad continuous volcanic rock as the reservoir, this large gas field is composed of multiple gas reservoirs (Fig. 3) [34].

2.3. The accumulation of the late Permian Longtan Formation coal into gas in Sichuan Basin

South China's Upper Permian Longtan Formation coal zones are mainly distributed in the Yangtze region. Yangtze region horizontally distributes two formations with the same period and different facies of late Permian: Longtan Formation and Wujiaping Formation. Wujiaping Formation, dominated by marine carbonate rocks with mud shale, is mainly distributed in the eastern Sichuan Basin and middle Yangtze region, but the discussion for that has nothing to do with the subject of this paper. Longtan Formation is mainly formed in gulf lagoon facies and delta plain swamp, the upper and middle dominated by black mudstone, shale, silty mudstone and coal, part with powder sandstone, the main distribution in Lower Yangtze area and the upper Yangtze area of the midwest Sichuan Basin [35,36]. Many oil and gas shows have been found in Longtan Formation of the Lower Yangtze region [4], but there are no related coal-derived gas fields yet, and that will not be discussed here. Longtan Formation in Sichuan Basin of the Upper-Yangtze area is generally 20−250 m thick, some coal reaching 2−10 layers [35], coal seam 3 m thick near Yilong [37]. Well, Yunan 19 in northeast Sichuan develops typical Longtan stratum, mudstone TOC content from 1% to 10%, mostly more than 2%, average 5.04%, source rocks 170 m thick. Hydrocarbon source rocks around Chongqing, Zigong, and Ziyang areas are 80−120 m thick, TOC content 1%−4%. Kerogen types are III and II, average original hydrocarbon potential of coal and coal shale 5−12 mg/g, up to 46 mg/g, R_O 1.3%−3.4% [35,36]. Changxing Formation reef facies dolomite is Longtan Formation reservoir, in which solution pore residual raw dolomite, solution pore dolomite as the main reservoir in Yuanba area, mainly with mesopore and medium-low permeability reservoir, porosity with a maximum of 6.28%, the minimum value 2.36%, the average 3.76%, the permeability with a maximum of 0.73 $\times$ 10^{-3} μm^2, the minimum value 0.01 $\times$ 10^{-3} μm^2, a mean of 0.21 $\times$ 10^{-3} μm^2. Gypsum of Jialingjiang Formation and Leikoupo Formation is the regional cap rock, the fourth member of Feixianguan Formation gypsum and marl as direct cap rocks. Currently, two large gas fields, Yuanba (Fig. 4) [38] and Longgang, have been found in Sichuan Basin Changxing Formation.

3. Correlation between listed gas field and gas source

Listed gas field refers to the gas field published by China and related to the late Paleozoic coal (until the end of 2013).

3.1. Ordos Basin

Ordos Basin Benxi Formation, Taiyuan Formation, and Shanxi Formation coal measure form 12 gas fields (Fig. 5), and the general exploration and development situation of these gas fields are shown in Table 3. From Table 3, it can be concluded that Ordos Basin coal-derived gas fields contain the largest coal-derived gas field (Sulige), the smallest coal-derived gas field (Liujiazhuang), and the highest annual output coal-derived gas field (Sulige).

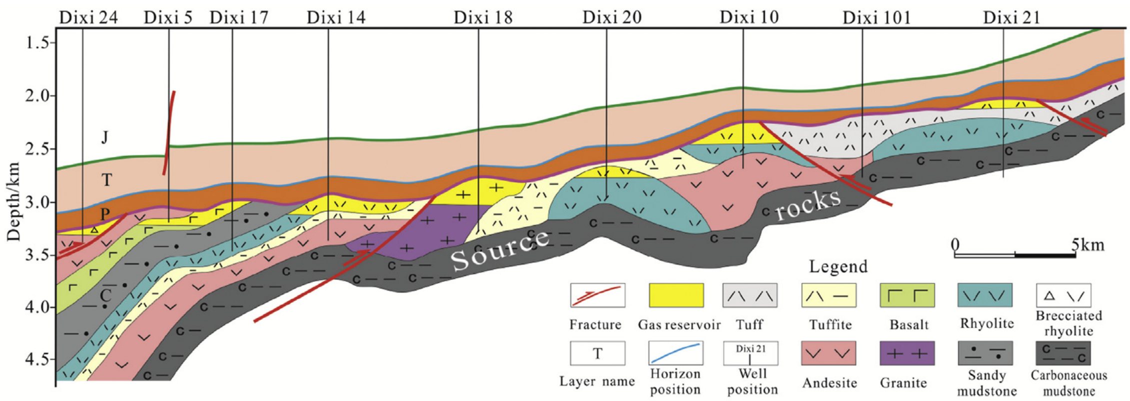

Fig. 3. Profile of Kelameili gas field (Ref. [34], 2011, supplement).

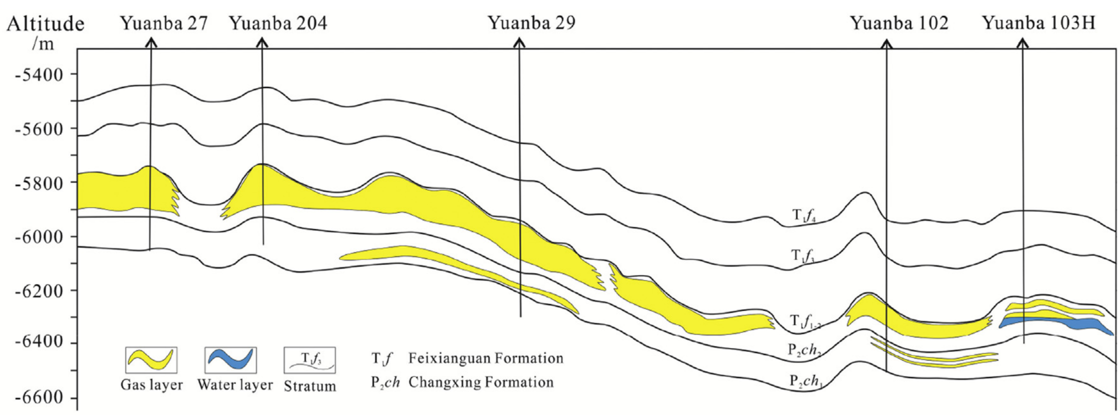

Fig. 4. Profile of reservoir in Changxing Formation, Yuanba gas field [38].

Natural gas geochemical parameters [11,18,39–44] of Ordos Basin which are being produced and already in production gas fields are shown in Table 4, including a lot of information of gas source correlation for listed gas fields. Many scholars pointed out that the $\delta^{13}C_2$ value is a good indicator to identify the coal-derived gas and oil-type gas. Zhang Shiya pointed out that the $\delta^{13}C_2$ is influenced by the hydrocarbon source rock maturity less than the $\delta^{13}C_1$, and $-29‰$ may be a boundary to distinguish oil-type gas and coal-derived gas, the $\delta^{13}C_2$ of coal-derived gas generally heavier than $-29‰$, while the $\delta^{13}C_2$ value of oil-type gas generally lower than $-29‰$ [45]. Wang Shiqian pointed out that the $\delta^{13}C_2 > -29‰$ for coal-derived gas [46]. Dai pointed out that the $\delta^{13}C_2$ value of coal-derived gas is basically higher than $-28‰$, and the $\delta^{13}C_2$ value of oil-type gas basically lower than $-28.5‰$, the $\delta^{13}C_2$ value between $-28‰$ and $-28.5‰$ for the mixture of these two types of gases and dominated by coal-derived gas [47]. According to the above, except Well Shan 5 and Well Shan 17 in Jingbian gas field for oil-type gas, all gases have the characteristics of coal-derived gas, shown in Table 4. Well Shan 5 and Well Shan 17 as oil-type gas are generated by intercalation limestone in Taiyuan Formation and Shanxi Formation [11,17–19].

Put the values of $\delta^{13}C_1$, $\delta^{13}C_2$, $\delta^{13}C_3$ in Table 4 to $\delta^{13}C_1$ -$\delta^{13}C_2$ -$\delta^{13}C_3$ identification chart (Fig. 6) [44], it indicates that, except Well Shan 5 and Well Shan 17, all gases in the area of coal-derived gas. Carbon isotope of benzene and toluene [48,49], and light hydrocarbon research [50] also proved they are coal-derived gas.

3.2. Bohai Bay Basin

The original deposition of the late Paleozoic coal measures in Bohai Bay Basin is similar to Ordos Basin. But due to the strong Mesozoic–Cenozoic tectonic movement, gas generation and accumulation is less than the Ordos Basin, for just a small area, small reserves, and low production medium-small gas reservoir (Table 5).

Table 6 shows the gas geochemical parameters from Carboniferous-Permian coal measure related gas wells of Bohai Bay Basin Dagang oil field, Shengli oil field, Huabei oil field, and Zhongyuan oil field [24,51–53]. According to $\delta^{13}C_2$ value indicator and $\delta^{13}C_1$ -$\delta^{13}C_2$ -$\delta^{13}C_3$ identification chart (Fig. 6) to identify, all natural gases in Table 6 are coal-derived gases, consistent with the conclusion from related research [23,54–56].

3.3. Junggar Basin

Two coal strata from Lower Carboniferous Dishuiquan Formation and the Upper Carboniferous Batamayineishan

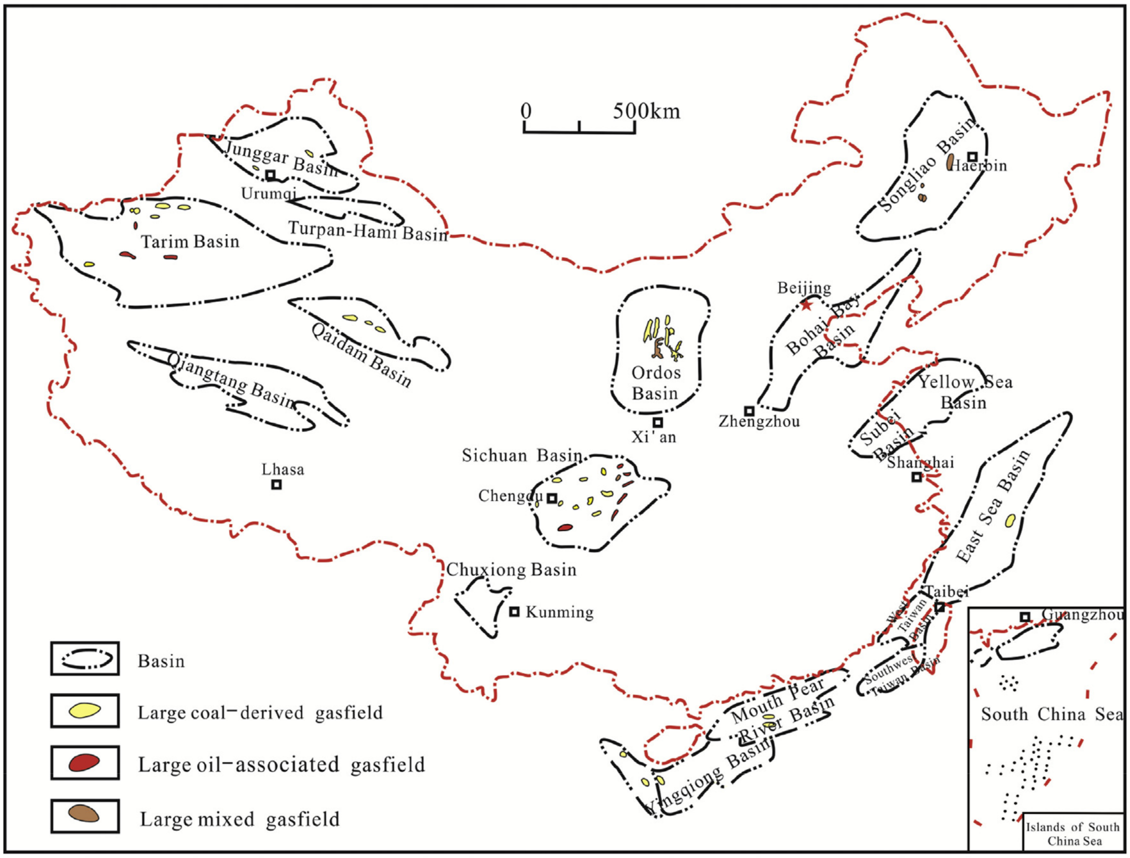

Fig. 5. Distribution of coal measure derived gas fields (reservoirs) of Late Paleozoic in China.

Formation formed Kelameili gas field and Wucaiwan gas field (Fig. 5, Table 7). They have two characteristics different from the coal-derived gas in China, one is the coal-derived gas field formed from China's oldest coal measure, and the second is the volcanic rock as a reservoir (Fig. 3).

Natural gases of the Kelameili gas field and the Wucaiwan gas field in Table 8 are formed by Upper and Lower Carboniferous coal measure, and natural gases of northern Kelamayi 5 Jiamuhe Formation gas reservoir (P_1j, Well Ke 82) and Wuerhe Formation gas reservoir (P_2w, Well Ke 75) formed by the Jiamusihe Formation type III source rocks [30]. According to $\delta^{13}C_2$ value indicator and $\delta^{13}C_1$ -$\delta^{13}C_2$ -$\delta^{13}C_3$ identification chart (Fig. 6) to identify, all natural gases in Table 8 are coal-derived gases, consistent with the conclusion from many scholars [11,29,30,32].

3.4. Sichuan Basin

Sichuan Basin Longtan Formation coal-bearing strata form Changxing Formation gas reservoir of Yuanba gas field and Longgang gas field (Fig. 5, Table 7), with two characteristics: first, it is different from Chinese coal-derived

Table 3
Exploration and development synopsis of coal-derived gas field in Ordos Basin.

Gas field	Main production layer	Discovered year	Total proven geological reserves by 2013/ ($\times10^8$ m^3)	Production in 2013/ ($\times10^8$ m^3)	Cumulative production/ ($\times10^8$ m^3)
Sulige	P_1x_8, P_1s_1	2001	12725.9	212.20	771.82
Jingbian	O_2, P_1x_8	1992	5528.04	41.76	510.53
Daniudi	P, C	2002	4545.63	34.34	236.31
Yulin	P_1s_2	1997	1807.50	59.85	438.88
Zizhou	P_1x_8, P_1s_2	2005	1151.97	13.87	51.63
Wushenqi	P_1x_8, O_2	1999	1012.1	6.95	46.75
Shenmu	P_1s, P_1s_2, C_3	2007	934.99	Not produced	0
Liuyangbao	C_3t^2	2012	549.65	Not produced	0
Mizhi	P_1x	1999	358.43	0.22	1.42
Dongsheng	P_1x^3, P_1x^2	2010	162.87	0.10	0.10
Shenglijing	P_2s	1982 (Discovered)	18.25	0	0
Liujiazhuang	P_1x^5	1969 (Discovered)	1.9	0	0

Table 4
Geochemical parameters of natural gas related to Carboniferous-Permian coal measure in Ordos Basin.

Gas filed	Well	Depth/m	Stratum	Main components of natural gas/%						$\delta^{13}C$/‰(VPDB)				Ref.
				CH_4	C_2H_6	C_3H_8	C_4H_{10}	CO_2	N_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	
Sulige	Su21		P_1s,P_2x	92.39	4.48	0.83	0.27	0.99	0.68	−33.4	−23.4	−23.8	−22.7	[11]
	Su75		P_2x	92.47	3.92	0.66	0.22	1.30	1.10	−33.2	−23.8	−23.4	−22.4	
	Su139		P_1s,P_2x	93.16	3.05	0.51	0.14	1.31	1.45	−30.4	−24.2	−26.8	−23.7	
	Su75-64-5X		P_2x	89.45	6.36	1.26	0.46	0.13	0.93	−33.5	−24.0	−23.3	−22.8	
	SU4-J1	3550.2	P_1s	92.46	4.68	1.22	0.53			−32.9	−23.6	−22.9	−22.4	[39]
	SUDONG37-44	3028.5	P_2h^8	94.18	3.36	0.54	0.19			−33.3	−24.3	−23.7	−22.5	
Yulin	Shan117		P_1s	64	3.99	0.63	0.11	1.51	0.51	−32.2	−26.0	−24.9	−23.5	[40]
	Shan215		P_1s	93.60	3.79	0.55	0.15	0.76	0.64	−30.8	−25.8	−24.4	−23.1	
	Yu43-10	2781.4−2798.3	P_1s	94.94	2.70	0.35	0.10	1.16	0.68	−31.9	−26.4	−23.0	−24.1	[41]
	Yu45-10	2726.7−2736.0	P_1s	94.26	3.39	0.51	0.15	0.99	0.54	−30.2	−26.1	−23.8	−21.9	
	Zhao4		Shihezi							−31.3	−23.7	−23.0	−22.5	[42]
	Qi2		P_1t							−31.6	−25.2	−22.8	−21.4	
Daniudi	D11	2600.5−2602.5	P	93.84	3.38	0.52	0.19	0.19	1.27	−34.5	−26.2	−24.7	−23.0	This paper
	D13	2702−2731.5	P_1s^2	89.81	6.02	1.65	0.59	0.52	0.90	−36.0	−25.7	−24.5	−22.7	
	D16	2698−2703	Shihezi 2	94.24	3.43	0.54	0.21	0.33	0.84	−35.2	−27.1	−26.0	−23.9	
	D24	2659−2685	Shihezi 1	89.12	6.70	1.89	0.59	0.33	0.86	−37.2	−26.1	−25.3	−24.0	
Jingbian	Shan5	3457−3484	O_1m_5	93.96	0.53	0.07	0.02	3.81	1.60	−32.2	−31.2	−25.7		[18]
	Shan2	3364.4−3369.4	$O_1m_5^+$	96.09	1.09	0.13	0.04	2.60		−35.3	−26.2	−25.5	−23.2	
	Shan17	3176.9−3182	$O_1m_5^4$	93.89	0.69	0.08	0.01	4.55	0.62	−33.3	−30.2	−27.8	−22.3	
	Shan21	3226−3230	$O_1m_5^2$	95.87	1.28	0.17	0.04	2.83	0.21	−34.9	−24.5	−24.7	−23.0	
	Shan34	3410−3413	$O_1m_5^{1-2}$	94.02	1.28	0.15	0.06	0.36	4.11	−35.3	−25.5	−24.4	−21.9	
	Shan65	3149−3154	P_1x	95.74	2.54	0.29	0.07	0.13	1.10	−29.1	−23.5	−25.5	−24.1	
	Shan85	3266.6−3287	O_1m_5	95.27	0.47	0.05	0.02	3.56	1.46	−33.1	−26.7	−20.9	−19.0	
Dongsheng	Yishen1			93.96	3.62	0.87	0.37	0.20	0.81	−33.5	−25.1	−24.6		This paper
	ESP2			93.74	3.64	0.85	0.29		1.32	−33.2	−25.3	−24.9		
	Jin11			93.69	3.57	0.87	0.34		1.34	−33.8	−25.0	−24.5		
Shenglijing	Ren4	2299−2303	Shihezi 3	91.09	4.79	0.70		0.19	3.23	−33.8	−26.4	−24.1		
	Ren9	2240−2243	Shihezi	91.84	3.86	1.21	0.51		2.40	−35.2	−26.6	−24.7		
	Ren11	2534−2537	Shihezi 4	93.78	3.36	1.07	0.43	0.09	1.19	−35.1	−26.7	−24.8		
Wushenqi	YU22-7	3119.8−3142.0	P_1x	92.51	4.10	0.69	0.22	0.55	1.67	−32.6	−23.7	−24.2	−21.9	
	G01-9	3038.0−3053.2	P_1x	93.46	3.92	0.54	0.14	0.45	1.38	−33.7	−23.1	−24.8	−22.7	
	Shan165	3103.2−3133.7	P_1x	93.17	3.46	0.60	0.19	0.65	1.67	−33.0	−24.0	−24.5	−22.3	
	Shan243	3042.2−3080.2	P_1x	90.85	5.46	1.03	0.35	0.54	1.55	−35.0	−24.0	−23.6	−22.5	
Zizhou	Zhou16-19	2712.5	P_1s	91.53	5.22	1.16	0.39			−34.5	−24.3	−21.7	−21.7	[39]
	Zhou17-20	2644.45	P_1s	91.55	5.07	1.13	0.40			−33.0	−24.5	−22.0	−21.7	
	Zhou19-22	2635	P_1s	93.00	4.43	0.84	0.31			−33.3	−24.7	−21.9	−21.6	
	Zhou22-18	2592	P_1s	93.12	4.22	0.76	0.27			−31.1	−25.7	−24.3	−23.1	
Mizhi	Mi4	2208	P_2h_8	93.73	4.44	0.09	0.02			−28.1	−22.0	−22.7	−21.6	[43]
	Mi17	2544	P_2h_8	92.75	4.39	0.86	0.33			−34.0	−23.7	−22.4	−21.2	
	Mi18	2303	P_2h_8	93.32	5.09	0.19	0.08			−34.1	−23.5			
	Mi21	2303.5	P_2h_8	95.18	3.38	0.50	0.16			−35.1	−22.7			
Shenmu	Shen1		P_2x	92.86	4.69	1.23	0.34		0.73	−37.1	−24.7	−24.5	−23.9	[44]
	Shuang15	2753.0−2756.5	P_1s	93.65	3.59	0.75	0.29	1.45	0.42	−35.9	−23.6	−22.6	−22.3	
	Shuang20		P_1s	93.06	3.22	0.56	0.21	2.47	0.82	−35.8	−25.6	−24.0	−23.0	

gas fields (reservoir) with marine reef and beach facies carbonate rocks as reservoirs (Fig. 4) [11,38,57,58], and second, it is the natural gas containing more H_2S (Table 9) [37,38,59].

Table 9 shows gas geochemical parameters of Yuanba gas field and Longgang gas field Changxing Formation [37,38,59]. According to $\delta^{13}C_2$ value indicator and $\delta^{13}C_1$ -$\delta^{13}C_2$ -$\delta^{13}C_3$ identification chart (Fig. 6) to identify, all natural gases in Table 9 are coal-derived gases. Some scholars have also pointed out that Changxing Formation of Longgang gas field and Yuanba gas field belongs to coal-derived gas [11,37,58]. But also, scholars think that the Yuanba gas field Changxing Formation gas reservoir belongs to oil-type gas [57].

4. The significance of late Paleozoic coal-related gas field in natural gas industry

4.1. The geological reserves and the annual production of Late Paleozoic coal-related gas fields accounting for one-third of the national

Fig. 7 and Fig. 8 show China's total geological reserves and annual production, and the change of the late Paleozoic, Mesozoic and Cenozoic coal-derived gas proportion this decade. In 2013, the late Paleozoic coal-derived gas reserves and annual production account for the country's 33.9% and 31.94% respectively, indicating that the late Paleozoic coal

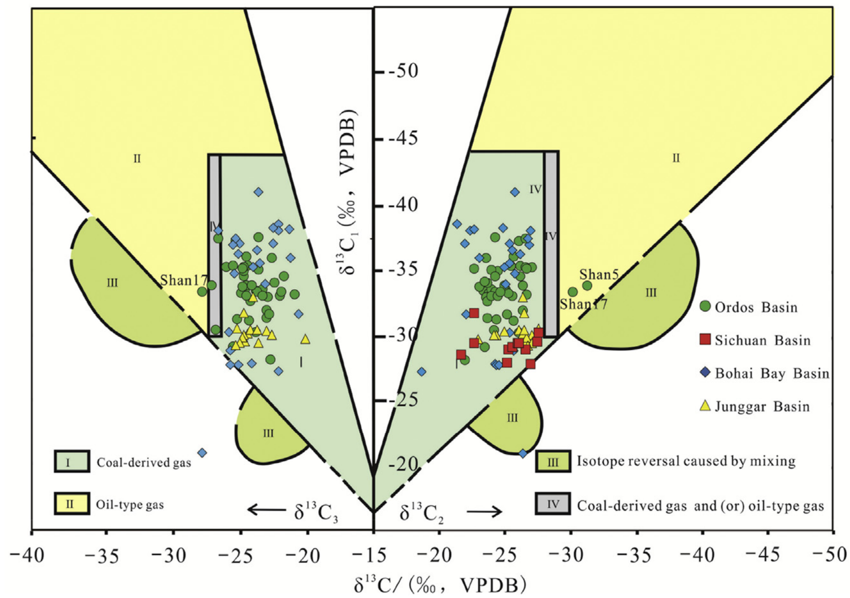

Fig. 6. $\delta^{13}C_1$ -$\delta^{13}C_2$ -$\delta^{13}C_3$ identification chart of alkane gas type in Ordos, Bohai Bay, Junggar, and Sichuan Basin.

Table 5
Exploration and development synopsis of coal-derived gas (oil) field in Bohai Bay Basin.

Gas field	Main production layer	Discovered year	Total proven geological reserves by 2013/ ($\times 10^8 m^3$)	Production in 2013/ ($\times 10^8 m^3$)	Cumulative production/ ($\times 10^8 m^3$)
Suqiao	O,P	1982	108.81	0.01	33.34
Wen'an	P_2s	1979	20.61	0	7.67
Guxinzhuang	O	1977	9.71	0.12	3.52
Wen23 (Wenliu)	E_3s^4	1977	154.12	0.64	108.28
Baimiao	E_3s^3	1980	126.23	0.30	8.18

related gas fields playing an important role in reserves and production in China.

4.2. The average reserves in coal related gas fields and large gas fields in late Paleozoic higher than the national gas fields and large gas fields

Sixteen coal-related gas fields of late Paleozoic have been found at the end of 2013, and 12 of them are large gas fields, which proved total geologic reserves of 32773.77 $\times$ 10^8 m^3 and 32590.73 $\times$ 10^8 m^3 respectively, the average geologic reserves of gas fields and large gas fields 2048.4 $\times$ 10^8 m^3 and 2715.9 $\times$ 108 m^3 respectively. At the end of 2013, China has found 253 gas fields, including 51 large gas fields, proved total geologic reserves 98006.64 $\times$ 10^8 m^3 and 81683.77 $\times$ 10^8 m^3 respectively, average geologic reserves of gas fields and large gas fields 387.4 $\times$ 10^8 m^3 and 1601.6 $\times$ 10^8 m^3 respectively. Thus, average geologic reserves of late Paleozoic coal-related gas fields and large gas fields, are 5.3 times and 1.7 times of the national gas fields and large gas fields respectively. After our country becoming a gas power with annual production of 1000 $\times$ 10^8 m^3, only the Late Paleozoic related gas fields and large gas fields with large reserves, make a greater contribution to the gas industry continued development.

4.3. Late Paleozoic coal measures forming the three key large gas fields to support our country becoming a big gas producer

The so-called key large gas fields refer to the large gas fields supporting the national to be the gas power, they often with the reserves located in the forefront of the country. China has five key large gas fields from 2011 to 2013 (Sulige, Jingbian, Daniudi, Puguang and Kela 2). The production of these key large gas fields in 2013 accounted for 38.0% of the national natural gas production [60], as the foundation of our country to be a gas power. Among them, all the gas sources of Sulige, Jingbian, and Daniudi are the Late Paleozoic coal-derived gas. Sulige gas field, is the largest gas field, with an annual production of 212.2 $\times$ 10^8 m^3 in 2013 (Table 3), accounting for 17.6% of the total gas production.

5. Conclusions

China's gas source rocks of the Late Paleozoic coal related gas fields are Lower Carboniferous Dishuiquan Formation, Upper Carboniferous Batamayineishan Formation, Benxi Formation, Lower Permian Taiyuan Formation and Shanxi Formation, and Upper Permian Longtan Formation, reservoirs mainly sandstone reservoir, secondly reef carbonate rocks, and

Table 6
Geochemical parameters of natural gas related to Carboniferous-Permian coal measure in Bohai Bay Basin.

Gas reservoir	Well	Depth/m	Stratum	Main components of natural gas/%							$\delta^{13}C$/‰(VPDB)				Ref.
				CH_4	C_2H_6	C_3H_8	C_4H_{10}	H_2S	CO_2	N_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	
Chenghai	Haigu1	4510–4587.7	O	50.43	0.22	0.03	0.02	11.79	33.6	3.86	−27.2	−18.7	−22.1		[24]
	Haigu101	5110–5187	O	55.64	0.15			6.03	33.33	1.95	−26.8	−14.1			
Kongxi	Wanggu1	3830.2–3867	P	84.09	6.29	1.98	0.93		3.84	2.06	−35.5	−25.4	−23.5	−24.7	
Wumaying	Wushen1	5456–5515	O	87.82					3.84		−38.5	−21.4	−22.1		
		5460–5496		88.86					2.54		−38.0	−22.4	−22.1		
Gubei buried hill	Yi132	3374.0–3387.0	C–P	82.10	8.10	3.43	1.79		1.87		−37.0	−25.4	−25.0	−25.5	[51]
	Gubeigu1	4020.9–4139.5	P	86.67	5.44	1.28	0.40		5.45		−35.9	−23.1	−21.2	−21.2	
	Gubeigu 2	3689.0–3731.0	C–P								−41.0	−25.8	−23.6	−23.6	
	Bo93	3230.0–3249.4	C–P	88.99	6.30	1.03	0.38		2.29		−38.1	−22.7	−21.3	−21.8	
Bogu4 buried hill	Bogu4	4375.0–4460.0	O	81.96	6.83	2.20	0.88		7.39		−38.2	−24.9	−22.5	−23.6	
Suqiao-Wen'an	Wen23	2710–2762.4	P	79.40	12.28	4.35	1.66		0.35	1.09	−36.9	−26.9	−25.5		This paper
	Su20	3344.6–3392.4	P	79.50	10.40	4.32	2.14		1.68	1.08	−37.4	−26.8	−25.3	−24.3	
	Su401	4848–4912.73	O	86.76	5.94	2.38	1.29		1.20	1.79	−36.5	−25.6	−23.7		
	Su402	4568–4700	O	86.02	7.25	2.28	0.94		1.37	1.88	−36.2	−26.2	−25.1		
	Su1-7	4145–4177	O_2	82.02	10.00	4.05	1.39		1.71	0.53	−38.0	−27.0	−26.6	−26.8	
	Ba21	3390.67–3553.6	O						2.80	8.59	−37.0	−22.0	−22.5	−23.8	
Shenxian	Ze79	3658.7–3720	O	64.21	10.85	4.92	2.27		12.84	3.32	−35.2	−25.0	−24.0	−23.7	
	Ze85	3939.4–3941.1	O	87.66	3.70	1.33	1.06		3.27	0.98	−33.9	−25.1	−23.1		
Wenliu	Wen23	2813.2–3026.8	Es_4	93.61	1.81	0.35	0.21		0.99	2.34	−27.8	−24.3	−24.1	−23.9	
	Wen23	2969.8–2987.0	Es_4	95.20	2.39	0.64	0.67		0.46	0.19	−28.8	−25.7	−25.7	−26.1	
	Wen31	2968–2987	Es_4	96.50	0.60	0.17	0.12		0.48	2.07	−27.7	−24.4	−25.1	−26.1	
	Wen105	2800–2890	Es_4								−27.7	−24.6	−25.7	−26.0	
Hubuzhai	Wei112	2741–2807	Es_3^1	81.56	6.51	2.32	1.79		1.19	1.05	−34.7	−25.8	−25.4	−25.7	
	Wei79-9		Es_4	92.80	3.04	0.75	0.27				−30.2	−25.4	−25.8		[52]
	Wei351-2	3342–3346	Es_3	92.86							−20.9	−26.4	−27.8		
Machang	Kai33	3344–3346.5	Es_4	95.70	0.83	0.13	0.05		0.38	2.93	−31.6	−22.1	−20.6		[53]

Table 7
Exploration and development synopsis of coal-derived gas fields in Junggar Basin and Sichuan Basin.

Basin	Gas field	Main production layer	Discovered year	Total proven geological reserves by 2013 ($\times 10^8 m^3$)	Production in 2013 ($\times 10^8 m^3$)	Cumulative production ($\times 10^8 m^3$)
Junggar	Kelameili	C_2b	2008	1053.34	6.96	29.87
	Wucaiwan	C_2b		8.33	Not produced	0
Sichuan	Yuanba	P_2ch, T_1f	2011	2194.57	Not produced	0
	Longgang	P_2ch, T1f	2010	720.33	9.15	55.54

Table 8
Geochemical parameters of coal-derived natural gas related to Carboniferous coal measure in Junggar Basin.

Gas field (Reservoir)	Well	Depth/m	Stratum	Main components of natural gas/%						$\delta^{13}C$/‰(VPDB)				Ref.
				CH_4	C_2H_6	C_3H_8	C_4H_{10}	CO_2	N_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	
Kelameili	Dixi 10	3024	C_2b	90.97	2.48	0.73	0.41	0.38	4.05	−29.5	−26.6	−24.6	−24.5	[11]
	Dixi 14	3582	C_2b	92.32	3.51	1.07	0.54	0.09	2.14	−30.5	−27.6	−25.2	−25.3	
	Dixi 17	3662	C_2b	85.44	6.12	2.10	1.36	0.28	3.48	−30.1	−26.4	−24.4	−24.8	
	Dixi 18	3510	C_2b	83.95	6.31	2.55	1.51	0.02	3.74	−30.0	−27.1	−24.7	−24.7	
	Dixi 20	3313	C_2b	81.91	4.79	1.94	1.18	0.06	9.45	−29.8	−26.7	−24.8	−25.1	
	Dixi 21	2849	C_2b	86.08	3.24	1.52	0.74	0.11	8.11	−29.4	−27.1	−25.0	−24.4	
	Dixi 171	3670	C_2b	90.07	4.17	1.41	0.86	0.05	0.81	−30.4	−26.1	−24.2	−24.2	
	Dixi 172	3552	C_2b	88.14	4.56	1.40	1.14	0.21	3.90	−29.4	−25.9	−23.6	−24.0	
	Dixi 182	3635	C_2b	84.83	5.84	2.45	1.59	0.04	4.45	−30.4	−26.5	−23.7	−23.7	
	Dixi 5	3650–3665	C_2b							−29.2	−26.8	−25.3	−25.2	[30]
Wucaiwan	Cai25	3028–3080	C_2b	94.37	2.13	0.46		0.11	2.60	−30.0	−24.4	−22.6	−22.3	
	Cai27	2778–2790	C_2b	73.71	6.89	4.33		0.03	11.53	−30.3	−25.0	−23.0	−22.6	
Northern Kelamayi 5	Ke75	2604.9–2672	P_2w	93.20	3.70	0.90	0.37			−31.7	−26.5	−24.7	−24.5	
	Ke77	2763–2768	P_2w	91.50	4.30	1.10	0.49			−32.9	−26.4	−24.0	−24.8	
	Ke82	4070–4084	P_1j							−29.7	−23.0	−20.1	−20.0	
	Ke82	4184–4166	P_1j							−30.0	−24.2	−22.6	−20.0	

Table 9
Natural gas geochemical parameters of Yuanba gas field and Longgang gas field Changxing Formation.

Gas field	Well	Depth/m	Stratum	Main components of natural gas/%						$\delta^{13}C$/‰(VPDB)		Ref.
				CH_4	C_2H_6	C_3H_8	H_2S	CO_2	N_2	CH_4	C_2H_6	
Yuanba	YB1-1	7330−7367.6	P_2ch^2	86.72	0.04	0	6.61	6.25	0.28	−28.9	−25.3	[59]
	YB27	7330.7−7367.6	P_2ch^2	90.71	0.04	0	5.14	3.12	0.83	−28.9	−26.6	
	Y104	6700−6726	P_2ch^2	87.09	0.04	0	7.04	5.23	0.52	−29.1	−25.6	[38]
	Y204	6523−6590	P_2ch^2	91.23	0.04	0.005	2.36	4.32	1.54	−29.4	−26.0	
	Y205	6448−6480	P_2ch^2	89.14	0.05	0	5.33	5.03	0.00	−29.5	−27.5	
	Y27	6262−6319	P_2ch^2	89.03	0.09	0.002	4.08	5.06	1.22	−28.9	−26.6	
	YB1	7081−7150	P_2ch^2	53.25	0.09	0.09	13.33	30.20	3.04	−30.2	−27.6	[37]
	YB11	6797−6917	P_2ch^2	80.55	0.05	0	11.80	0.23	7.37	−27.9	−25.2	
Longgang	LG1	6202−6204	P_2ch^2	92.33	0.07	0	2.50	4.40	0.70	−29.4	−22.7	
	LG2	6112−6132	P_2ch^2	89.03	0.06	0	4.53	6.07	0.31	−28.5	−21.7	
	LG9	6353−6373	P_2ch^2	63.50	0.26	0.04	6.19	30.00	0.01	−31.7	−22.7	
	LG11	6045−6143	P_2ch^2	84.56	0.07	0.01	9.11	6.08	0.17	−27.8	−27.0	
	LG27	4904−4953	P_2ch^2	95.28	0.27	0.01	0	3.90	0.54	−29.4	−26.1	

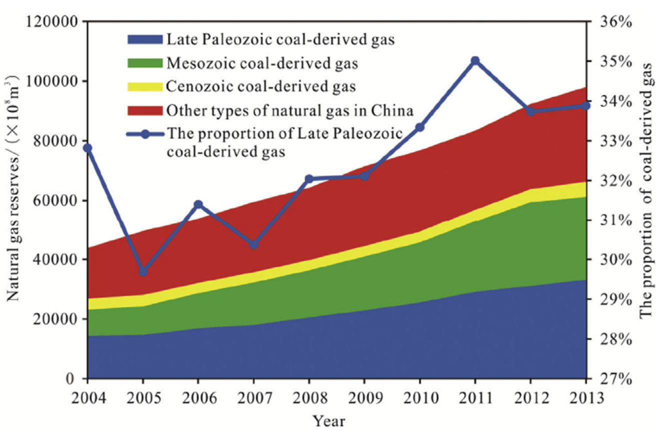

Fig. 7. Reserves of natural gas and coal-derived gas of Late Paleozoic, Mesozoic and Cenozoic from 2004 to 2013 in China.

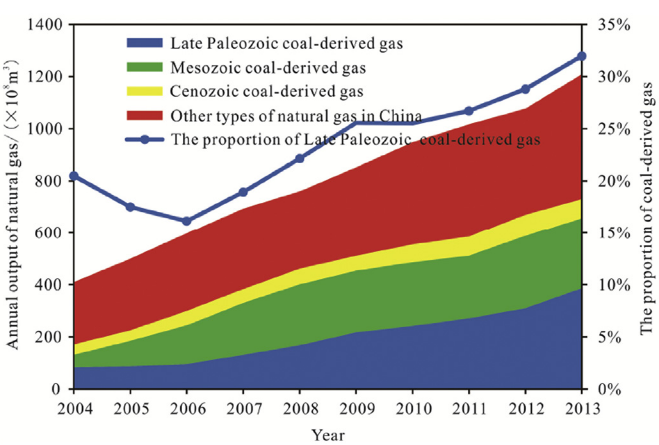

Fig. 8. Annual output of natural gas and coal-derived gas of Late Paleozoic, Mesozoic and Cenozoic from 2004 to 2013 in China.

volcanic rocks, forming the gas to accumulate in Ordovician, Carboniferous, Permian, and the Paleogene System, which are distributed in Ordos Basin, Bohai Bay Basin, Junggar Basin, and Sichuan Basin. A total of 16 gas fields have been found, and 12 of them for large gas fields.

Based on 99 samples of gas component and alkane gas carbon isotopic composition, using $\delta^{13}C_2 > -28.5‰$ and $\delta^{13}C_1$ -$\delta^{13}C_2$ -$\delta^{13}C_3$ identification chart to identify, the gas sources of gas fields above are all coal-derived gas.

Late Paleozoic coal related gas field is of great significance to China's gas industry rapid development: first, it is accounting for one-third of China's natural gas proven total geological reserves and annual production at the end of 2013; second is three (Sulige, Jingbian and Daniudi) of the five key large fields, which support China to be a gas power, with the gas source as coal-derived gas; third is the average reserves of the late Paleozoic coal related gas fields and large gas fields, being 5.3 times and 1.7 times of the national gas fields and large gas fields, indicating that the late Paleozoic coal-related gas field and large gas fields have a greater contribution to the gas industry's continued development.

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Conflict of interest

The authors declare no conflict of interest.

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