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Original research paper

The origin of gas in the Changxing−Feixianguan gas pools in the Longgang gas field in the Sichuan Basin, China☆

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Abstract

In this paper, the origin of natural gas in the formations of the Changxing−Feixianguan within the Longgang gas field was studied in detail using geochemical methods. The gas discovered has a very high dryness coefficient, yet low ethane and other less heavy hydrocarbons content. Apart from a small amount of N_2 and CO_2 gasses it generally contains H_2S. In the field location, the Changxing−Feixianguan formations itself does not have a hydrocarbon generation potential. Nearing the edge of the Kaijiang-Liangping Trough, there developed the Dalong Formation. However, it also has a very low TOC content in the area of the Longgang gas field, and it cannot act as an effective source rock. The geochemistry of natural gas is much different from the gasses generated by the Silurian and Cambrian source rocks. Therefore, it is impossible that the gas in the Longgang gas field is from the Silurian and Cambrian source rocks. Gas reservoirs generally contain bitumen which is considered a product of crude oil cracking. The carbon isotope fractionation between the bitumen and methane is not distinct, and it indicates that the gas is not directly from oil cracking. The carbon of methane and ethane has isotopically less negative value, which is considered to be in a high-overmature coal-formed gas, mainly from the Longtan Formation coal measures. In comparison to the gas from high overmature stage obtained from the Xujiahe coal measure source rock in the Western Sichuan Depression. The methane in the Longgang gas field has abnormal less negative carbon isotopic value. It is due to the superposition of these two factors together: higher evolution of source rocks and mixing of gas degassing from the water. It is not caused by TSR that most researchers believed at present because the methane carbon isotopic values have no relationship with H_2S content.

Keywords: Sichuan Basin; Longgang gas field; Changxing−Feixianguan formations; Natural gas; Gas origin

1. Introduction

The Longgang gas field of the Sichuan Basin is located in the northeast region of the mid-Sichuan area, west of the Kaijiang-Liangping Trough. It's a recently discovered large gas field with two major gas layers, the Changxing Formation (P_3ch) and the Feixianguan Formation (T_1f) reef flat, and is currently the greatest discovery area in the Permian−Triassic reef flat reservoirs in Sichuan. The field consists of a series of independent gas reservoirs mainly distributed along the platform margin (Fig. 1). Its origin, genesis, and gas accumulation have received widespread attention. Considering a number of resource rock sets within this field might develop, the methane carbon isotope value is unusually less negative, as a result, there are many questions concerning the sources of natural gas, natural gas accumulation, and other issues.

Firstly, as regards to the Changxing−Feixianguan formations gas pool source, some hold the view that natural gas comes from the Longtan coal measure, and some other supports the opinion

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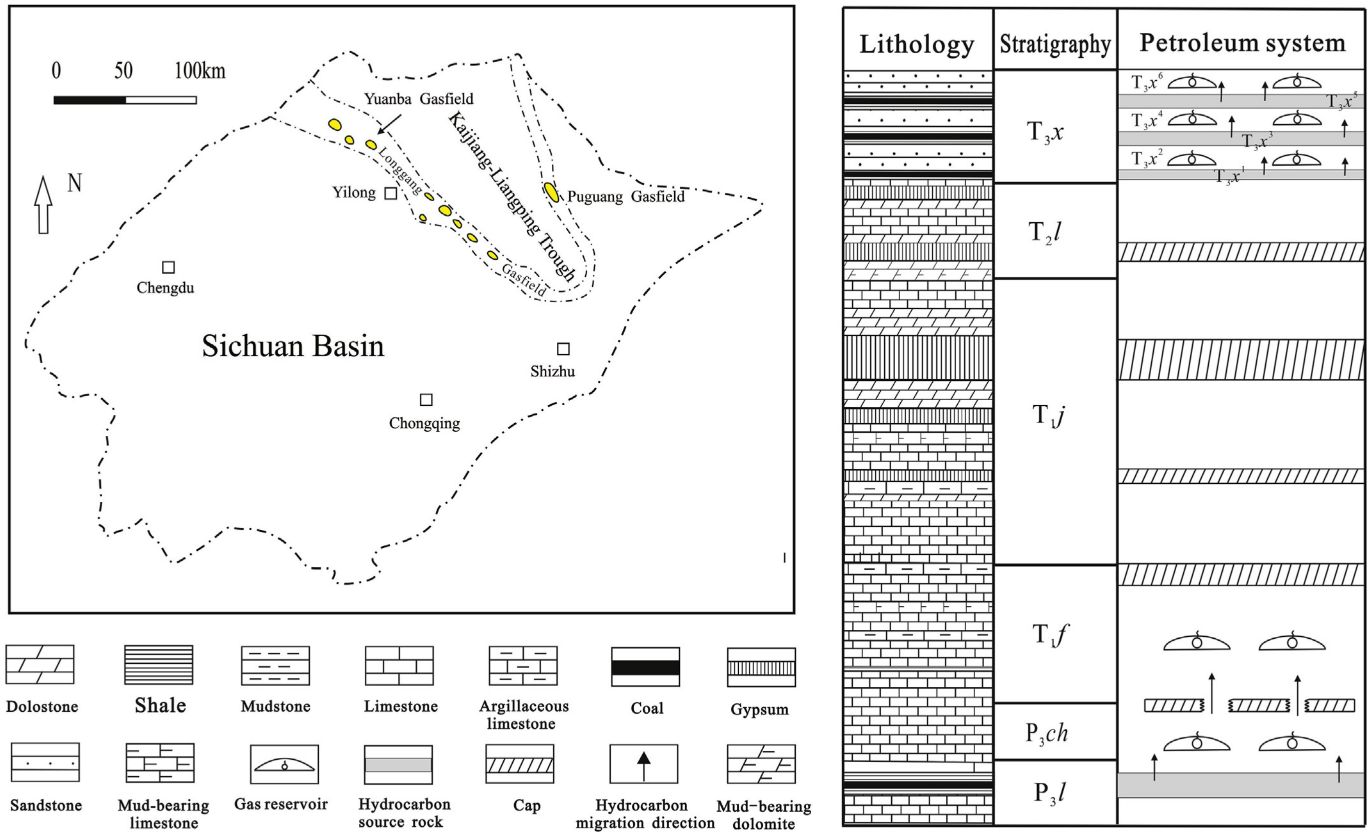

Fig. 1. Location and petroleum systems of Longgang gas field.

that it may come from the marine limestones of the Changxing−Feixianguan formations itself. There are researchers who believe that there hydrocarbon source rocks may exist under the Longgang area such as the lower Silurian Longmaxi Formation and lower Cambrian Qiongzhusi Formation. Is it possible that the natural gas comes from higher mature marine source rock in the lower Paleozoic?

Secondly, Longgang, Changxing, and Feixianguan formations' gas reservoirs generally contain highly evolved asphalt, which is generally recognized as the product of crude cracking. In this case, people tend to believe that natural gas is the oil cracking gas. It still remains an open question.

Thirdly, methane carbon isotope in the Longgang gas field is abnormally less negative, due to the ubiquitous presence of H_2S in the gas reservoir. For this reason, many scholars believe that the presence of H_2S in the Changxing−Feixianguan formations of the Sichuan Basin results from thermochemical sulfate reduction (TSR). It's said that TSR has an influence on the formation of H_2S; it made the methane carbon isotope value less negative [1−5]. It is not hard to imagine that if the TSR effect is the major cause of a higher methane carbon isotope value, along with an ever-increasing effect of TSR, H_2S content will increase even more evidently, and the degree of methane carbon isotope becoming heavier will extend. But then again, through further studies, it's found that H_2S content and methane carbon isotope doesn't relate to each other as mentioned above. The issue awaits other explanations.

In light of the issue above, this research discusses the phenomenon of less negative methane carbon isotope value on the basis of researching the gas source of the Changxing−Feixianguan formations in the Longgang gas field.

2. Geological background

2.1. Formation

The gas reservoirs along reef beaches of the Longgang gas field can be traced back to the Triassic and Permian. From up above to down below, the Triassic formation includes the Upper Triassic Xujiahe Formation (T_3x), Middle Triassic Leikoupo Formation (T_2l), Lower Triassic Jialingjiang Formation (T_1j), and Feixianguan Formation (T_1f). The Xujiahe Formation is mainly composed of coal; it developed multi-layer coal measures hydrocarbon source rock and sandstone interbed [6,7]. The Leikoupo Formation contains mostly gray muddy dolostone, lime dolomite, dolomitic limestone, mixed with light gray gypsum, and thin film shale; this is a kind of high-quality cap rock in the region. The gray micrite interbeds with dolomicrite and interspersed with dolomitic gypsum layer, gypsum layer, and argillaceous dolomite forms the Jialingjiang Formation reservoir. It's also of high-quality cap rock in the region. The rock on top of the Feixianguan Formation is made of mudstone, dolomitic mudstone, gypsum, dolomicrite, micrite, and marl, while the lower-middle part consists of dissolved pore and oolitic limestone with great permeability; these shows to be a regional reservoir rock with prime quality [8−10].

Upper Permian includes Changxing Formation (P_3ch) and Longtan Formation (P_3l). Changxing Formation contains mainly crumbs micrite, reef limestone and dolomite, also being one of the most important reservoirs in the middle of the Sichuan area [11]; Longtan Formation is mostly sea-land transitional-phase coal formation and marine biological limestone, being another important hydrocarbon source rock.

2.2. Structure

The Longgang gas field has experienced major geological movements throughout the history including the Dongwu Movement, Indosinian Movement, Yanshan Movement, and Himalayan Movement [12]. Nevertheless, the Himalayan Movement plays a pivotal role among them all. The Dongwu Movement made the Yangtze paraplatform go through land lifting once more after the Early Permian basin deposition. Since the early stages of the Late Permian, the local fault movement has been recurring on the mentioned paraplatform causing the Kaijiang-Liangping Trough to form in the Changxing period. Up to the end of the Feixianguan Formation, the fault movement has ceased. The fault movement in this phase caused distinct differences between lithofacies paleogeographic environment. The edge zone surrounding Kaijiang-Liangping Trough is a favorable environment for developing Changxing Formation shelf margin reef and the set of Feixianguan Formation oolitic beach and dam [13]. It also lays a foundation for Changxing Formation reefs in Longgang gas field, and the oolite beach reservoir of Feixianguan Formation. Indosinian Movement makes the entire middle Sichuan area transformed from splitting-active into pressure-active. Marine sedimentary ceased, continental sedimentation began [14]. During the Indosinian and Yanshan movements, Longgang gas field has accumulated a great amount of thick sediment; the depth of hydrocarbon source rocks buried underground increases rapidly, reaching its maximum at the end of the Cretaceous. The hydrocarbon source rock evolution reached a post-mature stage; crude oil reservoir went through thorough cracking, left with bitumen and part of all the gas. During the Himalayan Movement, parts of the gas field were lifted to various heights averaging out at 2500 m. Gas and water in the reservoir were redistributed, hence, contributing to the reservoir's final shape.

2.3. Gas reservoir types

The gas reservoir of the Changxing–Feixianguan formations in the Longgang gas field is collectively controlled by reservoirs in reefs and beaches, the inside of which have a strong heterogeneity. In addition to the reservoir development, the interior and the areas around have non-reservoir layers generated. This contributes to evident horizontal segmentation in the gas reservoir, forming a gas reservoir distribution model of "a reef being a reservoir" and "a beach being a reservoir". Among them, the Changxing Formation reefs are mainly about lithologic gas reservoirs, the Feixianguan Formation is given priority to the structure-lithologic composite gas reservoir.

The Early Indosinian Movement made the Yangtze platform rise to land, the sea subsides, and the large inland lake basin began to appear. It's a huge turning point to when the Sichuan Basin changed from marine deposition to inland lake deposition. In the Early Jurassic, the Sichuan Basin went through lake basin sedimentation under stable conditions. In the Middle Jurassic, plain river and shallow lake facies deposited rapidly. This is the main continental basin sedimentation period. Gradually, turbulent rivers and lakes deposition took place in the Late Jurassic. And then the Himalayan movement sediment layer was completely uplifted with all folds. That's when tectonic structure largely finalized [15]. The Himalayan movement in the middle of the Sichuan area is integrally lifted without generating any large fracture system, which is advantageous to the late gas preservation and degassing accumulation of water-soluble gas.

3. Geochemical characteristics of natural gas

The natural gas samples are taken from the wellhead by a liter double valve cylinder, basically covering the vast majority of the current development wells in the gas field.

The natural gas component uses Agilent GC6890N gas chromatograph, using He as the carrier gas, with a double TCD detector to test. Carbon isotope detection adopts MAT252 isotope mass spectrometer. According to the SY/T 5238-2008, the China petroleum and natural gas industry standards of the People's Republic of China, the gas components are separated to single component gas, then oxidizing it into CO_2 by CuO in a high-temperature condition and testing the carbon isotope of CO_2 derived from a single component gas. Using He as the carrier gas, the calibration of CO_2 as the standard gas in the mass spectrometer was used for testing.

3.1. Gas components

The geochemical characteristics of the natural gas of the Changxing Formation and Feixianguan Formation in the Longgang gas field are basically identical (Table 1). The natural gas is mainly alkane gas, and almost all of alkane gasses are methane. There's minimal ethane or other heavy hydrocarbon content. Most samples have ethane content less than 0.10%, with propane and other hydrocarbon gasses being hardly detected, thus, leading to a high gas dryness coefficient (C_1/C_1^+) close to 1.

Among the non-hydrocarbon gasses, N_2 content is relatively low, the CO_2 content is slightly higher, with the former being 0.09%–2.84% content, averaging out at 0.84%, and the latter being 0.79%–16.78%, averaging out at 5.35%. The natural gas generally contains H_2S, field test suggests its content is between 0.04% and 9.09%, with an average amount of 2.79%.

3.2. The carbon isotope of natural gas

Methane and ethane carbon isotope contained from Changxing–Feixianguan formations reef gas reservoirs both are much heavier, with an average of −29.2‰ and −25.0‰, respectively. Depending on their gas categorization criteria [16], ethane carbon isotope is above −28.0‰, which suggests it should be a

Table 1
Molecular and stable carbon isotopic values of natural gasses in the Longgang gas field.

Well no.	Horizon	Depth/m	Gas composition/%									Carbon isotope/(VPDB) ‰		
			He	H_2	N_2	CO_2	H_2S	CH_4	C_2H_6	C_3H_8	C_1/C_1^+	δCH_4	δC_2H_6	δC_{CO2}
Longgang 001-2	P_3ch	6735–6828	0.02	0	2.28	3.76	N.D.	93.88	0.06		0.999	−28.8	−25.4	−9.7
Longgang 001-3	P_3ch	6353.01	0.01	0.01	0.44	5.35	5.36	88.80	0.04		1.000			
Longgang 1	P_3ch	6202–6240	0.02	0.01	0.70	4.41	2.48	92.33	0.07		0.999	−29.4	−24.3	−17.2
Longgang 2	P_3ch	6112–6124	0.01	0	0.31	6.07	4.52	89.03	0.06		0.999	−28.5	−21.7	1.2
Longgang 6	P_3ch	5111–5189.3	0.03	0.14	0.94	8.63	3.34	86.85	0.07		0.999			
Longgang 6	P_3ch	5305–5339	0.03	0.02	0.40	11.19	0.09	85.23	0.04		1.000			
Longgang 8	P_3ch	6713–6731	0.02	0.02	0.25	8.63	7.24	83.80	0.05		0.999	−29.0	−22.1	1.6
Longgang 11	P_3ch	6045–6143	0.01	0	0.17	6.08	9.09	84.56	0.07	0.01	0.999	−27.8	−27.0	2.8
Longgang 26	P_3ch	5774–5796	0.02	0	0.64	4.71	1.67	92.88	0.08		0.999	−29.4	−23.0	−0.5
Longgang 26	P_3ch	4904–4953	0.02	0	0.74	5.62	4.15	89.41	0.06		0.999			
Longgang 28	P_3ch	5996.7	0.02	0	0.58	2.48	0.70	96.15	0.07		0.999	−29.3	−24.7	
Longgang 29	P_3ch	6020–6244	0.01	0.13	1.46	4.98	4.78	88.52	0.10	0.01	0.999	−29.3	−25.2	−1.5
Longgang 39	P_3ch	6459–6490										−30.3	−23.8	0.4
Longgang 62	P_3ch	6351.6–6480	0.02	0	0.22	4.23	5.61	89.86	0.03	0.03	0.999			
Longgang 63	P_3ch	6988.1–7045	0.02	0.1	0.52	16.78	2.56	79.87	0.03	0.03	0.999			
Longgang 001-1	T_1f	6015.5	0.03	0	0.92	2.40	1.21	95.38	0.07		0.999			
Longgang 001-3	T_1f	6104.41	0.01	0	0.68	3.74	2.68	92.82	0.07		0.999	−29.8	−28.3	−0.9
Longgang 001-3	T_1f	6141.77	0.02	0	1.21	2.32	1.44	94.94	0.07		0.999	−29.4	−28.3	−3.4
Longgang 001-6	T_1f	6086.55	0.04	0	0.76	2.31	1.24	95.58	0.07		0.999	−28.6	−24.7	−8.0
Longgang 001-6	T_1f	6069.11	0.03	0	0.64	2.95	1.16	95.15	0.07		0.999	−28.3	−25.7	−5.1
Longgang 001-6	T_1f	6094.08	0.04	0	1.15	2.47	1.22	95.05	0.07		0.999	−28.2	−25.1	−3.9
Longgang 001-6	T_1f	6090–6130	0.02	0	1.49	3.42	1.89	93.10	0.07		0.999			
Longgang 001-11	T_1f	5946.7–6088										−29.2	−23.1	−1.0
Longgang 2	T_1f	5953–5990	0.02	0	0.20	4.77	3.06	91.90	0.05		0.999	−28.5	−24.3	1.5
Longgang 3	T_1f	5905–5917	0.03	0.26	1.76	15.84	0.04	81.96	0.11		0.999			
Longgang 3	T_1f	5984–5998										−30.2	−21.0	−5.6
Longgang 6	T_1f	4854–4890	0.02	0.11	0.44	3.34	2.58	93.44	0.06	0.01	0.999			
Longgang 12	T_1f	6046.4	0.01	0	0.49	2.37	N.D.	97.01	0.12		0.999	−30.4	−27.6	
Longgang 12	T_1f	6130.1	0.04	0.21	2.84	1.12	N.D.	95.70	0.09		0.999	−30.5	−27.3	−11.4
Longgang 12	T_1f	6314	0.03	0.15	1.23	0.79	N.D.	97.74	0.07		0.999			
Longgang 26	T_1f	5558.98	0.01	0	0.26	4.27	0.13	95.23	0.10		0.999	−31.1	−29.8	−1.6
Longgang 26	T_1f	4694–4728	0.02	0	0.59	7.09	2.75	89.48	0.06	0.01	0.999	−29.1	−25.8	−1.0
Longgang 27	T_1f	4772–4795										−29.5	−26.0	
Longgang 61	T_1f	6261–6330	0.02	0.01	0.09	1.84	3.01	94.95	0.08		0.999	−27.4	−22.2	1.9
Longgang 62	T_1f	6220–6285	0.01	0.01	1.70	11.77	1.52	84.91	0.06	0.02	0.999			

Note: N.D.: not detected.

coal-derived gas. The gas samples distributing in different areas derive from Jurassic hydrocarbon source rocks, Silurian hydrocarbon, and Cambrian sapropel type hydrocarbon source rocks (Fig. 2). The carbon isotope value of carbon dioxide is more negative; in addition, Well Longgang 1, Well Longgang 001-2, Well Longgang 12, and the rest of the samples are less than − 8‰. According to the index [17], the CO_2 of Well Longgang 1, Longgang Well 001-2, and Well Longgang 12 is organic in origin, and that other drilling wells is inorganic.

4. The origin of natural gas

Since there are many underlying formations in the Longgang gas field, various sets of hydrocarbon source rocks may exist. Therefore, no universal agreement has been agreed upon on the origin of natural gas in the Changxing–Feixianguan formations. The origin of the Longtan Formation is often considered to be hydrocarbon source rocks. Apart from that, whether there are hydrocarbon source rocks in the Changxing–Feixianguan formations themselves have been perplexing the explorer. In addition, since the Longgang gas field is

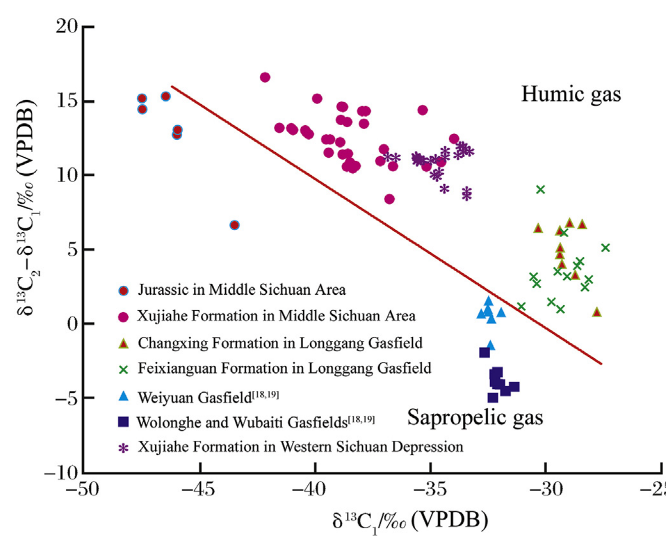

Fig. 2. Genetic types of natural gasses in the Longgang gas field.

located near the hydrocarbon source rocks distribution zone of the Longmaxi Formation in the northeast Sichuan, is it possible that the natural gas comes from the Longmaxi Formation? As the Cambrian strata are widely distributed in Sichuan Basin, is it possible that the natural gas is from the Lower Cambrian Qiongzhusi Formation hydrocarbon source rocks? To determine the gas origin of the Longgang reef, the author studied the organic carbon of relevant formations and made gas - gas comparisons at the same time.

4.1. Absence of prerequisites for hydrocarbon generation of the Changxing–Feixianguan formations

Through the analysis of 477 samples taken from the Feixianguan Formation limestone, it's found that the samples have very low organic carbon content. For most samples, the TOC content is below 0.2%; only 12.17% of the samples have a TOC content of more than 0.2%, and the percentage of samples with a content of more than 0.4% is barely 5.24%. This is significantly below the standard of hydrocarbon source rocks (Fig. 3).

By analyzing the samples taken from the Well Longgang 3, Well Longgang 8, and Well Longgang 9 of the Feixianguan Formation, it is found that they had low organic carbon contents from 0.05% to 1.52%, with 0.17% on average, which is below the standard of hydrocarbon source rocks. The organic carbon analysis of limestones from Well Longgang 11 of the Changxing Formation ends up with an average of only 0.07%, notably far from the standard of hydrocarbon source rocks (Table 2).

In conclusion, in the Longang gas field, neither the Feixianguan Formation nor the Changxing Formation could be considered an effective hydrocarbon source rocks in the Longgang gas field.

4.2. Did natural gas originate from the Cambrian and Silurian hydrocarbon source?

The Cambrian is generally developed in the entire Sichuan Basin, while Silurian was only chiefly developed in the northeastern, eastern, and southern Sichuan. During the development era of the Longgang gas field, hydrocarbon source rocks from both the Qiongzhusi Formation of the Cambrian and the Longmaxi Formation of the Silurian could come into being. Is it possible that the Longgang gas field originated from the hydrocarbon source rocks?

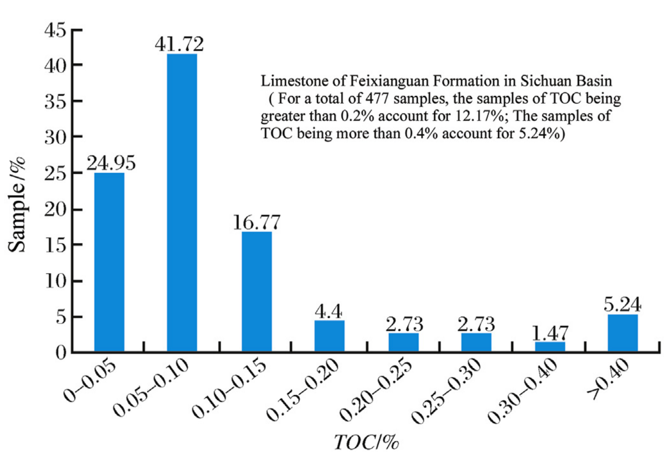

Fig. 3. Histogram of TOC of the Feixianguan Formation's limestone in the Sichuan Basin.

To further analyze this argument, we compared the carbon isotope values of natural gas from the Sinian reservoir layer of the Weiyuan gas field, which originated from the Cambrian hydrocarbon source rocks, with the gas from Carboniferous reservoir layer of East Sichuan, which is derived from Silurian hydrocarbon source rocks, as well as the gas from the Changxing and Feixianguan formations. The result shows apparent differences in carbon isotopic values. The carbon isotopes of methane and ethane from the Changxing and Feixianguan formations are considerably heavier, which is in accordance with the traits of gas generated by humic parent material, while the gas from the Silurian and Cambrian is largely similar to the gas generated by sapropel parent material. This result indicates that the concerning gas' origin is not from hydrocarbon source rocks of either Silurian or Cambrian (Fig. 4).

4.3. The natural gas does not directly come from crude oil cracking

Asphalt is widely developed among the Changxing–Feixianguan formations. It is mainly distributed in pores and dissolved holes and is also visible by naked eyes. This asphalt is undoubtedly the product of crude oil cracking, which is similar to the phenomenon in the northeastern Sichuan [18]. Thus, it is reasonable to presume that the gas is also the product of crude oil cracking. According to the carbon isotope fractionation principle, if crude oil cracks into asphalt and natural gas, the order of carbon isotope would be: $\delta^{13}C_{gas} < \delta^{13}C_{oil} < \delta^{13}C_{asphalt}$. Meanwhile, the carbon isotope fractionation phenomenon of these three components would be quite obvious. After the cracking is completed, the fractionation would be even more obvious. In reality, the data in Tables 1 and 3 show no significant differences between $\delta^{13}C_{asphalt}$ and $\delta^{13}C_1$. The lack of carbon isotope fractionation indicates that the gas does not directly come from crude oil cracking.

4.4. Natural gas originating from hydrocarbon source rocks of the Longtan Formation

There are two typical coal accumulating periods in the Sichuan Basin, during which the Upper Permian series

Table 2
The TOC values of the Upper Permian and Lower Triassic limestone in the Longgang region.

Well no.	Horizon	Depth/m	Lithology	TOC/%
Longgang 11	P_3ch	6060.93	Gray limestone	0.07
Longgang 11	P_3ch	6058.78	Gray limestone	0.08
Longgang 8	T_1f	6522.26	Gray oolitic limestone	0.15
Longgang 8	T_1f	6529.06	Gray oolitic limestone	0.25
Longgang 9	T_1f	6003.89	Gray limestone	0.07
Longgang 9	T_1f	6011.45	gray limestone	0.05
Longgang 9	T_1f	6018.27	Gray limestone	0.08
Longgang 3	T_1f	5939.8	Dolomitic oolitic limestone	0.52

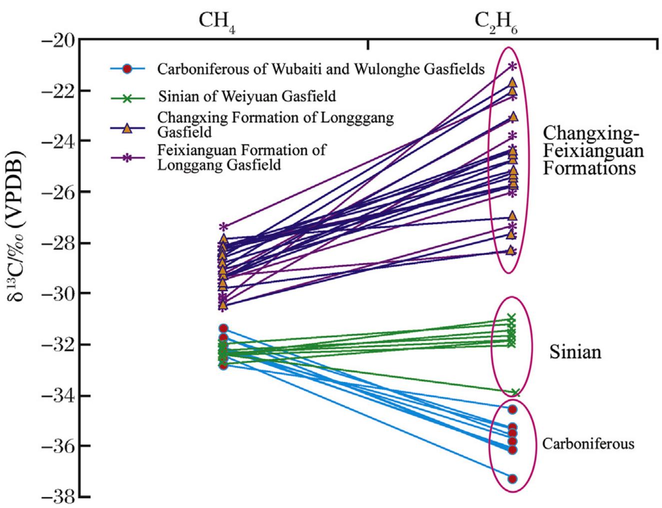

Fig. 4. Comparison on alkane carbon isotope between the Changxing–Feixianguan Formations as well as the Sinian and Carboniferous (Date of Sinian of Weiyuan gas field cited from Ref. [19,20]).

Table 3
Carbon isotope of reservoir bitumen in Changxing–Feixianguan formations of Longgang gas field.

Well no.	Lithology	Horizon	Depth/m	$\delta^{13}C$/‰(VPDB)
Longgang 2	Bituminous dolomite	P_3ch	6119.50	−28.6
Longgang 2	Bituminous dolomite	P_3ch	6121.80	−28.9
Longgang 2	Bituminous dolomite	P_3ch	6122.20	−28.8
Longgang 2	Bituminous dolomite	P_3ch	6130.95	−29.0
Longgang 2	Bituminous dolomite	P_3ch	6131.20	−28.9
Longgang 8	Bituminous dolomite	T_1f	6523.30	−32.2
Longgang 8	Bituminous dolomite	T_1f	6529.40	−32.3
Longgang 68	Bituminous dolomite	T_1f	7060.40	−29.9
Longgang 68	Bituminous dolomite	T_1f	7062.40	−29.6
Longgang 68	Bituminous dolomite	T_1f	7063.50	−29.7
Longgang 82	Bituminous dolomite	P_3ch	4220.20	−28.4
Longgang 82	Bituminous dolomite	P_3ch	4220.70	−29.0
Longgang 82	Bituminous dolomite	P_3ch	4221.50	−28.5
Longgang 82	Bituminous dolomite	P_3ch	4223.80	−28.7
Longgang 82	Bituminous dolomite	P_3ch	4234.50	−28.7
Longgang 82	Bituminous dolomite	P_3ch	4253.62	−28.2
Longgang 001-10	Bituminous dolomite	T_1f	5857.50	−28.4
Longgang 001-10	Bituminous dolomite	T_1f	5864.10	−28.7
Longgang 001-10	Bituminous dolomite	T_1f	5871.30	−28.5

Longtan coal measures and the Upper Triassic series Xujiahe Formation's coal measures were developed correspondingly. These periods are in line with that of the entire Southern China [21]. The exploration practice in the Longgang region proved the existence of Xujiahe Formation's coal measures. The Longtan coal measures haven't been completely proved by drilling since they are buried deeper in ground. However, from the regional coal accumulating environment's point of view, there are the Longtan coal measures present within the Longgang gas field [21]. Moreover, in the Puguang gas field, which is in the east of the Kaijiang-Liangping Trough, the gas of Changxing–Feixianguan formations also in a large part comes from the hydrocarbon source rocks of Longtan Formation's coal measures [1]. In the gas samples of the Longtan Formation from Well PG-2, Puguang gas field, the carbon isotope values of methane and ethane are −30.6‰, −25.2‰ respectively, which are nearly the same as that of the gas in Changxing–Feixianguan formations of Longgang gas field. Therefore, from all these analyzation aspects, it is certain that the gas in Changxing–Feixianguan formations of Longgang gas field comes from the hydrocarbon source rocks of Longtan Formation, and is mainly composed of kerogen pyrolysis gas.

5. Discussions regarding the high methane carbon isotope value

5.1. The phenomenon of the abnormally high methane carbon isotope value

The natural gas of the Xujiahe Formation is coal-derived in the West Sichuan Depression and Middle Sichuan Area (Fig. 2). The natural gas of Xujiahe Formation in West Sichuan Depression is mainly dry gas, while the natural gas of Xujiahe Formation in Middle Sichuan Area is primarily condensate gas. This is because the former is in high overmature stage [22,23], so that it has much more high evolution degree than the latter. The methane carbon isotope of the former is heavier than that of the latter, which is in accordance with their geological background. The natural gas of Changxing–Feixianguan formations in Longgang gas field also belongs to the coal-derived gas. By comparison, the methane carbon isotope of Changxing–Feixianguan formations in Longgang gas field is significantly less negative than that of Xujiahe Formation in the West Sichuan Depression, this phenomenon shows that the former is unusually less negative.

5.2. The relationship between the methane carbon isotope and H_2S content

The natural gas of the Changxing–Feixianguan formations in the studied area generally has H_2S. Many researchers attribute that to the thermochemical sulfate reduction (TSR). Through the enhancement of TSR reaction, the methane carbon isotope became less negative [2–4]. This is further than what we are focusing in this study. There is no significant relationship between the H_2S content and the methane carbon isotope in the Changxing–Feixianguan Formations (Fig. 5), thus, the TSR function is not the main reason for the abnormally less negative methane carbon isotope.

5.3. The reason behind the abnormally high methane carbon isotope value

According to Table 1, gas reservoir buried in the depth of Changxing Formation in the Longgang gas field ranges from 5111 m to 7045 m. The depths of the currently drilled wells still haven't reached the hydrocarbon source rocks of the Longtan Formation. The entire middle Sichuan area was uplifted for 2000–2500 m in the Himalayan period [24,25]. It could be inferred that the buried depth of the Longtan Formation hydrocarbon source rocks should be at least two miles deeper than that is now, which is deep enough to result in the mentioned hydrocarbon source rocks to reach a high over

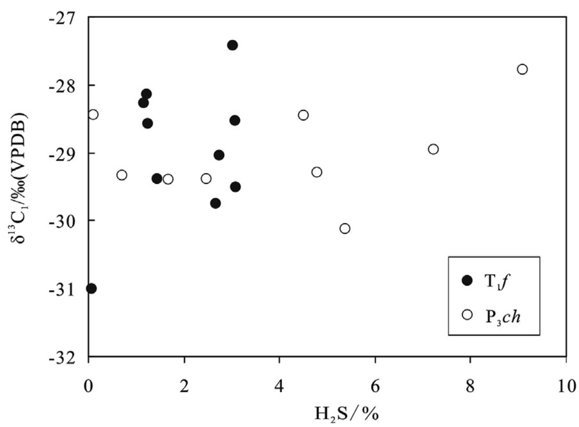

Fig. 5. Relationship of H_2S content and $\delta^{13}C_1$ in the Changxing–Feixianguan Formations of the Longgang gas field.

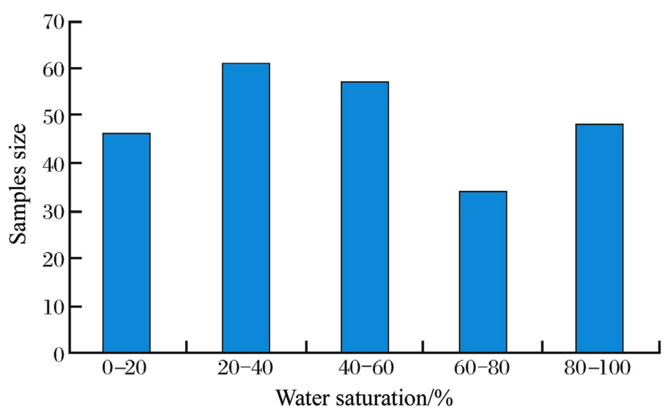

Fig. 6. Water saturation of the Changxing–Feixianguan Formations in the Longgang gas field.

mature stage. Furthermore, the test about reservoir bitumen from the well section 6118.84–6119.89 m of the Longgang Well 2 Changxing Formation was conducted. Results show asphalt reflectance was as high as 2.81%, which means that the development of hydrocarbon source rocks has reached the over mature stage. Therefore, it's possible to believe that the high developing stage is one reason for the abnormally less negative methane carbon isotope.

Another reason might be that the gas reservoir consists partly of dissolved gas from water. The methane carbon isotope of natural gas released from gas field water is heavier than that of free gas in the same formation [26]. During the tectonic movement of the Himalayan Period, the stratum was uplifted and the water soluble gas was released to free gas reservoir due to the pressure relief and degasification, which can be used as a supplement for the gas reservoir.

Studies show that the Changxing–Feixianguan formations of the Longgang gas field has good water soluble gas accumulation conditions.

First of all, the mentioned gas reservoir consists of a large area of water; hence, that water is abundant. The reservoir's water saturation is high. Several samples displayed and proved water saturation to be over 40% (Fig. 6). The rich underground water can dissolve a large amount of natural gas eventually forming a considerable amount of water soluble gas.

Secondly, the gas field's water in the Longgang gas field retains good preservation condition. Only if the gas field water was preserved well, the dissolved gas could exist largely. According to the analysis of gas field water (Table 4), although the geochemical characteristics of the gas field water are very heterogeneous and the degree of mineralization has large differences, the water type of all samples is $CaCl_2$, it indicates that the formation water doesn't be influenced by surface water. Besides, the strong heterogeneity of the gas field water reveals the poor liquidity, which is good for the preservation of water soluble gas.

Finally, the substantial uplift that Longgang gas field has experienced during the later stage is good for the discharge of the water soluble gas. The Himalayan Movement fully folded the sedimentary covers of the Sichuan Basin, as well as connected folds and fractures of different periods and regions together. Thus, the basic pattern of the basin was settled [15]. The tectogenesis uplifted the stratum of the Longgang region another time. The uplift and erosion made the buried depth shallow, and it reduced the temperature. As a result, the gas generation from hydrocarbon source rocks was terminated, and the temperature and pressure of the reservoir reduced. The large amount of dissolved gas released from the gas field water, is partly supplemented for the later period of natural gas accumulation.

Table 4
Main ion contents and salinity of the Changxing–Feixianguan reservoirs' water in the Longgang gas field.

Well no.	Horizon	Depth/m	Ion content/(mg/L)						Salinity/(g/L)	Water type
			K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}		
Longgang001-1	T_1f	6015.5	465	18113	4726	342	31498	6277	61.4	$CaCl_2$
Longgang001-1	T_1f	6069.5	3157	26624	4034	361	50187	4148	88.5	$CaCl_2$
Longgang001-6	T_1f	6090–6130	374	11280	7774	3599	42370	449	67.1	$CaCl_2$
Longgang001-10	T_1f	5862.7	1360	39861	710	181	52667	15030	110.0	$CaCl_2$
Longgang2	T_1f	5953–5990	716	13991	7168	2909	39257	29	64.3	$CaCl_2$
Longgang3	T_1f	5905–5917	361	13622	5817	37	31429	14	52.9	$CaCl_2$
Longgang6	P_3ch	5111–5189	1294	6285	25308	5314	73724	604	116.0	$CaCl_2$
Longgang7	P_3ch	6632.7	1871	19216	1289	80	32575	1896	57.1	$CaCl_2$
Longgang12	T_1f	6130.1	3104	39670	2703		66529	5572	118.0	$CaCl_2$
Longgang13	T_1f	5530–5545	694	12189	7039	1258	34709		56.9	$CaCl_2$
Longgang16	T_1f	5836.1	1945	34836	2320	352	62462	527	106.0	$CaCl_2$

6. Conclusions

Although there are many developed sets of marine hydrocarbon source rocks in the Sichuan Basin, the natural gas from the Changxing−Feixianguan formations in the Longgang gas field originates from the high-over mature coal measure hydrocarbon source rocks of the Longtan Formation. It has no relationship with the hydrocarbon source rocks of the Cambrian and Silurian. Since its TOC contents are too low to generate hydrocarbon effectively, it is concluded that the natural gas is not from the Changxing−Feixianguan formations and the Dalong Formation themselves. Even though the reservoir generally develops asphalt that comes from paleo oil reservoir cracking, the natural gas is mainly from the late-stage kerogen cracking gas rather than oil cracking gas. The abnormally less negative methane carbon isotope from the reservoir is due to the mixing of the high overmature kerogen cracking gas with the natural gas dissolved from water; this is not the result of the TSR reaction. The Longgang gas field has good geological conditions for the accumulation and release of water soluble gas led by the uplift of the tectonic setting at a later stage.

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Conflict of interest

The authors declare no conflict of interest.

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