Geochemical evidence for in situ accumulation of tight gas in the Xujiahe Formation coal measures in the central Sichuan Basin, China

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Abstract: The study of accumulation mechanisms of tight gas has attracted much attention in recent years. One of the focuses is whether natural gas can migrate on a large scale in tight reservoirs. In this work, geochemical parameters of the tight gas reservoirs in the Central Sichuan Basin, China have been studied to characterize the accumulation mechanisms in these fields. Results show that the tight gas accumulation in the Xujiahe Formation in the Central Sichuan is in situ, and natural gas has not experienced large-scale migration. Based on geochemical indicators of natural gas, the gases of Xujiahe Formation in the Central Sichuan Basin originated from the local coal measures of the Xujiahe Formation in horizontal direction with little contribution from the Western Sichuan. In Central Sichuan Basin, there is also no horizontal migration of natural gas in the same formation between adjacent gas fields. Vertically, the Xujiahe Formation is an independent gas generating system and has no relationship with the underlying Mid-Lower Triassic formation and the Jurassic natural gas formation above it. There is a clear distinction in the geochemical characteristics of natural gas between the upper and lower gas reservoirs in the Xujiahe Formation, indicating that there is no obvious vertical migration of natural gas. Geochemical evidence show that there is no large-scale gas migration in the Xujiahe Formation. The tight gas is generated in situ and accumulated in the formation in the Central Sichuan basin.

Key words：Sichuan Basin, Xujiahe Formation, coal measure, tight gas, in situ accumulation, geochemical evidence

1. Introduction

With the development of oil and gas explorational technologies, unconventional oil and gas have become the center of focus. In China, tight oil and gas exploration is currently under fast development as a potential oil and gas resources (Jia et al., 2012). Many tight gas fields have been found in Sichuan Basin, Ordos Basin and Tarim Basin in China, and the proven reserves and annual production of tight gas has been increasing with time (Dai et al., 2012a). Together with the unconventional oil and gas exploration, some issues have arisen. Among them, the accumulation mechanisms of tight gas have drawn huge attention. Previous research on the formation of tight gas mainly focused on the evolution of geological conditions in tight gas reservoirs (Che et., 2007; Bian et al., 2009; Tong et al., 2012; Chen et al., 2014; Wei et al. 2016; Wei et al., 2017), formation characterization (Xie et al., 2009) and reservoir geochemistry (Xiao et al., 2008; Dai et al., 2012a, 2012b; Wu et al., 2017). Few studies have been carried out on tight gas migration mechanisms. It is unclear if the natural gas in the tight gas reservoir is generated and accumulated in situ or migrated over a long distance or migrated from sources close to a reservoir. In view of these research questions, this paper takes the coal derived tight gas reservoir in the Xujiahe Formation in the Central

Sichuan Basin as the study site. The aim is to understand the accumulation processes associated with this tight gas reservoir by characterizing the geochemistry of the natural gas in the reservoir.

The Xujiahe Formation in the Sichuan Basin is mainly composed of a set of coal deposits originated from fluvial, lacustrine and swamp facies (Yang et al., 2009; Xu et al., 2009). It is the first continental strata formation after evolution of the Sichuan basin from marine facies to continental facies. It is commonly developed in the entire Sichuan basin. The formation experienced multiple sedimentary cycles and developed into multiple sets of coal measures interbedded with multiple sets of tight sandstones overlapping each other. Due to the fact that the depositional center of Xujiahe Formation is in the western part of the Sichuan basin, the thickness of coal-bearing source rocks gradually decreases from the west towards the central Sichuan basin (Liu et al., 2005; Chen et al., 2007; Yang et al., 2010), the gas generation intensity of the Xujiahe Formation coal-bearing source rocks is relatively low, less than $20 \times 10^8 m^3 km^{-3}$ in most areas (Fig. 1). This value is the minimum gas-generating intensity to form a reserve of $100 \times 10^8 m^3$ in China (Dai et al. 1997). Based on past exploration experience, such a low gas intensity is unlikely to form a large gas field with a reserve of $1000 \times 10^8 m^3$. Although the gas intensity is low, but so far a number of large-scale gas fields with proven reserves exceeding $1000 \times 10^8 m^3$ have been discovered in the Xujiahe Formation in the Central Sichuan Basin, such as the Xujiahe reservoir in the Anyue gas field, Guang'an gas field, Hechuan gas field, and a series of small and medium gas fields. Some researchers suggested that natural gas in the Xujiahe Formation reservoirs in the Central Sichuan basin mainly comes from the Western Sichuan basin and that the natural gas generated from the thick coal-bearing source rocks in the Xujiahe Formation in the Western Sichuan has laterally migrated long distances to the Central Sichuan Basin. Others proposed that the Xujiahe Formation in the Central Sichuan basin could migrate only short distance because of the strong heterogeneity of the reservoir and the relatively gentle strata (Jiang et al., 2006; Zhao et al., 2011). However there is a lack of geochemical evidence for both hypotheses. There is also a view that the Xujiahe Formation gas reservoir is a "continuous" lithologic gas reservoir formed by evaporative hydrocarbon expulsion of coal-bearing source rocks in a large area (Zou, C., 2009; Yi et al., 2013). It is also suggested that natural gas in the Xujiahe Formation in the Central Sichuan basin is not "large-area contiguous" but dispersed into discrete sheet-type reservoirs (Zhao et al., 2010).

To distinguish between the in-situ and near-field accumulation mechanisms of natural gas in the Xujiahe Formation in the Central Sichuan basin, natural gas migration parameters are used in this study. Results show that natural gas in the Xujiahe Formation originates from coal-bearing source rocks in the Xujiahe Formation itself, with little contribution from other sources. The possibility of natural gas coming from the Xujiahe Formation source rock in the western Sichuan depression has been ruled out. Horizontal and vertical connectivity between the gas reservoirs in different sections in the Xujiahe Formation in the Central Sichuan Basin have also been studied using gas geochemical approaches.

2. Geological Background

2.1 Strata

The exposed strata in the central Sichuan basin is composed of, from top to bottom, Jurassic (J), Triassic (T), Permian (P), Ordovician (O), Cambrian (∈) and Sinian (Z) stratum, missing Carboniferous (C) and Silurian (S) stratum (Figure 1).

The Upper Jurassic (J3) stratum is mainly a red-brownish mudstone, which forms a good regional seal. The Middle Jurassic (J2) is mainly composed of purple-reddish mudstone, gray-greenish mudstone, silty mudstone and sandstone, which is a good reservoir. Black lacustrine shale developed in lower Jurassic (J1) is not only a good source rock but also a good seal for the underlying gas reservoir.

The Triassic stratum, from top to bottom, includes the Xujiahe Formation (T_3x), Leikoupo Formation (T_2l), Jialingjiang Formation (T_1j) and Feixianguan Formation (T_1f). The Xujiahe Formation, from bottom to top, developed from Xu1 member (T_3x^1) to Xu6 member (T_3x^6), with Xu1 (T_3x^1), Xu3 (T_3x^3) and Xu5 (T_3x^5) members dominated by coal and dark mudstone, interbedded with thin layers of sandstone, which form main hydrocarbon source rock. The Xu2 (T_3x^2), Xu4 (T_3x^4) and Xu6 (T_3x^6) members are predominantly white and gray fine-medium sandstone reservoirs (Figure 1). The Leikoupo Formation is dominated by dolomite, intercalated with gypsum and thin gray-black shale, which forms the region's high-quality seal. The dolomite within the Leikoupo Formation is also a good reservoir; The Jialingjiang Formation is limestone interbedded with dolomite and gypsum layer. It developed well as both the reservoir and cap rock. The Feixianguan Formation is mainly composed of oolitic and limestone with dissolved pores, which form high-quality regional reservoir rocks.

The upper Permian stratum is dominated by bioclastic limestone, reef limestone and dolomite. The transitional coal measure and limestone are developed in the middle part of the Permian stratum. The limestone and dolomitic limestone form the lower part of the Permian stratum. The bottom of Permian stratum is composed of thin-layer shale, sandstone and limestone. The Ordovician stratum is dominated by biogenic limestone and oolitic limestone and has been denuded in the upper part of the stratum. The Cambrian stratum is mainly limestone and dolomite, the lower part of the stratum has been developed into thick gray-black shale, which forms high-quality source rock. The Sinian stratum is dominated by dolomite intercalated with thin gray-black shale.

2.2 Structure

According to the tectonic division of the Sichuan Basin, the central Sichuan basin is also termed "the gentle tectonic zone in the middle of Sichuan ". Sedimentary cap rocks in the central Sichuan basin are thin and stressed weakly. The slipping layer has not been developed. It forms a gentle slope structure (Wang et al., 2005). The Central Sichuan basin was uplifted to land by Indosinian movement in early Middle Triassic. Since the late Triassic continental deposition began to develop and formed the Xujiahe Formation, which is a sedimentary assemblage of coal-bearing source rocks interbedded with sandstones.

In the Early Jurassic, lacustrine sediments deposited in the Sichuan Basin under a stable environment, forming the lacustrine source rocks. In The Middle Jurassic, rapid deposition from rivers and shallow lakes forms the main sedimentary period of the continental basin. In the Late Jurassic, deposition from turbulent lake and fluvial sediments lasted until the end of Jurassic. Due to intensive uplift and denudation caused by Himalayan movement, the upper Jurassic and strata above it were missing in most areas. Thickness of the eroded stratum is about 2500m (Chen, et al., 2007). Stratum uplift and denudation contributed to lower formation temperature and pressure, and hindered further hydrocarbon generation by organic matter in the source rocks. The Himalayan movement uplifted the central Sichuan basin as a whole. There were no large fault systems created. This is favorable to the later natural gas preservation.

2.3 Gas Reservoir Types

Gas reservoirs in the Xujiahe Formation in the Central Sichuan basin are widely distributed covering a large area. They are found in $T3x^2$, $T3x^4$ and $T3x^6$ longitudinally. Currently the structural high is in the south part of the basin with north part as a structural low to form a large regional monocline. Tectonic stress of Hechuan, Guang'an, Moxi-Longniansi, Nanchong and Bajiaochang areas are relatively strong. Most of the structures are relatively gentle and the gas reservoirs are dominated by structural-lithologic gas reservoirs (Wang et al., 2005; Xu et al., 2009).

According to statistics of tens of thousands of physical data, reservoir properties of the Xujiahe Formation are poor. Porosity is ranging between 4-8% and permeability distribution is within the range of 0.01-1mD, which suggest that reservoirs can be categorized as low porosity-low permeability and ultra-low porosity and ultra-low permeability reservoirs (Yang et al., 2010; Zhang et al., 2011). Such kind of low porosity and low permeability tight sandstone reservoirs require horizontal fracturing and other stimulation measures to obtain industrial gas flow (Shanley et al., 2004). The gas reservoirs also have high water content and the reserve abundance is 1-3 $\times 10^8 m^{-3}$, which belongs to medium-low abundance high water gas reservoirs (Zhao et al., 2010).

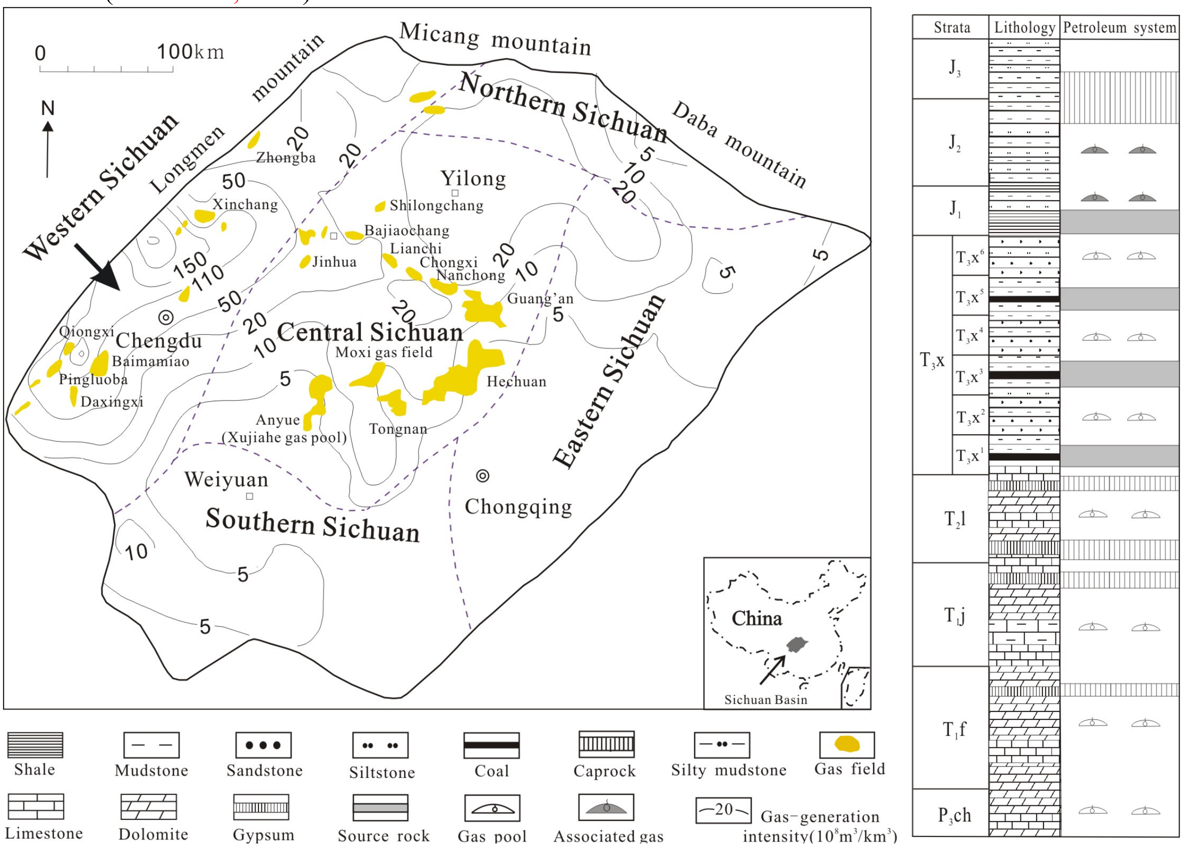

Fig. 1. Map of gas field distribution in the Xujiahe Formation and stratigraphic column in the Central Sichuan basin.

3. Sampling and analytical methods

3.1. *Sample collection*

Natural gas samples were taken from the Middle-Upper Jurassic, Upper Triassic Xujiahe Formation, Middle Triassic Leikoupo Formation, Lower Triassic Jialingjiang Formation in the Central Sichuan Basin, and the Xujiahe Formation reservoirs in the Western Sichuan Basin. To eliminate the interferences of external factors and ensure representativeness of the natural gas in these reservoirs, all samples were collected from wells with long-term normal production without application of de-foaming or any other chemical agents recently.

Gas samples in reservoirs were taken at the wellheads by using steel cylinders. To take such samples, the pressure gauge was dismantled before connecting the steel cylinder with sampling tubing. Prior to taking samples, wellhead natural gas was used to flush the steel cylinder thoroughly for about 3 minutes. The sampling steel cylinder was then filled with natural gas equilibrated to the wellhead pressure.

3.2 *Analytical methods*

Samples were analyzed in the Key laboratory of the Research Institute of Exploration and Development of PetroChina. Natural gas compositions were determined using an Agilent 6890N gas chromatograph (GC) with He and N_2 as the carrier gases. Double thermal conductivity detectors (TCD) and a 30m × 0.25mm × 0.25μm quartz capillary column were used. The inlet temperature was 150 °C, and the TCD temperature was 200 °C. The initial oven temperature was maintained at 40 °C for 7.5 min isothermally, then rose from 40 °C to 90 °C at 15 °C/min, and finally rose from 90 °C to 180 °C at 6 °C/min.

The on-line analysis was conducted for the measurement of carbon isotopic compositions with a MAT 253 gas isotopic mass spectrometer. Natural gas samples were separated to methane, ethane, propane, butane and CO_2 through the chromatography column of a SRI 8610C gas chromatograph. They were then transferred into combustion furnace by carrier gas (He) and oxidized into CO_2 by CuO at 850 °C. All of the converted species were transferred by carrier gas (He) into MS to measure the isotopic compositions. Dual inlet analysis was performed with international measurement standard of NBS-19 CO_2 ($\delta^{13}C_{VPDB}$=1.95±0.04‰, International Atomic Energy Agency, 1995) and the stable carbon isotopic values were reported in the δ notation in per mil (‰) relative to the Peedee belemnite standard (VPDB). Reproducibility and accuracy were estimated to be ±0.2‰ with respect to VPDB standard.

4. Result

Many researchers have carried out studies on the natural gas geochemistry in the Xujiahe Formation in the Sichuan basin. They have reached similar conclusions that the gas in the formation is mainly coal-type gas (Xiao et al., 2008; Dai et al., 2012a, 2012b; Wu et al., 2017). Here we are not repeating similar research in this paper, but focusing on some geochemical features that were not discussed in previous work.

Table 1

Molecular composition of natural gases in Xujiahe Formation in the Central Sichuan Basin

Gas field	Well	Strata	Main molecular composition (%)											Calculated parameters		
			N_2	CO_2	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5	C_{6+}	C_{1+}	iC_4/nC_4	iC_5/nC_5	C_1/C_{1+}
Hechuan	Hechuan 1	T_3x^2	1.42	0.12	88.84	6.39	1.58	0.39	0.27	0.16	0.07	0.33	98.02	1.45	2.43	0.906
	Hechuan 101	T_3x^2	0.08	0.19	93.29	4.54	0.64	0.12	0.07	0.03	0.01	0.11	98.82	1.77	2.90	0.944
	Hechuan 102	T_3x^2	0.00	0.23	87.05	5.65	1.43	0.36	0.24	0.15	0.06	1.21	96.15	1.54	2.30	0.905
	Hechuan 105	T_3x^2	0.16	0.22	91.41	5.71	1.01	0.21	0.15	0.07	0.03	0.22	98.81	1.39	2.18	0.925
	Hechuan 106	T_3x^2	0.00	0.16	90.15	5.95	1.48	0.38	0.29	0.18	0.08	0.57	99.06	1.29	2.33	0.910
	Hechuan 110	T_3x^2	0.00	0.03	92.83	4.43	0.76	0.18	0.11	0.07	0.03	0.24	98.65	1.69	2.44	0.941
	Hechuan 112	T_3x^2	0.00	0.19	90.47	6.05	1.42	0.36	0.23	0.13	0.05	0.24	98.96	1.56	2.54	0.914
	Hechuan 117	T_3x^2	0.04	0.23	90.43	5.88	1.41	0.40	0.27	0.14	0.05	0.16	98.74	1.49	2.77	0.916
	Hechuan 118	T_3x^2	0.01	0.1	89.41	6.28	1.57	0.42	0.31	0.19	0.08	0.83	99.10	1.37	2.26	0.902
	Hechuan 119	T_3x^2	0.10	0.12	89.93	5.64	1.23	0.37	0.26	0.20	0.09	0.61	98.33	1.46	2.36	0.915
	Hechuan 124	T_3x^2	0.02	0.42	89.78	5.83	1.46	0.43	0.33	0.25	0.11	0.57	98.75	1.31	2.33	0.909
	Hechuan 4	T_3x^2	0.81	0.06	88.88	6.21	1.71	0.67	0.49	0.41	0.17	0.00	98.54	1.37	2.41	0.902
	Hechuan 5	T_3x^2	0.15	0.09	92.96	5.08	0.96	0.26	0.17	0.09	0.03	0.00	99.55	1.53	3.00	0.934
	Hechuan 6	T_3x^2	0.98	0.27	88.23	6.97	1.84	0.45	0.33	0.18	0.08	0.47	98.55	1.34	2.33	0.895
	Hechuan 7	T_3x^2	0.69	0.39	90.82	5.88	1.35	0.33	0.24	0.12	0.05	0.00	98.79	1.38	2.40	0.919
Tongnan	Tongnan 001-1	T_3x^2	0.02	0.31	88.07	7.22	2.05	0.46	0.40	0.20	0.09	0.41	98.90	1.14	2.25	0.891
	Tongnan 001-5	T_3x^2	0.05	0.25	87.02	7.28	2.25	0.58	0.51	0.28	0.13	0.41	98.47	1.14	2.10	0.884
	Tongnan 102	T_3x^2	1.15	0.53	85.77	8.27	2.60	0.58	0.51	0.22	0.10	0.20	98.25	1.12	2.13	0.873
	Tongnan 107	T_3x^2	0.06	0.29	87.94	7.49	2.02	0.44	0.37	0.17	0.08	0.29	98.80	1.19	2.25	0.890
	Tongnan 108	T_3x^2	0.00	0.3	84.73	8.43	2.80	0.58	0.60	0.27	0.15	0.50	98.05	0.97	1.82	0.864
	Tongnan 110	T_3x^2	0.00	0.43	86.82	7.35	2.05	0.49	0.45	0.30	0.16	1.10	98.71	1.09	1.89	0.880
	Tongnan 113	T_3x^2	0.10	0.63	82.29	8.26	2.89	0.76	0.69	0.36	0.17	0.41	95.82	1.11	2.06	0.859
	Tongnan 114	T_3x^2	0.00	0.37	83.98	7.98	2.98	0.61	0.70	0.32	0.21	0.76	97.53	0.88	1.54	0.861
	Tongnan 3	T_3x^2	2.00	0.32	78.91	8.76	3.78	1.25	1.43	1.13	0.64	1.63	97.52	0.88	1.76	0.809
	Tongnan 6	T_3x^2	0.05	0.37	88.56	6.62	1.78	0.39	0.35	0.18	0.09	0.56	98.52	1.14	2.01	0.899
Nanchong	Xi 20	T_3x^2	0.88	0.35	89.82	5.72	2.07	0.40	0.43	0.12	0.06	0.07	98.70	0.93	1.95	0.910
	Xi 35-1	T_3x^2	1.48	0.17	86.77	6.08	1.88	0.58	0.47	0.35	0.18	2.01	98.32	1.25	2.01	0.883
	Xi 13-1	T_3x^4	1.50	1.69	85.00	6.64	2.74	0.52	0.65	0.26	0.17	0.69	96.66	0.79	1.56	0.879
	Xi 32	T_3x^4	3.99	0.21	82.72	7.20	3.30	0.63	0.84	0.31	0.21	0.54	95.76	0.76	1.48	0.864
	Xi 48	T_3x^4	1.32	0.87	88.18	6.07	2.09	0.42	0.47	0.18	0.11	0.20	97.73	0.89	1.62	0.902
	Xi 56	T_3x^4	0.15	0.66	88.00	6.22	2.32	0.48	0.53	0.20	0.12	0.34	98.20	0.89	1.66	0.896
	Xi 57	T_3x^4	0.94	0.1	83.78	8.55	3.60	0.75	1.05	0.41	0.23		97.97	0.72	1.58	0.855
	Xi 58	T_3x^4	1.42	0.82	85.62	7.08	2.84	0.52	0.60	0.19	0.13	0.63	97.61	0.86	1.54	0.877
	Xi 62	T_3x^4	2.14	0.38	82.33	7.58	3.57	0.74	1.12	0.49	0.38	1.25	97.45	0.66	1.31	0.845
	Xi 64	T_3x^4	0.76	0.28	88.92	6.03	2.16	0.44	0.48	0.20	0.13	0.53	98.88	0.91	1.58	0.899
	Xi 65	T_3x^4	1.65	0.24	87.71	6.22	2.32	0.44	0.54	0.21	0.14	0.50	98.08	0.81	1.54	0.894

	Xi 69	T_3x^4	0.02	0.74	89.62	5.27	1.89	0.41	0.46	0.18	0.12	0.36	98.31	0.88	1.59	0.912
	Xi 71	T_3x^4	0.16	0.73	88.66	5.99	2.00	0.42	0.47	0.18	0.12	0.45	98.29	0.90	1.59	0.902
	Xi 72	T_3x^4	0.20	0.26	87.31	6.68	2.83	0.57	0.72	0.30	0.19	0.90	99.50	0.79	1.56	0.877
	Xi 73X	T_3x^4	0.88	0.70	79.01	6.24	3.49	1.43	2.26	1.86	1.29	2.83	98.40	0.63	1.44	0.803
Guang'an	Guang'an 003-2	T_3x^4	0.00	0.31	93.97	3.71	0.63	0.13	0.08	0.04	0.01	0.13	98.70	1.61	2.50	0.952
	Guang'an 106	T_3x^4	0.03	0.34	93.25	4.32	0.75	0.14	0.10	0.04	0.02	0.16	98.78	1.50	2.32	0.944
	Guang'an 112	T_3x^4	0.92	0.41	92.71	4.52	0.86	0.15	0.12	0.05	0.02	0.19	98.62	1.26	2.38	0.940
	Guang'an 113	T_3x^4	0.90	0.36	93.51	4.01	0.70	0.14	0.10	0.05	0.02	0.14	98.65	1.44	2.65	0.948
	Guang'an 114	T_3x^4	0.35	0.27	94.72	3.84	0.55	0.08	0.06	0.02	0.01	0.07	99.35	1.33	2.00	0.953
	Guang'an 116	T_3x^4	0.83	0.20	93.07	4.60	0.77	0.16	0.10	0.05	0.02	0.16	98.93	1.64	2.72	0.941
	Guang'an 121	T_3x^4	1.17	0.29	92.49	4.67	0.83	0.18	0.12	0.06	0.03	0.08	98.45	1.45	2.32	0.939
	Guang'an 122	T_3x^4	1.42	0.27	92.21	4.59	0.76	0.19	0.11	0.06	0.02	0.14	98.07	1.76	2.77	0.940
	Guang'an 123	T_3x^4	1.05	0.37	91.85	5.11	0.95	0.22	0.17	0.09	0.03	0.07	98.49	1.26	2.78	0.933
	Guang'an 125	T_3x^4	1.37	0.24	92.11	4.73	0.90	0.21	0.13	0.07	0.02	0.09	98.26	1.63	2.96	0.937
	Guang'an 126	T_3x^4	0.75	0.33	93.32	4.43	0.75	0.15	0.10	0.05	0.02	0.09	98.90	1.49	2.42	0.944
	Guang'an 127	T_3x^4	1.29	0.33	92.21	4.76	0.82	0.17	0.10	0.04	0.01	0.05	98.16	1.63	3.33	0.939
	Guang'an 128	T_3x^4	0.14	0.37	93.01	4.38	0.76	0.15	0.10	0.05	0.02	0.16	98.63	1.51	2.30	0.943
	Guang'an 130	T_3x^4	1.09	0.26	92.37	4.94	0.96	0.16	0.11	0.03	0.01	0.05	98.62	1.47	2.70	0.937
	Guang'an 131	T_3x^4	0.15	0.24	93.16	4.39	0.74	0.14	0.10	0.04	0.01	0.08	98.66	1.48	2.69	0.944
	Guang'an 133	T_3x^4	0.92	0.92	92.30	4.20	0.68	0.13	0.09	0.05	0.02	0.50	97.98	1.44	2.08	0.942
	Guang'an 134	T_3x^4	0.19	0.07	92.99	4.45	0.68	0.13	0.08	0.03	0.01	0.07	98.43	1.68	2.55	0.945
	Guang'an 136	T_3x^4	0.89	0.28	92.15	4.94	0.94	0.22	0.14	0.07	0.03	0.19	98.68	1.56	2.39	0.934
	Guang'an 142	T_3x^4	0.14	0.33	92.33	4.69	0.90	0.21	0.14	0.08	0.04	0.30	98.69	1.56	2.37	0.936
	Guang'an 143	T_3x^4	0.20	0.29	93.10	3.91	0.62	0.11	0.07	0.03	0.01	0.19	98.04	1.61	2.58	0.950
	Guang'an 144	T_3x^4	0.03	0.30	93.35	4.27	0.70	0.15	0.09	0.04	0.02	0.13	98.74	1.68	2.56	0.945
	Guang'an 145	T_3x^4	0.15	1.60	94.06	2.32	0.23	0.04	0.03	0.01	0.01	0.09	96.79	1.48	2.00	0.972
	Guang'an 16	T_3x^4	0.64	0.41	92.32	4.94	1.05	0.24	0.18	0.07	0.03	0.07	98.89	1.35	2.67	0.934
	Guang'an 17	T_3x^4	0.61	0.46	93.10	4.50	0.88	0.19	0.13	0.06	0.02	0.05	98.92	1.42	2.62	0.941
	Guang'an 20	T_3x^4	0.22	0.27	91.89	4.68	0.97	0.23	0.17	0.11	0.05	0.51	98.59	1.35	2.19	0.932
	Guang'an 3	T_3x^4	1.99	0.35	93.73	3.31	0.42	0.07	0.04	0.02	0.01	0.00	97.60	1.73	2.83	0.960
	Guang'an 002-21	T_3x^6	0.84	0.63	89.46	6.26	1.68	0.33	0.35	0.13	0.07	0.17	98.45	0.96	1.83	0.909
	Guang'an 002-X77	T_3x^6	0.01	0.44	89.37	5.97	1.72	0.35	0.36	0.16	0.09	0.43	98.44	0.96	1.72	0.908
	Guang'an 103	T_3x^6	0.72	0.64	87.40	7.59	2.10	0.40	0.37	0.14	0.07	0.15	98.22	1.07	2.03	0.890
	Guang'an 104	T_3x^6	0.83	0.63	88.85	6.56	1.77	0.35	0.35	0.15	0.07	0.36	98.45	1.00	2.03	0.902
	Guang'an 105	T_3x^6	0.92	0.54	89.20	6.10	1.81	0.39	0.40	0.16	0.08	0.27	98.40	0.96	2.11	0.907
	Guang'an 109	T_3x^6	0.71	0.57	89.16	6.13	1.72	0.34	0.34	0.14	0.07	0.29	98.19	1.01	2.09	0.908
	Guang'an 110	T_3x^6	0.81	0.39	89.81	6.08	1.65	0.33	0.32	0.13	0.07	0.33	98.71	1.02	1.97	0.910
	Guang'an 111	T_3x^6	0.06	0.36	89.29	6.39	1.79	0.35	0.36	0.15	0.09	0.29	98.71	0.97	1.61	0.905
	Guang'an 112	T_3x^6	1.61	0.33	89.66	5.92	1.39	0.24	0.26	0.11	0.06	0.18	97.82	0.90	1.98	0.917
	Guang'an 114	T_3x^6	2.30	0.35	90.61	4.99	0.98	0.143	0.149	0.054	0.022	0.091	97.04	0.96	2.45	0.934
	Guang'an 115	T_3x^6	2.23	0.19	88.05	6.58	1.74	0.36	0.35	0.13	0.07	0.23	97.51	1.02	1.94	0.903
	Guang'an 118	T_3x^6	1.53	0.38	90.33	5.84	1.23	0.17	0.19	0.07	0.03	0.16	98.01	0.87	2.41	0.922
	Guang'an 122	T_3x^6	0.71	0.31	90.14	6.14	1.53	0.34	0.30	0.13	0.07	0.23	98.88	1.11	1.89	0.912
	Guang'an 130	T_3x^6	0.00	0.76	86.22	6.00	1.75	0.37	0.36	0.17	0.09	0.24	95.20	1.03	2.01	0.906
	Guang'an 133	T_3x^6	0.13	0.45	86.21	7.15	2.70	0.71	0.76	0.38	0.20	0.65	98.76	0.93	1.87	0.873
	Guang'an 15	T_3x^6	1.48	0.05	86.47	7.29	2.81	0.55	0.61	0.20	0.15	0.35	98.43	0.90	1.33	0.878
	Guang'an 2	T_3x^6	0.15	0.19	89.03	6.65	1.93	0.39	0.40	0.16	0.09	0.34	98.99	0.96	1.68	0.899
	Guang'an 3	T_3x^6	0.97	0.20	90.92	4.20	1.74	0.26	0.53	0.18	0.21	0.70	98.74	0.49	0.86	0.921
	Guang'an 7	T_3x^6	0.25	0.63	88.30	7.32	2.10	0.39	0.40	0.17	0.08	0.33	99.10	0.96	2.04	0.891

4.1 Characteristics of natural gas composition in Xujiahe Formation in the Central Sichuan basin

The natural gas from Xujiahe Formation in the central Sichuan basin is dominantly composed of hydrocarbon gases, ranging between 95.2% and 99.5% with an average of 98.3%. There is also minor amount of non-hydrocarbon gases such as N_2 and CO_2, with the average composition of 0.70% and 0.39%, respectively. Among the hydrocarbon gases, heavy hydrocarbon gases such as ethane have high concentrations, and the dryness coefficient of natural gas (C_1 / C_{1+}) is between 0.803 and 0.972, with an average of 0.910. If the dryness coefficient of 0.95 is used as the boundary between dry gas and wet gas, the natural gas from Xujiahe Formation in the Central Sichuan basin is mainly wet gas (Table 1). iC_4/nC_4 and iC_5/nC_5 ratios are also significantly different within different sections of the Xujiahe Formation. In general, the lower the section, the higher the ratios. In T_3x^6, T_3x^4 and T_3x^2, iC_4/nC_4 are 0.95, 1.28 and 1.29 respectively, and the ratios of iC_5/nC_5 are 1.87, 2.20 and 2.25, respectively. Different gas fields also have different ratios. For example, in the T_3x^2 gas reservoir, the value of iC_4/nC_4 reaches the highest in Hechuan gas field with an average of 1.46. However, the ratio drops down to the lowest value of 1.07 in Tongnan gas field.

4.2 The carbon isotopes in natural gases from the Xujiahe Formation in the central Sichuan basin is relatively more negative.

Carbon isotopes in alkane gases derived from coal (humic kerogen) is significantly less negative than the carbon isotopes in alkane gases derived from oil (sapropel kerogen), even they are generated from source rocks with similar maturity. Although alkane gases from the Xujiahe Formation in the Sichuan Basin belong to heavy carbon isotope series, the carbon isotope values in different regions are significantly different from each other. The carbon isotopes of alkane gases in the central Sichuan basin are relatively lighter than those in the alkane gases in the western Sichuan (Table 2, Figure 2). The carbon isotope of methane is remarkably different in gases from the central and western Sichuan basin. In gases from the central Sichuan basin, $\delta^{13}C_1$ ranges from -44.1 ‰ to -37.1 ‰ with an average of -40.1 ‰. While in the gases from the western Sichuan basin, $\delta^{13}C_1$ is between -35.5 ‰ and -30 ‰ with an average of -32.2 ‰. Difference of maturities between the Xujiahe formation in the central Sichuan basin and western Sichuan basin can explain the difference between methane carbon isotopic values in these two areas. The sedimentary center of Xujiahe Formation is located in the western Sichuan basin, which has a higher maturity level than that in the central Sichuan basin. This is consistent with the geological background. In the central and western Sichuan basin, there is a small difference in the carbon isotopes of ethane with the $\delta^{13}C_2$ in the central part of Sichuan basin slightly lighter than that in the western Sichuan basin. In the central Sichuan basin, $\delta^{13}C_2$ ranges between -28.3‰ and -25.9 ‰ with an average of -27.5‰, and in the western Sichuan basin, $\delta^{13}C_2$ is between -28.1‰ and -21.7‰ with an average of -24.4‰. Although the carbon isotopes of methane are greatly affected by the maturity of source rocks, carbon isotopes in ethane and other heavy hydrocarbon have less variation with slightly heavier isotopes with the increase of maturity. Due to this fact, carbon isotopes of ethane have been used as the most important indicator to identify natural gas genetic types.

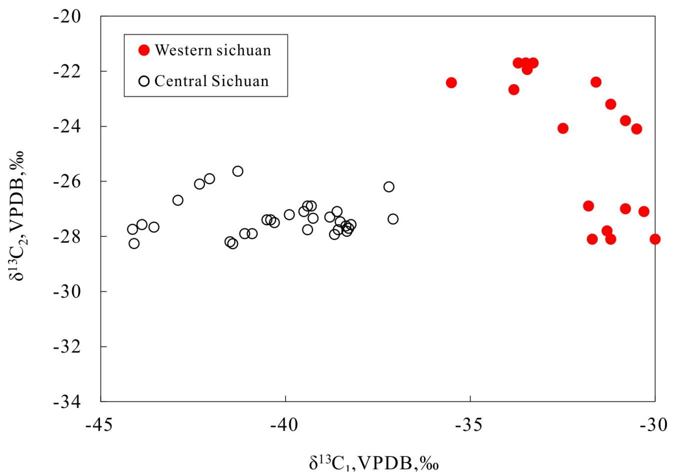

Fig. 2. $\delta^{13}C_1$ vs. $\delta^{13}C_2$ in natural gases from Xujiahe Formation in the Sichuan Basin

Table 2

Abundance and stable carbon isotopic values in natural gases from the Western and Central Sichuan Basin

Gas field	Well	Strata	Main molecular composition (%)									$\delta^{13}C$,VPDB (‰)				References
			N_2	CO_2	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5	C_1	C_2	C_3	C_4	
Anyue	Yue101-11	T_3x^2	0.63	0.76	88.47	7.31	1.80	0.34	0.28	0.20	0.06	-42.9	-26.7	-23.2	-24.1	This paper
	Yue 103	T_3x^2	0.47	0.33	89.15	7.11	1.80	0.45	0.38	0.17	0.04	-42.1	-25.9	-23.0	-23.6	
	Yue 104	T_3x^2	0.13	3.05	85.24	8.25	2.46	0.39	0.33	0.10	0.03	-43.6	-27.7	-24.7	-25.5	
	Yue 114	T_3x^2	0.57	0.00	87.79	7.82	2.54	0.48	0.47	0.19	0.00	-44.1	-28.3	-25.1	-26.8	
	Yue 118	T_3x^2	0.61	0.29	87.89	7.85	2.31	0.38	0.37	0.12	0.03	-43.9	-27.6	-24.7	-25.6	
	Yue 137	T_3x^2	0.59	2.36	85.22	8.24	2.52	0.42	0.41	0.12	0.00	-44.1	-27.7	-24.6	-25.7	
Tongnan	Tongnan 101	T_3x^2	0.93	0.16	87.27	7.26	2.74	0.53	0.53	0.23	0.11	-41.5	-28.2	-25	-26.1	Qin et al.,2018
	Yue 111	T_3x^2	0.72	0.17	87.95	7.12	2.48	0.53	0.48	0.23	0.10	-41.1	-27.9	-24.7	-25.6	
	Yue 104	T_3x^2	0.70	0.16	87.88	7.14	2.52	0.56	0.50	0.22	0.10	-40.9	-27.9	-24.6	-25.7	
	Yue 001-2	T_3x^2	0.65	0.19	88.74	6.78	2.12	0.51	0.43	0.23	0.10	-40.5	-27.4	-24.4	-25.6	
	Yue 105	T_3x^2	0.60	0.14	89.57	6.49	1.85	0.43	0.35	0.19	0.08	-40.3	-27.5	-24.5	-25.0	
Hechuan	Hechuan 124	T_3x^2	0.78	0.15	89.19	6.57	1.68	0.44	0.33	0.21	0.09	-40.4	-27.4	-24.5	-25.3	
	Hechuan 106	T_3x^2	0.53	0.36	89.27	6.75	1.73	0.40	0.31	0.17	0.07	-39.4	-26.9	-24.1	-24.6	
	Hechuan 001-30-X1	T_3x^2	0.87	0.22	90.31	6.07	1.36	0.36	0.26	0.16	0.06	-39.5	-27.1	-24.3	-24.8	
	Hechuan 108	T_3x^2	0.77	0.43	89.80	6.42	1.43	0.34	0.27	0.16	0.07	-38.6	-27.1	-25.2	-26.3	
	Hechuan 125	T_3x^2	0.69	0.12	92.83	4.82	0.82	0.23	0.15	0.11	0.04	-37.2	-26.2	-24.5	-26.3	
	Hechuan 001-18-X2	T_3x^2	0.68	0.15	89.92	6.67	1.57	0.29	0.25	0.12	0.05	-38.8	-27.3	-24.6		
	Hechuan 001-2	T_3x^2	0.78	0.18	89.53	6.71	1.68	0.39	0.28	0.15	0.06	-39.3	-26.9	-23.9	-24.0	
Nanchong	Xi 20	T_3x^4	0.64	0.36	88.68	6.07	2.41	0.48	0.52	0.21	0.12	-41.4	-28.3	-25.3	-24.4	
	Xi 51	T_3x^4	0.63	0.23	87.71	5.85	1.92	0.38	0.45	0.29	0.21	-39.9	-27.2	-24.5	-24.0	
Guang'an	Guang'an 002-11-H2	T_3x^6	1.19	0.35	89.31	6.15	1.85	0.34	0.33	0.13	0.07	-38.3	-27.7	-26.3	-25.1	
	Guang'an 002-23	T_3x^6	0.40	0.37	89.88	6.32	1.88	0.34	0.33	0.13	0.07	-38.5	-27.5	-26.1	-25.3	
	Guang'an 002-40	T_3x^6	0.55	0.30	89.42	6.40	1.98	0.38	0.38	0.16	0.09	-38.7	-27.9	-26.4	-25.8	
	Guang'an 002-X37	T_3x^6	0.82	0.59	89.01	6.33	2.01	0.38	0.38	0.15	0.08	-38.3	-27.8	-26.0	-25.4	
	Guang'an 002-X38	T_3x^6	0.53	0.34	89.18	6.57	2.07	0.39	0.38	0.15	0.08	-39.4	-27.8	-26.0	-25.0	
	Guang'an 002-X70	T_3x^6	0.61	0.39	88.76	6.63	2.23	0.42	0.41	0.16	0.09	-38.6	-27.8	-26.3	-25.4	
	Guang'an 002-X72	T_3x^6	0.50	0.49	88.94	6.30	1.91	0.37	0.37	0.17	0.10	-38.2	-27.6	-26.3	-25.4	
	Guang'an 51	T_3x^6	0.70	0.59	89.58	6.22	1.80	0.33	0.31	0.13	0.07	-38.4	-27.6	-26.0	-25.3	
	Guang'an 1	T_3x^6	0.04	0.13	90.14	6.66	1.87	0.36	0.33	0.14	0.07	-39.3	-27.3	-25.1	-23.9	Li et al, 2007
	Guang'an 11	T_3x^6	0.95	0.16	95.85	2.03	0.44	0.10	0.08	0.04	0.02	-37.1	-27.4	-22.7	-23.7	Li et al, 2007
Xinchang	X 2	T_3x^2	0.00	0.00	97.37	0.91	0.08	0.01	0.01	0.01	0.00	-31.3	-27.8	-28.0		Leng et al，2011
	X 3	T_3x^2	0.00	0.00	97.31	0.96	0.09	0.01	0.01	0.00	0.00	-31.2	-28.1	-25.1	-23.8	
	X 851	T_3x^2	0.00	0.00	97.37	0.83	0.09	0.01	0.01	0.00	0.00	-30.3	-27.1			
	X 856	T_3x^2	0.00	0.00	97.19	0.86	0.07	0.01	0.01	0.00	0.00	-30.8	-27.0	-26.5		
	X 150	T_3x^2	0.00	0.00	96.95	0.74	0.08	0.01	0.01	0.00	0.00	-30.0	-28.1	-27.3	-22.7	
	X 202	T_3x^2	0.31	0.89	96.69	0.77	0.07	0.01	0.01	0.00	0.00	-31.7	-28.1			
	X 853	T_3x^2	0.00	0.00	97.07	0.79	0.08	0.01	0.01	0.00	0.00	-31.8	-26.9	-25.7		
Pingluoba*	Pingluo 1	T_3x^2	0.29	0.67	96.77	1.93	0.23	0.03	0.05	0.01	0.01	-33.8	-22.7	-22.8		Qin et al., 2007
	Pingluo 9	T_3x^4	0.24	0.38	96.32	2.51	0.41	0.03	0.07	0.01	0.01	-35.5	-22.4	-21.7	-23.9	
	Pingluo 12	T_3x^2	0.22	0.65	96.87	1.81	0.33	0.03	0.05	0.01	0.01	-33.5	-21.9	-21.1		
	Pingluo 8	T_3x^2	0.32	0.68	96.50	2.13	0.25	0.03	0.05	0.01	0.01	-32.5	-24.1	-19.4		

	Pingluo 3	T_3x	0.54	0.76	97.14	1.98	0.24	0.08	0.02			-33.3	-21.7	-21.2	-20.3	Fan et al., 2005
	Pingluo 6	T_3x	0.37	0.77	96.81	2.37	0.31	0.11	0.02			-33.5	-21.7	-22.6	-22.1	
	Pingluo 10	T_3x	0.39	0.81	96.78	2.34	0.33	0.13	0.02			-33.7	-21.7	-22.7	-22.5	
Qiongxi	QX 3	T_3x	0.25	1.67	93.30	3.91	0.63	0.10	0.08	0.01	0.01	-33.1	-23.0	-2.7	-20.3	Dai et al., 2012b
	QX 4	T_3x	0.24	1.47	93.52	3.91	0.62	0.10	0.08	0.01	0.01	-32.9	-23.2	-23.0	-22.0	
	QX 13	T_3x	0.25	1.47	93.30	3.91	0.63	0.10	0.08	0.01	0.01	-33.1	-23.0	-22.7	-20.3	
	QX 006-X1	T_3x^2	0.26	1.36	93.17	4.12	0.71	0.13	0.11			-31.6	-22.4	-22.4		Wu et al., 2011
	QX 6	T_3x^2	0.21	0.92	95.95	2.48	0.30	0.04	0.04			-31.2	-23.2	-23.1	-20.9	
	QX 14	T_3x^2	0.23	1.55	96.50	1.57	0.12	0.02	0.01			-30.5	-24.1	-23.8		
	QX 16	T_3x^2	0.23	1.39	96.46	1.74	0.16	0.02	0.02			-30.8	-23.8			
Gongshanmiao	Gong 16	J_2s										-42.9	-33.2	-30.3	-29.6	Chen et al., 2005
	Gong 13	J_1l										-42.3	-31.3	-30.2	-29.6	
	Gong 35	J_1dn										-48.5	-35.3	-31.0	-29.8	
Lianchi	Lian 14	J_1l										-43.2	-30.5	-27.6	-27.2	
	Lian 63	J_1z	0.00	0.21	82.34	9.68	5.02					-45.4	-34.2	-30.6	-29.6	
Jinhua	Jin 1	J_1z										-41.4	-32.0	-30.0	-30.0	
Nanchong	Xi 021-x1	J_1l	1.25	0.22	87.62	6.59	2.81	0.37	0.59	0.13	0.15	-43.3	-31.1	-28.5	-27.9	This paper
Longgang	LG 2	J_1z	0.94	0.46	77.71	12.24	4.46	0.63	1.38	0.63	0.65	-47.6	-33.0	-28.1	-27.4	
	LG 7	J_1z	0.54	0.95	74.42	12.82	6.01	0.89	1.76	0.61	0.61	-47.5	-32.3	-27.7	-26.8	
	LG 42	J_1l	1.17	0.09	66.57	16.02	9.79	1.51	2.82	0.61	0.67	-46.0	-33.2	-28.7	-28.1	
	LG 18	J_2s	63.62	0.12	33.78	1.08	0.36	0.05	0.11	0.04	0.17	-43.5	-36.8	-30.0	-27.6	
	LG 18	T_2l	0.12	4.59	94.34	0.79	0.07	0.01	0.01			-36.5	-35.5	-30.5	-27.1	
	LG 176	T_2l	0.34	2.42	95.16	1.71	0.23	0.02	0.02			-37.8	-32.5	-30.6		
Moxi	Mo 004-H9	T_2l	0.59	0.00	99.12	0.16	0.00	0.00	0.00	0.00	0.00	-35.0	-32.8			
	Mo 140	T_2l	0.23	0.00	99.54	0.17	0.00	0.00	0.00	0.00	0.00	-35.0	-32.4			
	Mo 144	T_2l	0.75	0.00	98.90	0.18	0.00	0.00	0.00	0.00	0.00	-34.9	-32.1			
	Mo 005-H10	T_1j	0.44	0.00	99.24	0.21	0.00	0.00	0.00	0.00	0.00	-34.6	-34.6			
	Mo 005-H9	T_1j	0.81	0.00	98.81	0.19	0.00	0.00	0.00	0.00	0.00	-34.8	-33.6			
	Mo 150	T_1j	0.21	0.04	99.50	0.21	0.00	0.00	0.00	0.00	0.00	-34.7	-33.7			
	Mo 160	T_1j	1.29	0.18	98.29	0.24						-32.3	-34.0			
	Mo 5	T_1j	0.80	0.00	98.85	0.17	0.00	0.00	0.00	0.00	0.00	-34.6	-33.2			

* Xinchang，Pingluoba and Qiongxi gas fields are located in the Western Sichuan Basin, other fields are located in the Central Sichuan Basin.

5. Discussion

5.1 Natural gas in the Xujiahe Formation in the central Sichuan basin is not migrated from the western Sichuan basin.

Since the thickness of the Xujiahe Formation and the thickness of the coal-based source rocks in the central Sichuan basin are much smaller than those in the western Sichuan basin, the gas generation intensity of the source rocks in the Xujiahe Formation in the central Sichuan Basin is much smaller than that in the western Sichuan basin. As shown in Fig. 1, the highest intensity of gas generation in the Xujiahe Formation in the Central Sichuan is only 20 $\times 10^8 m^3/km^3$. Based on previous research and exploration experience, it is not likely that a large gas field can be formed at such a low intensity of source rock. However, the studies on the geochemical characteristics of natural gas show that the natural gas in the Xujiahe Formation in the central Sichuan basin is a typical coal-type gas. Therefore, some researchers suggested that the natural gas in the Xujiahe Formation in the central Sichuan basin might come from the coal source rocks of the Xujiahe Formation in the western Sichuan basin. In this model, the natural gas generated from coal source rocks in the Xujiahe Formation traveled long distance to the central Sichuan Basin and accumulated in the Xujiahe Formation reservoir. However, it is a challenge to explain how the migration of natural gas can happen in terms of migration channels. The Xujiahe Formation and the overlying Jurassic and the underlying Leikoupa Formation are all sealed by non-permeable mudstone and natural gas cannot migrate along the contact surfaces between different formations. In addition, the reservoirs in both Western and Central Xujiahe Formation are tight sandstones, it is unclear whether natural gas can migrate long distances in the dense layer and there is no reliable conclusion so far. According to the results in Table 1 and Table 2, the geochemical characteristics of natural gas in the western Sichuan basin is significantly different from the gases from the Xujiahe Formation in the Central Sichuan Basin, both of which belong to the natural gas generated from coal with different maturity levels. As discussed previously, first of all, the dryness coefficients are different in two areas. Gases in the Central Sichuan Basin are mainly dry gas, and on the contrary, gases in the Western Sichuan basin are mainly wet gas (Fig. 3). Secondly, the carbon isotopes of alkanes from the Xujiahe Formation in the Central Sichuan Basin is lighter than those from the western Sichuan basin. In a Bernard diagram (Fig. 4), the natural gases in the Central and Western Xujiahe Formation are also lain in different regions. Gases from the Xujiahe Formation in the central Sichuan basin are in the region of thermogenic gas while gases from the Western Xujiahe Formation are in the type III kerogen region.

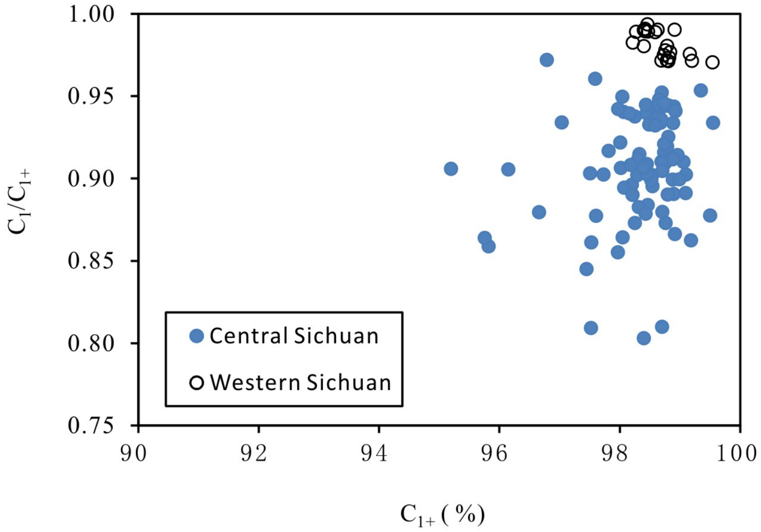

Fig.3. Relationship between natural gas dryness coefficient (C_1/C_{1+}) and total hydrocarbon gas content in the Xujiahe Formation in the Sichuan Basin.

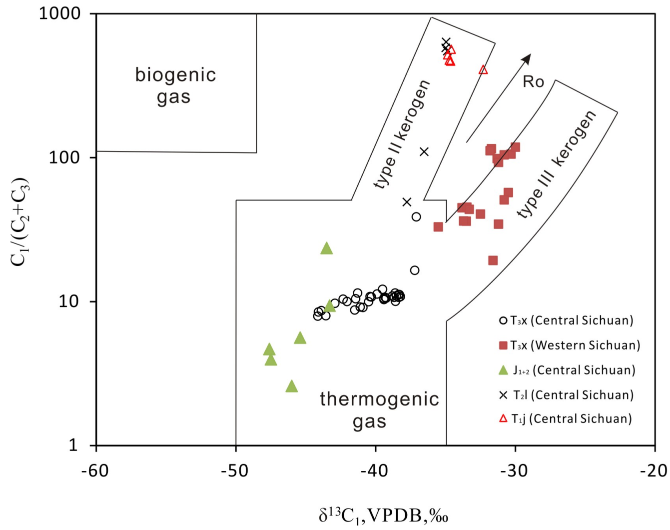

Fig.4. The 'gas wetness' $C_1/(C_2 + C_3)$ vs. $\delta^{13}C_1$ showing the differences of gases listed in Table 2 (modified from Bernard et al. (1978) and Whiticar (1999).

In addition, if the natural gas from the Xujiahe Formation in the central Sichuan basin came from the western Sichuan basin, the fractionation effect of natural gas components would be very obvious over such a long distance, especially in tight formations. Along the migration pathway, concentrations of molecules with small diameters and weights should increase. Natural gas dryness coefficient should also increase gradually. As a consequence, dryness coefficient in the natural gas from Xujiahe Formation should be higher than that in the western Sichuan. But our data show opposite direction (Figure 3). Therefore, we propose that gases in the Xujiahe Formation in the Central Sichuan basin are derived from the source rocks within the Xujiahe Formation in the Central Sichuan basin. They are not from the western Sichuan basin.

Difference between gases from the Xujiahe Formation in the central Sichuan basin and those from the western Sichuan basin is consistent with the geological background in both areas. According to the measured Ro values of the source rocks, the maturity of the source rocks in the Xujiahe Formation in the central Sichuan basin is indeed lower than that in the western Sichuan basin (Dai et al., 2012b).

5.2 There is no horizontal migration of natural gases among adjacent gas fields in the Xujiahe Formation in the Central Sichuan basin

In previous section, distinct geochemical characteristics in gases from the Western and Central Sichuan basin suggested that long distance gas migration did not occur. A question still remains that if there is significant lateral migration of natural gases between adjacent gas fields in the central Sichuan basin. To test this hypothesis, we selected the Hechuan and Tongnan gas fields in the southern part of the central Sichuan basin and the Guang'an and Nanchong gas fields in the northern part of the central Sichuan basin for our study. Gases in these fields are all from the Xujiahe Formation.

The proven natural gas reserves in the Hechuan and Tongnan gas fields are accumulated in T_3x^2 section. Although these two gas fields are not far from each other, the carbon isotopes of methane and ethane are significantly different. The natural gas in T_3x^2 gas reservoir in the Hechuan gas field is obviously heavier than that in the Tongnan gas field. The average carbon isotope ratios of methane and ethane in the Hechuan gas field are -39.0 ‰ and -27.0 ‰ respectively. The average carbon isotope ratios of methane and ethane in the Tongnan gas field are -40.9 ‰ and -27.8 ‰ respectively (Table 2, Figure 5). This suggests that the maturity of source rocks in the Hechuan gas field is higher than that in the Tongnan gas field. In addition, the natural gas dryness coefficient of the Hechuan Gas Field is significantly higher than that of the Tongnan Gas Field (Figure 6a). This is also due to the difference between the maturity of the source rocks and it is not caused by fractionation of gases due to lateral migration, because if the high dryness coefficient was due to fractionation associated with migration, the carbon isotope in methane in the Hechuan gas field should not be heavier than that in the Tongnan gas field as we observed.

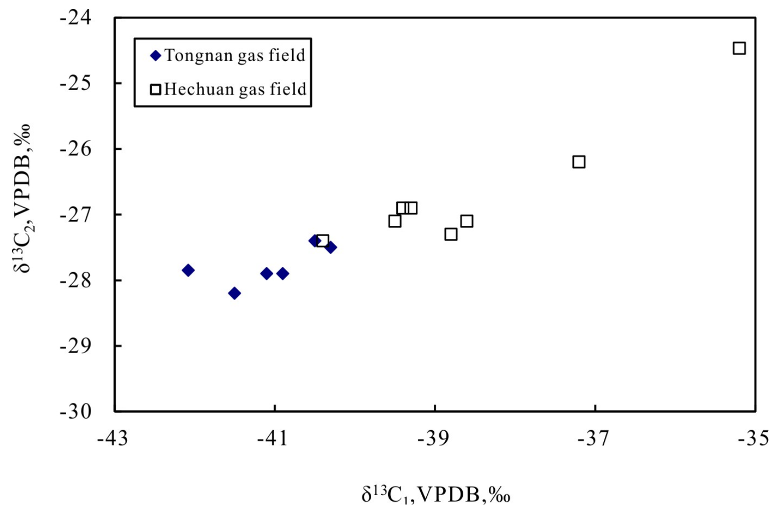

Fig. 5. $\delta^{13}C_1$ vs. $\delta^{13}C_2$ in natural gases from T_3x^2 reservoirs in the Hechuan and Tongnan gas fields.

Isomeric ratios in alkane gas in the Hechuan and Tongnan gas fields are also significantly different. They are higher in the Hechuan gas field than in the Tongnan gas field (Figure 6b). Due to low boiling point, high saturation vapor pressure and small intermolecular force, the diffusion coefficients of isomers of alkane gases are higher than normal alkane gases with the same carbon number. Therefore, iC_4 and iC_5

migrate faster than nC_4 and nC_5, respectively. Previous research shows that the diffusivity of iC_4 is greater than that of nC_4 in shale saturated with brine at 38 ℃, which are 1.26 $\times10^{-7}cm^2/s$ and 1.24 $\times10^{-7}cm/s$, respectively. The diffusivity of iC_5 is larger than that of nC_5, which are 7.0 $\times10^{-7}cm^2/s$ and 5.2 $\times$ $10^{-7}cm^2/s$, respectively (Hao et al., 1994). When gas chromatography is used for determination of natural gas abundances, isoparaffins are detected earlier than normal alkanes with the same carbon number. As a result, the ratios of iC_4/nC_4 and iC_5/nC_5 increase with the increase of gas migration distance. In this sense, the difference between the isomeric ratio of alkane gases from the Tongnan and Hechuan gas fields may also be explained by migration of natural gases. However, this contradicts the fact that methane isotopes in the gases from the Hechuan field are heavier than those from the Tongnan field. In general, natural gas tends to migrate from source rocks with high maturity to source rocks with low maturity. Therefore, under the same geological conditions, the gas generation intensity of source rock would be relatively high if the maturity of the source rock is high.

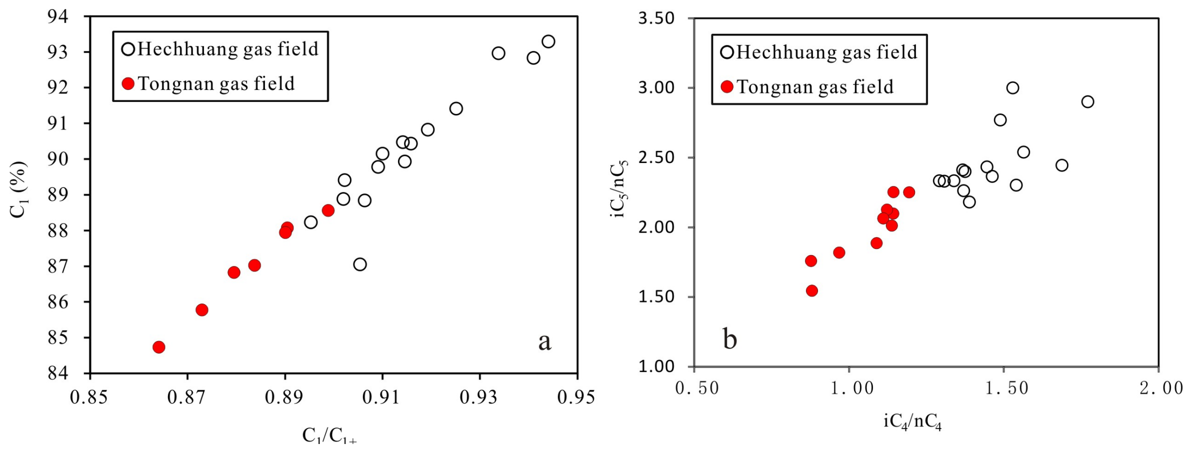

Fig. 6. Comparison of geochemical parameters in natural gases from the T_3x^2 reservoirs in the Hechuan and Tongnan gas fields

There is also an obvious difference in geochemical characteristics between gases from the Nanchong gas field and Guang'an gas field in the northern part of the central Sichuan basin. Althogh gases in both fields are from the T_3x^4 section of the Xujiahe Formation, the natural gas from the Guangxian field has a dryness coefficient larger than that in the Nanchong gas field. The isomerization of alkane gas is also obviously higher in the Guangxian field than that in the the Nanchong field. This difference can also be explained by the difference between the maturities of source rocks in both gas reservoirs.

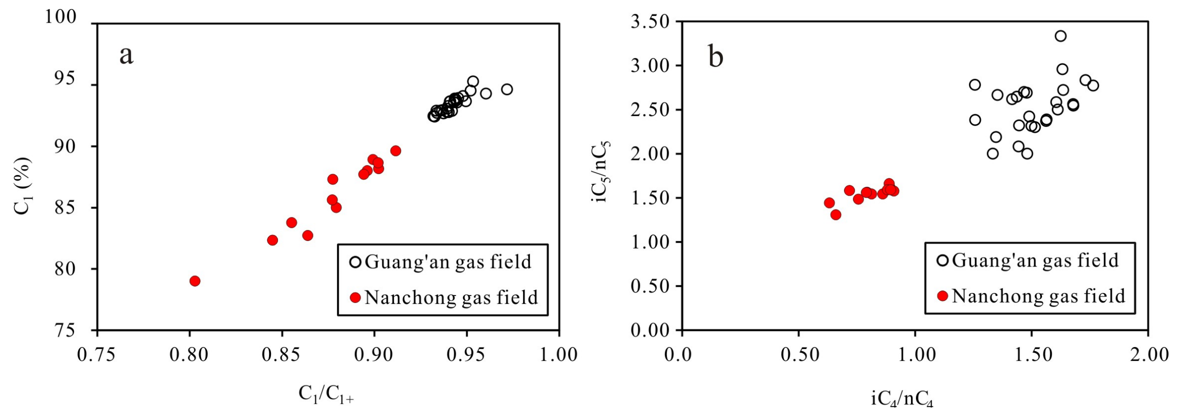

Fig. 7. Comparison of geochemical parameters in natural gases from the T_3x^4 reservoirs in the Guang'an and Nanchong gas fields

Based on the evidence that geochemical characteristics of the adjacent Xujiahehe gas fields in the central Sichuan basin are significantly distinct from each other and the difference can be caused by the different maturities of the source rocks which supply gases in the respective reservoirs, there is no significant lateral migration of natural gas among the Xujiahe Formation gas reservoirs in horizontal direction.

5.3 Gas reservoirs in the Xujiahe Formation in the central Sichuan basin are not intermixed with natural gases from other adjacent formations vertically

The Xujiahe Formation in the Central Sichuan Basin is overlaid by the formation of Jurassic age. Within it, the Lower Jurassic formation is characterized by thick, organic-rich gray-black shale, which is composed of lacustrine sediments with low form of organisms (Du et al., 2005). This is different from the coal derived source rocks in the Xujiahe Formation. In the Middle and Lower Jurassic formation, both petroleum reservoirs and associated gases were found. The Xujiakou Formation and the Jialingjiang Formation were found below the Xujiahe Formation. Although both the Leikoupo Formation and the Jialingjiang Formation are marine strata, It has not been determined whether effective source rocks have been developed in these formations. However, gas reservoirs have been discovered in both formations. Whether gases derived from coal-based source rock in the Xujiahe Formation migrated into the overlying Jurassic and underlying Leikoupo and Jialingjiang formations and whether gases from these formations migrated into the Xujiahe Formation remain an open question.

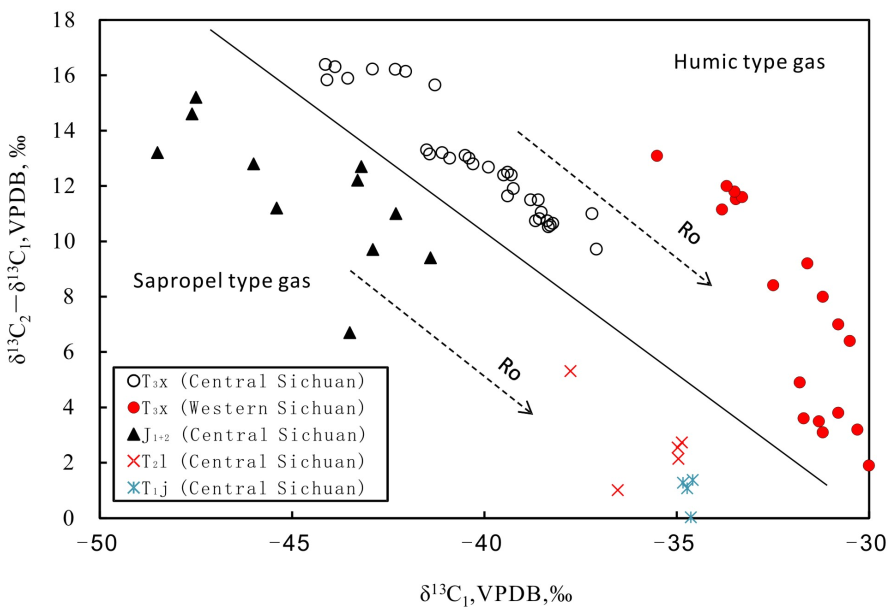

Fig. 8. Genetic natural gas types in the Central and Western Sichuan basin

It is shown in Table 2 and Figure 8 that the natural gases in the Xujiahe Formation in the Central Sichuan basin are clearly distributed in different regions with gases in the Jurassic, Leikoupo and Jialingjiang Formations being different gas types. The gas in the Xujiahe Formation is distributed in the coal-type gas region, and the natural gases in the Jurassic, Leikoupo and Jialingjiang formations are distributed in the oil-type gas region. Due to low maturity of Jurassic formation and lighter carbon isotopes in methane, natural gas in this formation is distributed in the region with low maturity. The natural gases in the Lekoukou and Jialingjiang formations are distributed in regions with high maturity. This geochemical characteristic of natural gas is consistent with the geological background. Source rocks in the Jurassic formation are shallow-deep lacustrine sediments. Organic matter is mainly sapropelic, which is type I-II kerogen. Both the Leikoupo and Jialingjiang formations and strata below are marine sediments with natural gas originated from marine source rocks. Organic matter in the marine source rocks is generally sapropelic, which is kerogen type Ⅰ-Ⅱ. Therefore, the natural gas in the Xujiahe Formation in the central Sichuan basin has neither migrated into the adjacent strata, nor has the natural gas from the adjacent strata migrated into the Xujiahe Formation.

5.4 There is distinct difference between gases from upper and lower gas reservoirs in the Xujiahe Formation in the Central Sichuan basin

By taking Guang'an gas field as an example, which produces gases from both the upper and lower Xujiahe formation, we aim to study the migration of gases within the Xiujiahe Formation. The main gas reservoirs in the Guang'an gas field are located in the T_3x^4 and T_3x^6 sections, with natural gas most likely coming from coal-based source rocks in the T_3x^3 and T_3x^5 sections below the gas reservoirs. Source rokcs in the T_3x^3 section is more mature than those in the T_3x^5 section.

If natural gas does migrate from the T_3x^4 gas reservoir to the T_3x^6 gas reservoir, the natural gas dryness coefficient, the alkane gas abundance and isomeric ratios in the T_3x^6 gas reservoir should be higher than those in the T_3x^4 gas reservoir. However, results show opposite direction. As can be seen in Figure 9, the natural gas dryness coefficient and the isomeric ratio of alkane gases in the T_3x^4 gas reservoir are significantly higher than those in the T_3x^6 gas reservoir. This phenomenon can be reasonably explained by difference in the maturities of source rocks. The distinctive geochemical parameters of natural gas in the T_3x^4 and T_3x^6 gas reservoirs also illustrate that there is no major mixing of natural gas in the upper and lower gas reservoirs in the Xujiahe Formation in the Central Sichuan Basin.

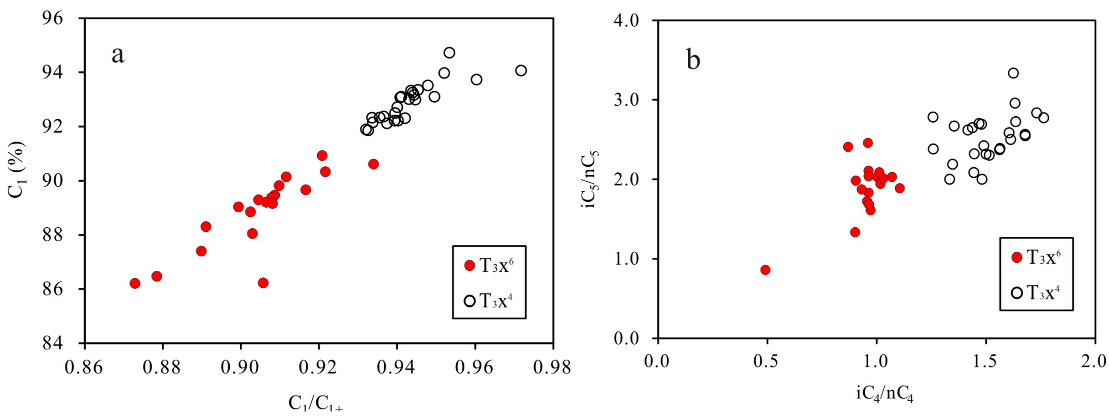

Fig. 9. Comparison of geochemical parameters in natural gases from T_3x^4 and T_3x^6 reservoirs in the Guang'an gas field.

We sampled a number of wells where gas samples can be taken from both the T_3x^4 and T_3x^6 gas reservoirs individually to study difference between the upper and lower gas reservoirs. Gas wetness coefficient (C_1 / (C_2 + C_3)) in the T_3x^4 gas reservoir is significantly higher than that in the T_3x^6 gas reservoir. Heavy hydrocarbon content in the T_3x^6 gas reservoir is higher than that in the T_3x^4 reservoir (Fig. 10).

We also listed density and methane content of natural gases in some wells drilled through the entire Xujiahe Formation in the Guang'an field and other fields to compare geochemical characteristics of natural gas at different depth of reservoirs (Table 3). Comparisons revealed that, from bottom to top, which is from T_3x^2 to T_3x^4 and T_3x^6 section, the natural gas density increased, and the methane content decreased (Table 3). This is consistent with the gradual decrease of maturity from $T_3x^1$to T_3x^3 and T_3x^5 source rocks. It also demonstrates that there is no mixing of natural gas between the upper and lower gas reservoirs in the Xujiahe Formation. Natural gas in the Xujiahe Formation is accumulated in situ and has not undergone any major migration process after generation.

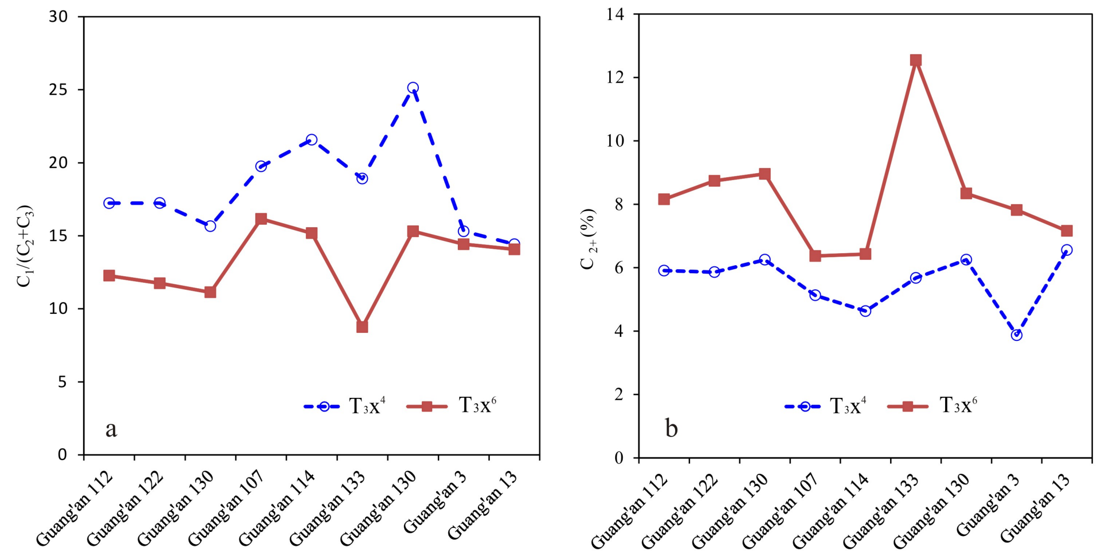

Fig. 10. Comparison of gas geochemical parameters in gases from T_3x^4 and T_3x^6 reservoirs in the same wells in the Guang'an gas field.

Table 3

Density and methane content of natural gases in the Xujiahe Formation in the Central Sichuan basin

Gas field	Well	T_3x^2		T_3x^4		T_3x^6	
		Density	CH_4（%）	Density	CH_4（%）	Density	CH_4（%）
Bajiaochang	Jiao 48	0.602	93.00	0.620	91.00	0.637	88.00
Suinan	Sui 12	0.638	89.00	0.648	86.00	0.686	83.00
Moxi	Mo 12	0.638	88.00	0.648	86.00		
Guang'an	Guang'an 112			0.603	92.70	0.621	89.66
	Guang'an 114			0.587	94.72	0.614	90.72
	Guang'an 133			0.610	92.30	0.670	86.21

5.5 In - situ accumulation of tight gas in the Xujiahe Formation in the central Sichuan basin is due to specific local geological setting

5.5.1 Development of favorable seals on both bottom and top of the Xujiahe Formation

First of all, the Xujiahe Formation, underlying Middle Triassic formations and overlying Jurassic formations in the Central Sichuan basin are sealed off by non-permeable rocks, which are not in favor of migration of natural gas in the Xujiahe Formation (Jiang et al., 2006). Secondly, the thick shale, developed at the bottom of the Lower Jurassic formation, not only provide oil and gas sources for the Jurassic reservoirs, but also provide high-quality caprock for Xujiahe Formation gas reservoirs. The Middle Triassic Leikoupo Formation and the Lower Triassic Jialingjiang Formation have all developed gypsum salt layers, which are good barriers to prevent the natural gas from migrating downwards.

5.5.2 Relatively stable tectonic history makes the in situ gas accumulate in the Xujiahe Formation possible

Tight sandstone reservoirs are widely distributed in the Xujiahe Formation. However, strong heterogeneity of the reservoirs and gentle slope of the formation limit long-distance migration of oil and gas. Due to stable regional tectonic activities, the regional tectonic stress in sedimentary formation is weak. As a consequence, faults and fissures are not developed. Therefore, hydrocarbon migration in tight sandstone is limited (Jiang et al., 2006). The regional overpressure of the fluids in the reservoir also reflects that fluid migration in the Xujiahe Formation in the Central Sichuan Basin is hindered. The reservoirs in the Xujiahe Formation in the central Sichuan basin are overpressured in general, and the overpressure in different regions at the same depth varies (Table 4). This suggests that the reservoirs in the Xujiahe Formation have low porosity and permeability, poor reservoir connectivity, strong heterogeneity. There is no effective "pressure release mechanism", resulting in overpressure anomaly and heterogeneous pressure distribution in the Xujiahe Formation in the Central Sichuan basin.

Table 4

Statistics of stratigraphic pressure in the Xujiahe Formation in the Central Sichuan basin

Gas field	Well	Measured depth（m）	Strata	Pressure（MPa）	Pressure coefficient
Moxi	Mo 11	2146	T_3x^2	30.84	1.47
	Mo 76	2072.2	T_3x^2	30.17	1.48
Tongnan	Tongnan 101	2241.4	T_3x^2	31.60	1.44
	Tongnan 102	2240.85	T_3x^2	29.65	1.35
Hechuan	Hechuan 1	2135	T_3x^2	22.57	1.08
	Hechuan 3	2130.8	T_3x^2	25.28	1.21
	Hechuan 5	2265	T_3x^2	30.07	1.35
Nachong	Chongshen 1	2205.6	T_3x^4	31.23	1.44
	Chongshan 2	2225.25	T_3x^4	29.03	1.33
	Chongshen 1	2205.6	T_3x^4	31.23	1.44
Bajiaochang	Jiao 13		T_3x^4	55.14	1.81
	Jiao 45		T_3x^4	56.19	1.79
Guang’an	Guang’an 135	2475.22	T_3x^4	36.19	1.49
	Guang’an 138	2526.75	T_3x^4	32.41	1.31
	Guang’an 139	2370.4	T_3x^4	35.72	1.54
	Guang’an 2	1782.45	T_3x^6	19.55	1.12
	Guang’an 131	2589	T_3x^6	34.41	1.36
	Guang’an 103	1799.7	T_3x^6	18.38	1.04

6. Conclusion

Although the Central Sichuan basin has experienced many tectonic movements, it has not experienced large-scale extrusion deformation. The structures in the central Sichuan basin is relatively stable. There is no effective communication system formed in the tight reservoirs in the Xujiahe Formation, which limits the migration of natural gas. Geochemical studies of natural gas show that the natural gas in the Xujiahe Formation is accumulated in independent reservoirs. There is no significant horizontal and vertical migration between the gas reservoirs in the Xujiahe Formation. The tight gas in the Xujiahe Formation is generated and accumulated in situ.

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