

REVIEWS

Geological and Geochemical Characteristics and Exploration Prospect of Coal-Derived Tight Sandstone Gas in China: Case Study of the Ordos, Sichuan, and Tarim Basins

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Abstract: This work extensively investigated global tight sandstone gas, and geologically and geochemically analyzed the tight sandstone gas in China's Ordos, Sichuan, and Tarim basins. We compared typical tight sandstone gas in China with that in North America. We proposed six conditions for the formation of China's tight sandstone gas, and illustrated the geological characteristics of tight sandstone gas. In China, gas-bearing tight sandstones were mainly deposited in continental lake deltas and marine-terrigenous facies basin environments, associated with coal-measure strata, and were mostly buried deeper than 2000 m under a formation pressure of 20–30 MPa, with pressure coefficients varying from overpressure to negative pressure. In other countries, tight gas bearing sandstones were dominantly deposited in marine to marine-terrigenous facies environments, occurred in coal-measure strata, and were mostly buried shallower than 2000 m in low-pressure systems. We systematically analyzed tight sandstone gas in the Ordos, Sichuan, and Tarim basins in terms of chemical compositions, geochemical characteristics of carbon isotopes, origins, and sources. Tight sandstone gas in China usually has a hydrocarbon content of >95%, with CH₄ content >90%, and a generally higher dry coefficient. In the three above-mentioned large tight sandstone gas regions, $\delta^{13}\text{C}_1$ and $\delta^{13}\text{C}_2$ mainly ranges from –42‰ to –28‰ and from –28‰ to –21‰, respectively. Type III coal-measure source rocks that closely coexist with tight reservoirs are developed extensively in these gas regions. The organic petrology of source rocks and the carbon isotope compositions of gas indicate that tight sandstone gas in China is dominantly coal-derived gas generated by coal-measure strata. Our analysis of carbon isotope series shows that local isotope reversals are mainly caused by the mixing of gases of different maturities and that were generated at different stages. With increasing maturity, the reversal tendency becomes more apparent. Moreover, natural gas with medium-low maturity (e.g., Xujiahe Formation natural gas in the Sichuan Basin) presents an apparent reversal at a low-maturity stage, a normal series at a medium-maturity stage, and a reversal tendency again at a high-maturity stage. Finally, we proposed four conditions for preferred tight sandstone gas “sweep spots,” and illustrated the recoverable reserves, proven reserves, production, and exploration prospects of tight sandstone gas. The geological and geochemical characteristics, origins, sources, and exploration potential of tight sandstone gas in China from our research will be instructive for the future evaluation, prediction, and exploration of tight sandstone gas in China and abroad.

Key words: coal-derived gas, tight sandstone gas, geological characteristics, geochemistry, origin, exploration potential

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1 Introduction

Tight sandstone gas is an unconventional hydrocarbon resource that is becoming increasingly important worldwide. The United States Geological Survey (USGS) states that, globally, approximately 70 basins have been discovered to contain or presumed to contain tight sandstone gas, with estimated resources of $210 \times 10^{12} \text{ m}^3$ (Rogner, 1997). A different estimate by Total (2006) predicted global tight sandstone gas resources to be $(310\text{--}510) \times 10^{12} \text{ m}^3$. Additionally, the World Petroleum Council reported $114 \times 10^{12} \text{ m}^3$ of technically recoverable tight sandstone gas resources around the world. Lastly, reports by Aguilera (2008) and the International Energy Agency (2009) estimated worldwide technically recoverable tight sandstone gas resources of $428 \times 10^{12} \text{ m}^3$ and $110 \times 10^{12} \text{ m}^3$, respectively. These estimates suggest immense potential and promising prospects of tight sandstone gas globally.

The first tight sandstone gas field was discovered in the Mesaverde Group of the Blanco Field, in the United States' San Juan Basin in 1927. In 1955, acid fracturing was carried out in the Cotton Valley tight sandstones of the Cauthage gas field. This process increased daily gas production to $340 \times 10^4 \text{ m}^3$, making it one of the largest gas fields in the United States by 1976. In that same year, the Elmworth tight sandstone gas field was discovered in Canada's western Alberta Basin, marking the beginning of rapid growth in tight sandstone gas exploration and development in North America. In the United States, tight gas production surpassed $600 \times 10^8 \text{ m}^3$ in 1990 and $1000 \times 10^8 \text{ m}^3$ in 1998. As of 2010, approximately 900 tight sandstone gas fields had been discovered in 23 basins, with remaining proven recoverable reserves of more than $5 \times 10^{12} \text{ m}^3$ and more than 10×10^4 production wells. In 2010, tight sandstone gas production was $1608 \times 10^8 \text{ m}^3$, accounting for 26% of total U.S. gas production. Meanwhile, tight sandstone gas production was accelerating elsewhere around the world. In 2009, global yearly tight sandstone gas production was up to $4000 \times 10^8 \text{ m}^3$, accounting for approximately 13% of gas production worldwide. It is obvious that tight sandstone gas has become a major unconventional gas development focus around the world.

In China, scholars have carried out significant amounts of tight sandstone gas research, mainly regarding tight sandstone gas forming conditions and migration and accumulation mechanisms (Jiang Zhenxue et al., 2006; Zhang, 2007; Zou et al., 2013, 2014; Zhang et al., 2016; Feng Congjun et al., 2017; Han et al., 2017; Wang et al., 2017; Yang et al., 2017; Zhao et al., 2017). Their studies often focus more on geological evaluation, exploration, and development than on geochemistry and tight

sandstone gas origins (Dai et al., 2014; Liu et al., 2016; Zhang Li et al., 2017; Yang et al., 2017; Chang et al., 2017). Additionally, they focus much less on stable carbon isotopes, which are significant for gas source tracing, identification, and accumulation. Thus far, researchers have investigated carbon isotopes of tight sandstone alkane gas in two deep-basin gas fields in the west Canada Basin (James, 1990) and stable carbon and hydrogen isotopes of deep-basin gas in the north Appalachian Basin (Burruss et al., 2010). In this paper we systematically discuss alkane gas carbon isotopes and tight sandstone gas chemical composition in 15 large tight sandstone gas fields in China's Ordos, Sichuan, and Tarim basins. These efforts were to promote research on the geology, geochemistry, and origin of tight sandstone gas and exploration evaluation of this resource.

2 Overview of Coal-Derived Tight Sandstone Gas in China

Tight sandstone gas is natural gas contained in sandstone reservoirs with an overburden matrix permeability of $\leq 0.1 \times 10^{-3} \mu\text{m}^2$, from which natural productivity either has not been revealed by a well or where a well has a gas flow lower than the commercial lower limit. In the latter case, a commercially acceptable gas production rate can be realized using various technical measures under certain economic conditions (Zou Caineng et al., 2011a; Xu Guosheng et al., 2011). Such measures typically include fracturing, and the use of horizontal or multi-lateral wells. Overburden matrix permeability is measured by applying a net overburden pressure to unfractured cores (i.e., matrix). For tight sandstone gas, formation permeability, formation pressure, water saturation, and porosity are key evaluation parameters.

Tight sandstone gas is abundant in China. The Sulige tight gas region, China's largest, has $3.9 \times 10^{12} \text{ m}^3$ of proven tight sandstone gas reserves in place and yearly gas production of up to $212 \times 10^8 \text{ m}^3$. During the past decade, China's yearly incremental proven in place tight sandstone gas was $2760 \times 10^8 \text{ m}^3$ on average, which accounts for roughly 50% of the incremental proven gas in place in China. From 2011 to 2013, China's tight gas production increased from $256 \times 10^8 \text{ m}^3$ to $340 \times 10^8 \text{ m}^3$, with tight gas production rising from 25% to 29% of the country's total gas production. Two major tight gas regions have been developed, the Sulige gas field in the Ordos Basin and the Xujiahe Formation in the Sichuan Basin. Moreover, there have been tight gas exploration breakthroughs in the Tarim, Tuha, Songliao, and Bohai Bay basins, making them promising targets for new reserves and increased production (Fig. 1).

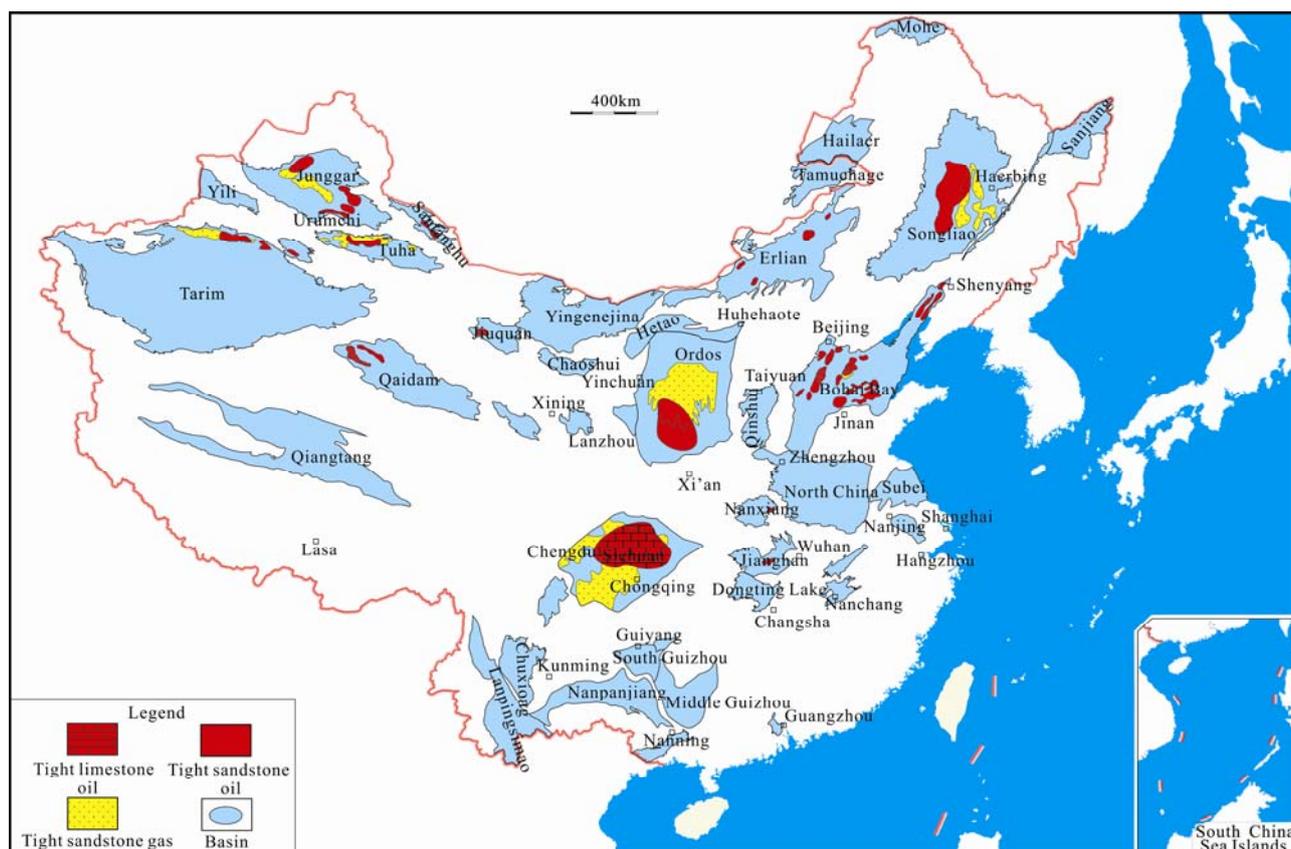


Fig. 1. Distribution of coal-derived tight sandstone gas in China (China basemap after China National Bureau of Surveying and Mapping Geographical Information).

Tight sandstone gas reservoirs have been discovered in China's Ordos, Sichuan, Tarim, and Bohai Bay basins (Yang Hua et al., 2012; Dai et al., 2005, 2012; Zou Caineng et al., 2011b; Han et al., 2017; Yang et al., 2017). The first of these was discovered in 1973, in the second member of the Xujiache Formation (T_3x^2) in the Zhongba field of the Sichuan Basin, and this reservoir has been in production for many years. This sandstone gas reservoir's average porosity, based on statistics from 1435 cores, is 6.4%, and its average permeability is $0.0804 \times 10^{-3} \mu\text{m}^2$, as revealed by 1319 cores. Large tight sandstone gas fields are crucial to China's natural gas industry, contributing 37.3% of China's total proven gas in place and accounting for 23.5% China's total gas production in 2010. The Sulige tight gas field provides the largest share of gas reserves and production in China, with 2011 gas production at $137 \times 10^8 \text{ m}^3$ (Yang Hua et al., 2012). By the end of 2014, $3.018 \times 10^{12} \text{ m}^3$ of coal-derived tight sandstone gas in place was proven in the Sulige gas field of the eastern Ordos Basin, the Xujiache Formation of the Sichuan Basin, and the Kuqa Depression in the Tarim Basin. Tight sandstone gas should be made an unconventional gas exploration and development priority in China as opposed to shale gas and coalbed methane (Dai et al., 2012).

3 Forming Conditions and Geological Characteristics of Coal-derived Tight Sandstone Gas in China

3.1 Differences of tight sandstones gas between China and other countries

In China, tight sandstone gas differs from gas in other countries in its regional geologic setting and tectonic-sedimentary environment aspects. Tight sandstones in China have differing formation and distribution compared to those in North America's Denver, San Juan, Alberta, and Appalachian basins (Table 1).

Tight sandstone development zones in China experienced intensive late tectonic movements in a multi-cycle structural evolution setting, which affected their preservations in a way. In other countries, structures are stable with dominant single-cycle or few-cycle structural evolution.

In China, tight gas was mainly deposited in continental lake basin delta and marine-terrestrial facies environments, and is commonly associated with coal-measure strata. Tight gas deposits in other countries are associated with marine to marine-terrestrial facies environments and coal-measure strata.

China's tight sandstone reservoirs are strongly

heterogeneous, thin, and show great lateral variation, presenting mostly as thin interbeds or reservoirs with thick sandstone with relatively low porosity. On the other hand, tight sandstone reservoirs in other countries are thick and have high porosity.

In China, tight sandstone gas is mainly found in slope zones and piedmont tectonic belts. In other countries, tight sandstone gas, which is predominantly a basin centered gas, occurs mainly in sag zones or foredeep belts.

In China, tight sandstone gas pressure coefficients vary from overpressure to negative pressure. Additionally, there are diverse oil-water-gas relationships and water is commonly present. Oil-gas-water inversion is common for tight sandstone gas deposits in other countries and low pressure is dominant.

3.2 Tight sandstone gas formation conditions

Extensive and continuous deposits of tight sandstone gas are often formed under the following six conditions:

A large gentle structural setting. Sedimentary structures were gentle with a low slope gradient during initial sedimentation. These formations are currently generally gentle, with higher stratigraphic dip in regions close to foreland thrust belts. Areas in the same structural setting are extensively distributed.

A continuous and extensively subsiding sedimentary environment. Tight sandstone gas formation areas mainly consist of the continuously subsiding sedimentary environments of depressions, forelands and rifted basins in large continental lake basins, and marine and marine-terrestrial sedimentary environments.

Effective mature source rocks extending over a large

area. Tight sandstone gas formation takes place primarily in Type III source rocks in coal-bearing strata with a thermal evolution maturity (R_o) >1.0%, and secondarily in Type I and II source rocks (TOC over 1.5%) with R_o values higher than 1.3% over a larger area.

Tight sandstone reservoirs with nanoscale pore throats. Reservoirs with an air permeability $<1 \times 10^{-3} \mu\text{m}^2$ are distributed in a large area, accounting for more than 80% of the reservoir.

Source rocks and reservoirs that are integrated or in close contact. An effective source-reservoir assemblage is formed inside high-quality mature source rocks or is composed of high-quality mature source rock in close contact with tight sandstones.

Primary migration or short-distance secondary migration is dominant. Continuous charging, diffusion, and accumulation are predominant in the reservoir, the floatation process is limited, and non-Darcy flow is dominant. Increased pressure resulting from hydrocarbon generation and density difference is the main driver of natural gas migration and accumulation. Continuous hydrocarbon generation by coal-measure source rocks and continuous reservoir charging are the bases of tight sandstone gas accumulation.

3.3 Geological characteristics of tight sandstone gas

Tight sandstone reservoirs are characterized by extremely low porosity and permeability, also known as tightness. Strong vertical heterogeneity and poor lateral continuity in these reservoirs leads to complex oil-gas-water relation and a low degree of oil-gas-water differentiation. However, there is generally no uniform oil-

Table 1 Characteristics of tight sandstone gas in typical basins in China and North America

Basin	Denver Basin	San Juan Basin	Alberta Basin	Appalachian Basin	Ordos Basin			Sichuan Basin		
Oil/gas field	Wattenberg	Blanco Mesaverde	Elmworth-Wapiti	Appalachian	East Sulige 1	Yulin	Hechuan	Guang'an		
Horizon	Muddy	Mesaverde	Sprit River	Clinton-Medina	He 8	Shan 1	Shan 2	T_3x^2	T_3x^6	T_3x^4
Burial depth of target formation (m)	2070–2830	1677–1900	823–1433	1220–1829	2854–3244	2906–3442	2500–3000	2209	1700–2000	2360
Thickness of target formation (m)	50–100	121–274	150–180	45.7	45–60	40–50	40–60	75–140	94–172	72–129
Porosity (%)	8–12	9.5	4–7	5–10	6–14 (9.5)	4–14 (8.8)	6.2	5.0–5.8	1–8 (4.6)	2–12 (5.84)
Permeability ($10^{-3} \mu\text{m}^2$)	0.05–0.005	0.5–2	0.001–1.2	<0.1	0.05–10 (0.88)	0.05–10 (0.67)	0.15–1.2	0.31	0.178	0.387
Formation pressure (MPa)	Abnormal low pressure	Abnormal low pressure	Low pressure	Low pressure	26	25	27.2	28.36	21.63	Overpressure
Gas saturation (%)	56	66	50–70	High free water saturation	63.7	63.2	74.5	61.7	53.7	56
Gas-bearing area (km^2)	300 (estimated)	410	5000	44011	710	760	1716	505	200	415
Effective thickness (m)	3–15.2	24	15–19	30–45	7.8	6.3	8.3	21.6	34.2	10.6

gas-water contact or uniform pressure system, and communication due to fractures in the rock makes it more complex.

3.3.1 Tight sandstone gas properties

Tight sandstone gas is distributed in strata with varying geological ages, though within an oil/gas region, there is a higher ratio of older strata. Tight sandstone gas that has thus far been discovered is dominantly distributed in medium-deep strata.

Tight sandstone gas has high light hydrocarbon content and low heavy hydrocarbon content. For example, natural gas in the Upper Triassic Xujiahe Formation in the Sichuan Basin has a CH₄ content of 82.55%–93.42%, and a much lower heavy hydrocarbon content (generally less than 10%, with a maximum less than 15%). The iC_4/nC_4 ratio of tight sandstone gas is mostly greater than 0.75 and its iC_5/nC_5 ratio is typically between 1.64 and 2.79. There is generally no hydrogen sulfide in the non-hydrocarbon portion of tight sandstone gas. Gas in each central Sichuan Basin reservoir is organic in origin, with a carbon isotope composition of $\delta^{13}C_1 < \delta^{13}C_2 < \delta^{13}C_3 < \delta^{13}C_4$.

3.3.2 Tight sandstone gas pressure system

Tight sandstone gas deposits contain multiple pressure systems, such as normal pressure, low pressure, high pressure, and abnormal pressure, with normal pressure being the predominant pressure system. For example, Sulige gas field reservoir in the Ordos Basin is buried 3200–3410 m deep in an abnormal low-pressure system, with a formation pressure of 27–32 MPa and a pressure coefficient of 0.83–0.89. The Guang'an gas field reservoir in the Sichuan Basin is buried 2100–2800 m deep and presents an abnormal pressure, with a formation pressure of 25–39 MPa and a pressure coefficient of 1.13–1.52. Formation pressure increases gradually from east to the west. The T_{3x}² gas reservoir of the Hechuan gas field in the Sichuan Basin is in a normal-high pressure system, with a pressure coefficient of 1.07–1.52.

3.3.3 Tight sandstone gas geological characteristics

Tight sandstone gas is often found in formations with an ambiguous caprock and trap border or an unclear gas reservoir boundary. Tight sandstone gas is continuously distributed over a large area with the following geological characteristics.

The formation contains diverse source rocks, such as coal-bearing strata with normal thermal evolution degrees, and lacustrine and marine source rocks. Coal-measure source rocks are typically dominant.

Hydrocarbon distribution in the formation is not controlled by structural belts. Slope belts and depressions

are often favorable areas and are widely distributed and locally enriched. For example, the Sulige, Yulin, and Daniudi gas fields are all in the North Shaanxi slope, which has gentle structure (slope gradient of 1–3°) and undeveloped faults. The Hechuan gas field is in the central Sichuan Basin's gentle slope belt (slope gradient of 2–3°), and its main part lies in the Guang'an structure, which has multiple nearly EW faults. A large gas-bearing zone remains in the gentle structures around the Guang'an structure.

Tight sandstone gas reservoirs are mostly characterized by extremely low porosity and permeability, strong heterogeneity, and higher water saturation, and are distributed over large areas. Reservoirs are dominantly pore and pore-fracture type reservoirs. For example, the porosity of sandstones in the Sulige gas field ranges between 5% and 12%, and permeability is $(0.1–0.82) \times 10^{-3} \mu\text{m}^2$. Reservoir properties are apparently affected by lithology. Coarse sandstone porosity is greater than 10% and its permeability is greater than $0.82 \times 10^{-3} \mu\text{m}^2$; however, fine sandstone porosity is generally lower than 5% and its permeability is lower than $0.03 \times 10^{-3} \mu\text{m}^2$. The porosity of the T_{3x}⁴ gas reservoir in the Guang'an gas field is mainly 6% to 14%, with an average porosity of 9.9%, and its permeability is $(0.2–5) \times 10^{-3} \mu\text{m}^2$. Locally developed intergranular pores and intragranular dissolved pores are dominant pore and fracture types in this reservoir, which is generally a fracture-pore type reservoir.

Source rocks and reservoirs exist in the same bed and are in close contact. The T_{3x}², T_{3x}⁴, and T_{3x}⁶ tight sandstone gas reservoirs in the Upper Triassic Xujiahe Formation in the Sichuan Basin directly contact the underlying T_{3x}¹, T_{3x}³, and T_{3x}⁵ source rocks; therefore, natural gas generated in the underlying layers can flow upward into the reservoirs through vertical migration.

Primary and short-distance secondary migration are dominant. Hydrocarbon mainly accumulates in the diffusion mode and the floatation process is limited. Hydrocarbon flows mainly take the form of a non-Darcy flow. Faults and fractures that connect lower source rocks can serve as dominant vertical hydrocarbon migration pathways. Lateral hydrocarbon migration mainly occurs through porous layers and fractures inside the Xujiahe Formation. The faults inside the Xujiahe Formation are relatively small, generally several thousand meters, and with throws mostly less than 100 m; however, there is a great quantity of faults with developed associated fractures. These faults and their associated fractures increase the lateral connectivity of Xujiahe Formation sandstone reservoirs, thus they are favorable for lateral hydrocarbon migration and accumulation.

Hydrocarbon charges and accumulates in multiple

stages. Source evolution and reservoir evolution and development history of the Upper Triassic Xujiahe Formation in the Sichuan Basin, together with thin section analysis, confirmed that Xujiahe Formation hydrocarbons in the central Sichuan-Southern Sichuan transitional zone underwent three migration-accumulation stages. The first stage was in the Late Jurassic early-middle Yanshan period, and corresponds to the initial hydrocarbon generation stage of Xujiahe Formation source rocks. During this stage, the T_3x^1 and T_3x^3 source rocks in the lower part of the Xujiahe Formation generated hydrocarbons. The second stage took place during the Cretaceous-Early Tertiary middle-late Yanshan period when Xujiahe Formation hydrocarbons in this area were generated, migrated, and accumulated in substantial amounts. During this stage, source rocks of each Xujiahe Formation member generated hydrocarbons at a peak rate. Some hydrocarbons were derived from underlying strata in some areas, but Xujiahe Formation natural gas was still predominant. The third stage has lasted since the Late Tertiary Himalayan movement. Tectonic activities helped distribute and migrate the generated natural gas, which was accumulated again, though some was lost during migration in outcrop areas.

Fluid differentiation is poor in reservoirs without uniform fluid contacts or a uniform pressure system. Saturation is greatly different, and oil, gas, and water tend to coexist.

Tight sandstone gas resource abundance is lower. Oil/gas regions may form horizontally, but they have no or extremely low natural productivity. Therefore, it is necessary to take suitable measures to realize commercial production and extend the stable production period.

4 Geochemical Characteristics of Coal-Derived Tight Sandstone Gas in China

4.1 Analysis method

We collected 78 gas samples from large tight sandstone gas fields in the Ordos, Sichuan, and Tarim basins. Table 2 shows the basic geochemical data of the samples, which were tested in the Laboratory Center of PetroChina Research Institute of Petroleum Exploration & Development and the Langfang Branch of the PetroChina Research Institute of Petroleum Exploration & Development.

Natural gas compositions were analyzed using a HP 6890 gas chromatograph. Hydrocarbon gas components were separated using one capillary column (Plot A1₂O₃ 50 m×0.53 mm) and rare gas was separated using two capillary columns (Plot 5 Å molecular sieve 30 mesh×0.53 mm and Plot Q 30 mesh×0.53 mm). The gas

chromatograph furnace temperature was initially set at 30°C for 10 min, and was then increased to 180°C at a rate of 10°C/min.

Natural gas carbon isotopes were analyzed using a Delta S GC/C/IRMS isotope mass spectrometer. The gas chromatograph separated gas components, which were then injected into the mass spectrometer after being transformed into CO. Individual alkane gas components (C₁–C₅) and CO were separated using the chromatographic column (Plot Q 30 m). Chromatographic column temperatures increased from 35°C to 80°C at a rate of 8°C/min and to 260°C at a rate of 5°C/min, and then maintained at 260°C for 10 min. Each sample was analyzed three times, and the stable carbon isotope (denoted as δ) was analyzed according to PDB criteria with a $\pm 0.5\%$ accuracy and $\%$ precision.

Alkane gas hydrogen isotopes were tested using a MAT 253 isotope mass spectrometer equipped with an Ultra TM chromatograph. Helium gas was adopted as the carrier gas and a HP-PLOT Q capillary chromatographic column (30 mesh×0.32 mm×20 μ m) was used at a 1.4 ml/min flow rate with an inlet set to 180°C. Methane hydrogen isotopes were measured in the fractional injection mode (diversion ratio 1:7). Chromatograph temperature was initially kept at 40°C for 5 min, and was then increased to 80°C at a rate of 5°C/min, to 140°C at 5°C/min, and to 260°C at 30°C/min. The reactor temperature reactor was 1450°C. Natural gas components were transformed into C and H₂, and H₂ was injected into the mass spectrometer to test the hydrogen isotope (denoted as δ) according to the SMOW criteria at a $\%$ precision. Alkane gas hydrogen isotopes were generally measured adopting standard H₂ samples. The international standard samples NG1 (coal-derived gas) and NG3 (oil-type gas) for hydrogen isotope calibration were developed by the Langfang Branch of the PetroChina Research Institute of Petroleum Exploration & Development and other well-known international laboratories (Dai *et al.*, 2012). The hydrogen isotope testing accuracy was $\pm 3\%$.

4.2 Geochemical characteristics of coal-derived tight sandstone gas

In this subsection, we discuss the geochemical characteristics and origins of coal-derived tight sandstone gas in China's Ordos, Sichuan, and Tarim basins.

4.2.1 Chemical composition of coal-derived tight sandstone gas

The hydrocarbon gas content of tight sandstone gas varies from basin to basin but is typically greater than 90%. In the Ordos Basin, Upper Paleozoic natural gas has a hydrocarbon content greater than 95%, with a CH₄

Table 2 Main components & carbon and hydrogen isotope of natural gas in tight sandstone gas field of China

Basin	Gas Field	Well number	Horizon	Main Components of Natural Gas								$\delta^{13}\text{C}_{\text{VPDB}}$ (‰)					Data Sources
				CH ₄	C ₂ H ₆	C ₃ H ₈	<i>i</i> C ₄	<i>n</i> C ₄	N ₂	CO ₂	Aridity coefficient	CH ₄	C ₂ H ₆	C ₃ H ₈	C ₄ H ₁₀	CO ₂	
Ordos Basin	Sulige	S40-16	P _{1x}	90.31	5.29	1.17	0.21	0.25	1.88	0.65	/	-32.6	-24.9	-25.2	/	-10.4	This work
		S8	P _{1x}	91.67	5.15	0.98	0.19	0.17	0.40	0.93	/	-33.5	-23.2	-23.5	/	-7.4	
		Y10	P _{1x}	91.57	5.53	0.82	0.15	0.11	1.76	/	0.93	-34.6	-24.4	-23.3	-22.8	/	
	Yulin	Y 10	P _{1s}	95.29	1.18	0.69	0.18	0.12	1.09	1.32	0.98	-33.9	-22.2	-20.5	-21.2	/	
		Y 12	C _{3t}	94.31	1.37	0.13	0.03	0.01	3.85	0.26	0.98	-36.9	-23.7	-23.5	-23.8	/	
		Y 36-9	P _{1s} ²	93.85	3.64	0.57	0.10	0.11	0.09	1.56	/	-32.9	-26.3	-24.2	/	-7.1	
		S143	P _{1s} ²	93.91	3.65	0.58	0.10	0.11	0.10	1.43	/	-33.6	-26.0	-24.4	/	/	
	Wushen	S 19	C _{2b}	94.95	1.86	0.24	0.04	0.03	0.12	2.69	0.98	-35.4	-25.8	-24.9	-23.2	/	
		S 231	P _{1s}	93.55	4.00	0.72	0.13	0.16	0.61	0.65	/	-34.2	-25.1	-25.7	/	-9.8	
		S 26	C _{3t}	87.22	1.84	0.17	0.02	0.02	3.03	7.05	0.98	-33.5	-23.2	-23.0	-22.3	/	
	Country	S 65	P _{1x}	95.74	2.54	0.29	0.03	0.04	1.10	0.13	0.99	-29.1	-23.5	-25.5	-24.1	/	
		S 83	P _{1s}	93.32	3.39	0.45	0.17	0.07	1.57	0.80	0.96	-32.6	-20.8	-19.6	-16.1	/	
		M1	P _{1x}	95.89	3.53	0.40	0.09	0.06	1.79	0.32	0.96	-32.6	-23.0	-21.9	-20.6	/	
		P2	P _{1s}	95.35	2.82	0.36	0.05	0.04	0.51	0.71	0.97	-32.3	-25.1	-23.1	-23.2	/	
	Mizhi	P3	C _{3t}	94.43	0.51	0.04	0.01	0.00	4.66	0.20	0.99	-31.5	-26.3	-27.6	-25.6	/	
ZC11		P _{1x}	91.19	6.00	1.06	0.24	0.16	1.17	0.05	0.92	-35.6	-24.5	-22.2	-21.7	/		
ZC11		C _{3t}	92.30	2.57	0.40	0.12	0.03	3.40	1.15	0.97	-35.1	-21.4	-19.4	-20.1	/		
Shenmu	S1	P _{1x}	92.86	4.69	1.23	0.16	0.18	0.73	/	0.94	-36.8	-25.0	-23.9	-23.4	/		
	S1	P _{1s}	83.25	8.67	1.54	0.17	0.20	4.11	1.97	0.89	-37.3	-23.9	-21.5	-22.0	/		
Daniudi	N1	P _{1x}	92.61	5.13	0.62	0.11	0.11	0.36	0.86	0.94	-35.5	/	/	/	/		
Sichuan Basin	Guang'an	GA106	T _{3x} ⁴	94.16	4.78	0.49	0.09	0.07	0.39	/	0.95	-37.8	-25.7	-24.7	-22.1	-8.4	
		GA 108	T _{3x} ⁶	92.35	5.81	0.95	0.20	0.21	0.36	/	0.93	-39.2	-26.9	-26.0	-24.7	-11.7	
		GA 111	T _{3x} ⁶	92.33	6.10	0.68	0.21	0.23	0.30	/	0.93	-39.9	-27.3	-26.7	-25.4	-10.6	
	Bajiaochang	GA 128	T _{3x} ⁴	94.31	4.33	0.54	0.10	0.07	0.59	/	0.95	-37.7	-25.2	-23.3	-21.1	-8.0	
		GA 002-23	T _{3x} ⁶	92.08	5.90	1.02	0.19	0.19	0.50	/	0.93	-39.4	-26.9	-26.2	-24.9	-11.3	
		GA 002-43	T _{3x} ⁶	90.83	6.04	1.32	0.25	0.26	1.15	/	0.92	-40.4	-28.6	-27.3	-25.9	-13.2	
		LS1	T _{3x} ⁴	91.88	5.92	1.22	0.21	0.22	0.42	/	0.92	-40.5	-27.4	-24.5	-23.4	-7.3	
	Lianchi	LS3	T _{3x} ⁴	90.62	5.92	1.76	0.24	0.44	0.83	/	0.92	-43.7	-29.9	-28.6	-25.6	-15.4	
		Xichong	T _{3x} ⁴	90.84	6.06	1.55	0.33	0.38	0.64	/	0.92	-41.7	-27.8	-25.4	-24.6	-15.6	
	Jinhua	J33	T _{3x} ⁶	92.28	5.02	1.20	0.23	0.27	0.86	/	0.93	-39.5	-25.7	-24.4	-23.1	-9.8	
		J 47	T _{3x} ⁶	92.80	5.07	1.20	0.21	0.24	0.32	/	0.93	-39.8	-25.7	-24.3	-23.0	-9.3	
		J 48	T _{3x} ⁶	91.90	5.30	1.38	0.26	0.31	0.67	/	0.93	-41.1	-26.2	-24.5	-23.6	-8.7	
		J 49	T _{3x} ²	96.26	2.85	0.53	0.10	0.09	0.11	/	0.96	-38.5	-27.2	-24.6	-23.1	-6.2	
		J 53	T _{3x} ⁴	92.95	4.93	1.14	0.20	0.24	0.38	/	0.93	-40.1	-27.4	-24.6	-24.4	-8.8	
	Suinan	J17	T _{3x} ⁴	92.20	5.88	1.07	0.20	0.20	0.30	/	0.93	-38.9	-25	-23.4	-22.6	-5.9	
S56		T _{3x} ²	89.76	7.23	1.62	0.37	0.34	0.46	/	0.90	-41.0	-26.6	-24.1	-24.5	-5.6		
M64		T _{3x} ⁴	89.73	7.02	1.59	0.30	0.31	0.84	/	0.91	-42.5	-28.2	-25.3	-25.8	-12.0		
Moxi	M85	T _{3x} ²	91.37	6.06	1.29	0.31	0.25	0.51	/	0.92	-41.6	-27.1	-23.8	-25.1	-7.1		
	N103	T _{3x} ²	92.88	5.61	0.79	0.21	0.16	0.26	/	0.93	-40.5	-27.2	-24.4	-24.3	-7.8		
Longnv	N106	T _{3x} ²	94.07	4.66	0.55	0.16	0.11	0.30	/	0.94	-39.2	-26.1	-23.5	-23.6	-6.6		
	Tongnan	T _{3x} ²	88.04	8.81	1.78	0.34	0.35	0.47	/	0.89	-42.1	-27.9	-24.8	-27.1	-15.0		
Tarim Basin	Dabei	DB101	K _{1bs}	95.70	2.22	0.40	0.29	/	1.20	0.22	0.97	-30.5	-22.6	-21.8	-22.8	/	
		DB102	K _{1bs}	95.30	2.22	0.28	0.25	/	1.29	0.71	0.97	-30.7	-22.3	-21.5	-25.8	/	
		DB104	K _{1bs}	/	/	/	/	/	/	/	/	-26.7	-19.2	/	/	/	
		DB104	K _{1bs}	/	/	/	/	/	/	/	/	-27.1	-21.4	/	/	/	
		DB103	K _{1bs}	94.30	2.45	0.51	0.45	/	1.27	0.99	0.97	-31.9	-24.2	-19.7	/	/	
		DB2	K _{1bs}	95.26	2.25	0.38	0.53	/	1.19	0.39	0.97	-30.8	-21.5	-19.8	/	/	
		DB201	K _{1bs}	95.80	1.90	0.27	0.18	/	1.42	0.44	0.98	-30.9	-22.1	-21.9	-23.4	/	
		DB201	K _{1bs}	96.10	1.98	0.37	0.31	/	0.64	0.54	0.97	-31.2	-22.0	-21.0	/	/	
		DB202	K _{1bs}	95.10	1.93	0.45	0.36	/	0.92	1.19	0.97	-29.3	-20.7	-22.1	-19.6	/	
		DB202	K _{1bs}	94.80	1.57	0.36	0.30	/	1.27	1.67	0.98	-30.4	-21.8	-22.5	-25.4	/	
Keshen	DB301	K _{1bs}	96.20	1.66	0.17	0.17	/	1.26	0.51	0.98	-29.9	-22.3	/	/	/		
	KS2	K	/	/	/	/	/	/	/	/	-28.3	-17.7	-15.7	/	/		
Keshen	KS1	K _{1bs}	98.50	0.36	0.01	0.01	/	0.51	0.59	0.99	/	/	/	/	/		
	KS201	K _{1bs}	97.20	0.57	0.04	0.07	/	1.34	0.74	0.99	/	/	/	/	/		
Keshen	KS5	K _{1bs}	97.40	0.27	0.01	0.02	/	0.97	1.36	0.99	-26.5	-17.8	-19.2	-28.2	/	Wang Zhaoming, 2014	

content of more than 90% (Table 2). Its higher dry coefficient suggests that it is mainly a “dry gas” (Fig. 2) and its condensate oil content is quite low. We performed statistical analyses of gas compositions of large tight

sandstone gas fields (e.g., Sulige, Yulin, Wushen Banner, Mizhi, Shenmu, and Daniudi) in the Ordos Basin, and determined their CH₄ (79.77%–97.49%), C₂H₆ (0.7%–8.18%), C₃H₈ (0.01%–2.56%), *i*C₄H₁₀ (0.03%–0.49%),

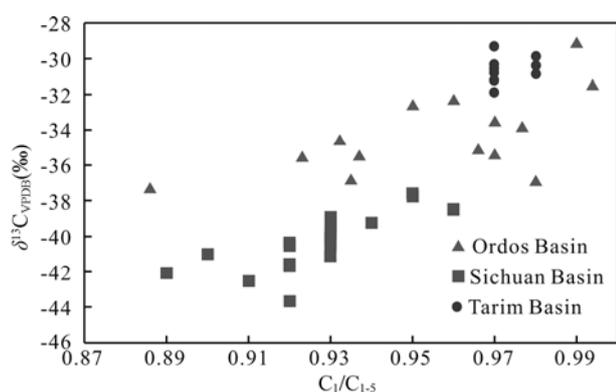


Fig. 2. $\delta^{13}\text{C}_1$ vs. $\text{C}_1/\text{C}_{1-5}$ of natural gas.

and $n\text{C}_4\text{H}_{10}$ (0.01%–0.64%) contents. The principal values of these compounds are in the ranges of 88%–94%, 3%–6%, 0.4%–1.3%, 0.07%–0.23%, and 0.08%–0.28%, respectively. In the Xujiahe Formation tight sandstone gas field in the Sichuan Basin, we determined the contents of CH_4 (81.64%–96.26%), C_2H_6 (2.85%–9.03%), C_3H_8 (0.49%–3.6%), $i\text{C}_4\text{H}_{10}$ (0.09%–0.82%), and $n\text{C}_4\text{H}_{10}$ (0.07%–0.96%). The principal values of these compounds were in the ranges of 82%–92%, 4%–7%, 0.5%–2.0%, 0.2%–0.4%, and 0.15%–0.38% respectively. In the Dabei and Keshen tight sandstone gas fields of Tarim Basin, we determined the contents of CH_4 (94.3%–98.5%), C_2H_6 (0.26%–0.245%), C_3H_8 (0.01%–0.51%) and C_4H_{10} (0.01%–0.53%), and their principal values were in the ranges of 95%–97%, 1.5%–2.2%, 0.2%–0.4%, and 0.15%–0.4%, respectively. The hydrocarbon composition of tight sandstone gas in the Ordos Basin is obviously characterized by high CH_4 content. Its heavy hydrocarbon (C_{2+}) content is affected by kerogen type, maturity, and migration distance, and is generally less than 10% and less than 5% in some cases. Natural gas in the Ordos, Sichuan, and Tarim basins is of proximal accumulation and Type III kerogen is dominant. Differences in methane and heavy hydrocarbon contents are mainly influenced by maturity. Tight sandstone gas in the Ordos Basin has a lower heavy hydrocarbon content than that of natural gas in the Xujiahe Formation in the Sichuan Basin, but it is slightly higher than that of gas in the Tarim Basin. Heavy hydrocarbon content variation reflects maturity differences in the three basins.

The non-hydrocarbon portion of tight sandstone gas in the Ordos, Sichuan, and Tarim basins consists mainly of N_2 and CO_2 . N_2 and CO_2 content in the tight sandstone gas of the Ordos Basin is 0%–13.93% and 0%–9.71%, respectively, with principal values of 0.2%–2.0% and 0.5%–1.8%. Tight sandstone gas in the Sichuan Basin has N_2 and CO_2 contents of 0.09%–4.11% and 0.03%–1.5%, respectively, with principal values of 0.3%–1.3% and 0.3%–0.6%. In Tarim Basin tight sandstone gas, N_2 and

CO_2 contents are 0.51%–1.42% and 0.22%–1.67%, respectively, with principal values of 1.0%–1.2% and 0.5%–1.2%. Tight sandstone gas in the Ordos, Sichuan and Tarim basins has relatively low non-hydrocarbon contents, but the contents vary depending on basins and gas fields. The Ordos, Sichuan, and Tarim basins have extremely low H_2 and He contents in tight sandstone gas, generally lower than 0.1%, and the H_2S content of these gas deposits is basically zero. Many factors, such as the lithochemical compositions of gas-bearing systems, subsurface fluids, dissolved gases, and introduced air, affect non-hydrocarbon compositions of tight sandstone gas.

4.2.2 Carbon isotope composition of coal-derived tight sandstone gas

Coal-derived tight sandstone gas is commonly heavier in terms of carbon isotopes than oil-type gases. The carbon isotope content of Ordos Basin tight sandstone gas varies in a limited range. Specifically, $\delta^{13}\text{C}_1$ ranges from -37.9‰ to -29‰ , with the majority between -35‰ and -31‰ ; $\delta^{13}\text{C}_2$ ranges from -27.8‰ to -22.1‰ , with the majority between -25‰ and -23‰ ; $\delta^{13}\text{C}_3$ ranges from -27.8‰ to -21.6‰ , with the majority between -25‰ and -22‰ ; and $\delta^{13}\text{C}_4$ ranges from -28.7‰ to -19.5‰ , with the majority between -24‰ and -22‰ (Fig. 3). Ordos Basin tight sandstone gas isotope composition is heavier than that in the Xujiahe Formation in the Sichuan Basin (Fig. 4). The $\delta^{13}\text{C}_1$, $\delta^{13}\text{C}_2$, $\delta^{13}\text{C}_3$, and $\delta^{13}\text{C}_4$ contents in the Xujiahe Formation natural gas range from -43.8‰ to -37.7‰ (most between -41‰ and -38‰), from -29.9‰ to -25‰ (most between -26‰ and -27‰), from -28.6‰ to -23.3‰ (most between -26‰ and -24‰), and from -27.1‰ to -21.1‰ (most between -25‰ and -23‰), respectively. On the other hand, Ordos Basin tight sandstone gas isotope composition is lighter than that of gas in the Tarim Basin (Table 2; Fig. 3). The $\delta^{13}\text{C}_1$, $\delta^{13}\text{C}_2$, $\delta^{13}\text{C}_3$, and $\delta^{13}\text{C}_4$ concentrations in Xujiahe Formation natural gas range from -31.9‰ to -26.5‰ (most between

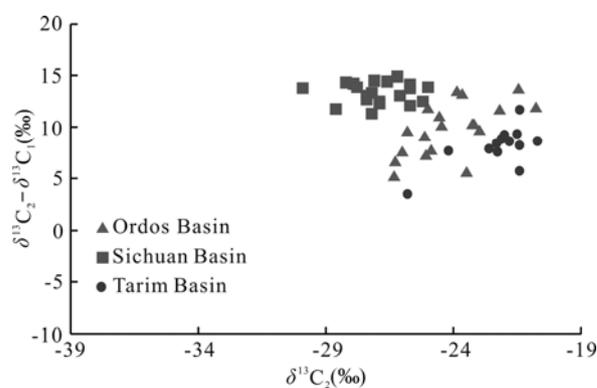


Fig. 3. $\delta^{13}\text{C}_2$ vs. $\delta^{13}\text{C}_2 - \delta^{13}\text{C}_1$ of natural gas.

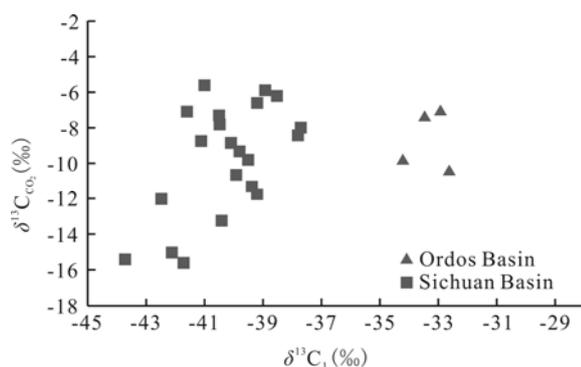


Fig. 4. $\delta^{13}\text{C}_1$ vs. $\delta^{13}\text{C}_{\text{CO}_2}$ of natural gas.

-30‰ and -28‰), from -24.2‰ to -17.7‰ (most between -22‰ to -20‰), from -22.5‰ to -15.7‰ (most between -21‰ and -19‰), and from -28.2‰ to -19.6‰ (most between -25‰ to -22‰) respectively. The above-mentioned tight sandstone gas carbon isotope compositions reveal that the gas is all coal-derived in the three basins. Isotope composition differences are controlled by kerogen and maturity. The maturity, R_o , of Carboniferous-Permian source rocks in the Ordos Basin (1.4%–2.8%) is higher than that of Xujiache Formation source rocks in the Sichuan Basin (1.0%–2.0%), but lower than that of Tarim Basin source rocks (1.5%–3.5%). Tight sandstones mostly show proximal accumulation, so there is less difference in migration distance, thus the fractional distillation effect on isotopes is less different.

4.2.3 Change of carbon isotope series in tight sandstone alkane gas

(1) Positive carbon isotope series in most tight sandstone alkane gas. Table 2 shows the positive carbon isotope series distribution of most tight sandstone alkane gases in the Ordos, Sichuan, and Tarim basins. A positive carbon isotope series means that carbon isotope $\delta^{13}\text{C}$ increases sequentially as alkane gas increases its molecular carbon number, i.e., $\delta^{13}\text{C}_1 < \delta^{13}\text{C}_2 < \delta^{13}\text{C}_3 < \delta^{13}\text{C}_4$. This characteristic presents in primary alkane gas that is not secondarily reworked (Dai et al., 2004). Extensive positive carbon isotope series exist in natural gas in global petroleum basins (Dai, 1992). Natural gas in China's large tight sandstone gas fields is all derived from coal, thus its $\delta^{13}\text{C}_1$ distribution range (-30‰ to -40‰) is the same for coal-derived gas. Patience (2003) put forward that the $\delta^{13}\text{C}_1$ of coal-derived gas should be between -38‰ and -22‰; however, the minimum and maximum $\delta^{13}\text{C}_1$ values shown in Table 2 are both lighter than those reported by Patience.

(2) Apparent influence of maturity on carbon isotopes of coal-derived tight sandstone gas, and partial reverse occurring when $R_o > 1.2\%$. Table 2 and Fig. 5

show that differences in carbon isotopes between heavy hydrocarbon gas and methane decrease as source rock matures. Additionally, the dry coefficient (C_1/C_{1-4}) of organic alkane gas increases as source rock matures (Stahl, 1979; Prinzhofer, 2000). As for the coal-derived gas in China's large tight sandstone gas fields, carbon isotope differences between heavy hydrocarbon gas and methane decrease as source rock matures. The coal-derived gas R_o can be calculated using the formula

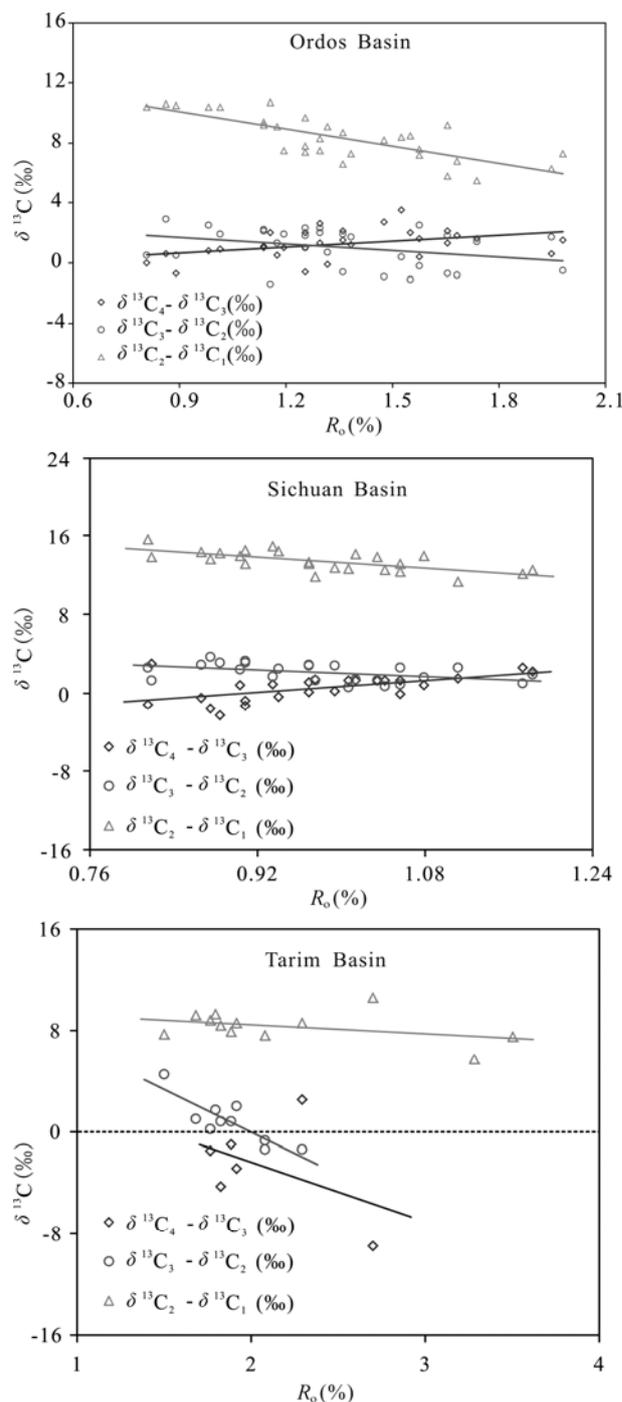


Fig. 5. $\delta^{13}\text{C}$ of natural gas vs. R_o values in the Ordos, Sichuan, and Tarim basins.

$\delta^{13}C_1 = 14.12 \lg R_0 - 34.39$ (Dai Jinxing et al., 1989). Figure 5 shows that the $\delta^{13}C_2 - \delta^{13}C_1$ and $\delta^{13}C_3 - \delta^{13}C_1$ values of the Ordos and Sichuan Basins decrease as source rock R_0 increases. Furthermore, carbon isotope differences between heavy hydrocarbon gas and methane decrease as C_1/C_{1-4} increases.

Figure 5 shows that a partial reverse occurs in coal-derived tight sandstone gas in the Ordos Basin when $R_0 > 1.2\%$. In other words, $\delta^{13}C_3 - \delta^{13}C_2$ becomes partially negative when $R_0 > 1.2\%$. In the Xujiahe Formation of the Sichuan Basin, $\delta^{13}C_3$ and $\delta^{13}C_2$ are basically equal when R_0 reaches 1.1%. Based on this change tendency, we predict that a partial reverse may occur when R_0 is greater than 1.2%. In the Tarim Basin, a partial reverse is apparent when $R_0 > 1.6$. If source rock maturity is high, the distribution tendency of the carbon isotope series in alkane gas changes, because the fractional distillation mechanism of alkane gas isotopes with different carbon chain structures differs at various maturity stages, and $\delta^{13}C_3$ and $\delta^{13}C_2$ become equal and then reverse. In summary, high source rock maturity may be an important reason for carbon isotope reversals in coal-derived tight sandstone gas.

(3) Reasons for stable carbon isotope reversal of alkane gas. When the $\delta^{13}C$ of alkane gas does not increase or decrease sequentially based on molecular carbon numbers, the chaotic arrangement is called a carbon isotope reversal, such as $\delta^{13}C_1 > \delta^{13}C_2 < \delta^{13}C_3 < \delta^{13}C_4$ or $\delta^{13}C_1 < \delta^{13}C_2 > \delta^{13}C_3 < \delta^{13}C_4$. The reversed carbon isotope ratio shown in Table 2 is about 1/3. It should be noted that carbon isotope reversals do not occur in large tight sandstone gas fields (Yulin, Zizhou, Daniudi, Mizhi, Shenmu, Xinchang, Guang'an, Bajiaochang, and Qiongxixi), but instead emerge in many wells in the Sulige, Hechuan, Anyue, and Dabei gas fields, as well as in several wells in the Wushen Banner and Luodai gas fields. Among the 18 gas samples we acquired from the Sulige gas field, 14 (78%) were observed to have a carbon isotope reversal. In the tight sandstone gas fields of the Ordos, Sichuan, and Tarim basins, $\delta^{13}C_2 > \delta^{13}C_3$ reversals were predominant (Fig. 6–8), and $\delta^{13}C_3 > \delta^{13}C_4$ is also common, being the main reversal in the Sulige gas field. It was previously proposed that $\delta^{13}C_3 > \delta^{13}C_4$ was common (Fuex, 1997) and $\delta^{13}C_2 > \delta^{13}C_3$ seldom occurred (Erdman, 1974), which is, in a way, different from our results in this paper (Table 2; Fig. 5).

Alkane gas carbon isotope reversal is caused by six factors: ① a mixture of organic and inorganic alkane gases; ② a mixture of coal-derived and oil-type gases; ③ a mixture of homotypic gases from different sources or cognate gases at different stages; ④ oxidization of one or more gas compositions by bacteria; ⑤ mixture of *in situ*

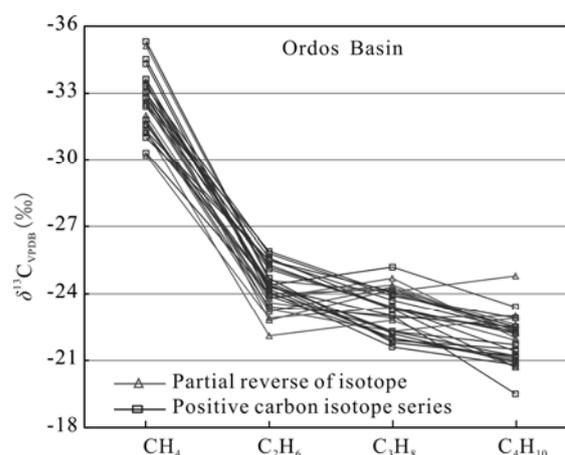


Fig. 6. Connection diagram of stable carbon isotopes of alkane gas in large tight sandstone gas fields in the Ordos Basin.

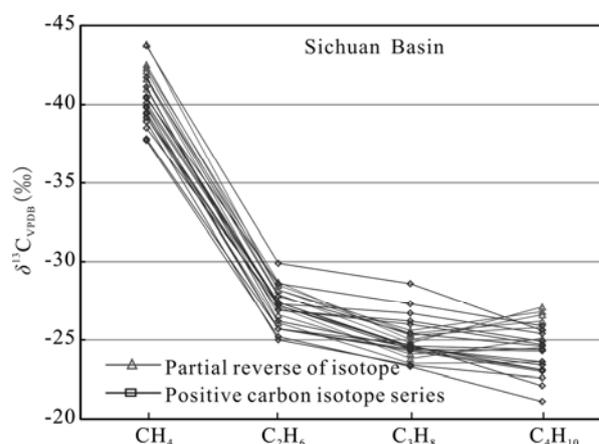


Fig. 7. Connection diagram of stable carbon isotopes of alkane gas in large tight sandstone gas fields in the Sichuan Basin.

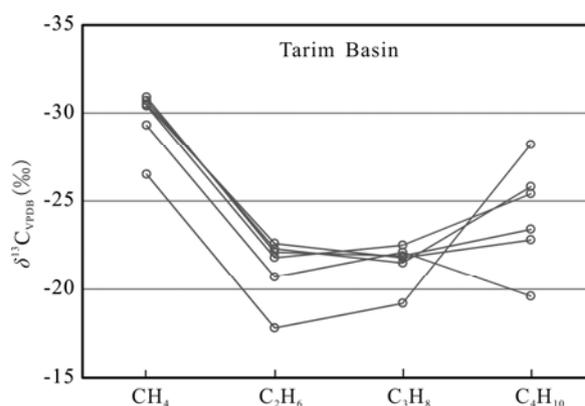


Fig. 8. Connection diagram of stable carbon isotopes of alkane gas in large tight sandstone gas fields in the Tarim Basin.

and water-soluble gases (Qin, 2012); and ⑥ thermal reduction reaction of sulfate (TSR; Liu et al., 2008; Hao et al., 2008).

In the Ordos, Sichuan, and Tarim basins, where large

tight sandstone gas fields are located, R/Ra presents the characteristics of crustal source gas. Additionally, the helium isotope in some reversed gas wells is also of crustal origin. Thus, we concluded that alkane gas in wells with carbon isotope reversal is of organic origin. Table 2 shows that alkane gas is mostly in the series of positive carbon isotopes, presenting the characteristics of organic gas without the negative carbon isotope series of inorganic alkane gas ($\delta^{13}\text{C}_1 > \delta^{13}\text{C}_2 > \delta^{13}\text{C}_3 > \delta^{13}\text{C}_4$; Des et al., 1981; Hosgörmez, 2007). In summary, carbon isotope reversal is not caused by mixing of organic and inorganic gases.

If one or more gas compositions are oxidized by bacteria, oxidized composition content will decrease. However, in Table 2, reversed composition content does not decrease. Moreover, bacteria generally reproduce at temperatures below 80°C. All Sulige gas field gas wells with carbon isotope reversals reach deeper than 3321 m and have formation temperatures higher than 80°C. We thus conclude that the reversal is not caused by bacterial oxidization.

The characteristics of coal-derived gas are reflected by the $\delta^{13}\text{C}_{1-4}$ values of natural gas produced from the Xujiahe Formation and its overlying parti-colored strata (i.e., Penglaizhen Formation (J_2p), Suining Formation (J_2sn), and upper Shaximiao Formation (J_2s)) in the Sichuan Basin. This is despite a small amount oil-type associated gas being generated by Type II source rocks in the first member of the Xujiahe (T_3x^1) and Ziliujing (J_2z) formations. We indicated that the carbon isotope reversal of alkane gas in the large tight sandstone gas fields of the Sichuan Basin is not caused by the mixing of coal-derived and oil-type gases. In the Ordos Basin, the upper Shihezi Formation (P_2sh) and lower Shihezi Formation (P_2x) in the parti-colored strata are non-source rocks, and the Shanxi (P_1s), Taiyuan (P_1t) and Benxi (C_2b) formations are the principal source rocks of coal-derived gas. However, the limestones of the Taiyuan and Benxi formations are of oil-type gas source rocks, and a small amount of oil-type gas has been discovered in Majiagou Formation (O_1m) reservoirs in the Jingbian gas field where limestone source rocks are developed. Consequently, carbon isotope reversal caused by the mixing of coal-derived and oil-type gases occurs (Xia Xinyu et al., 2000). The $\delta^{13}\text{C}_{1-4}$ value shown in Table 2 presents the characteristics of coal-derived gas. We indicate that the mixture of coal-derived and oil-type gases is not the reason for abundant carbon isotope reversals in the Sulige gas field and several carbon isotope reversals in the Wushen Banner gas field.

Coal-measure source rocks are characterized by “all-weather” gas generation and long-term charging. We confirmed that the carbon isotope reversal of tight sandstone alkane gas coexisting with coal-measure strata

is caused by the mixing of coal-derived gases of varying maturity at different stages, which has been proven by Jenden and Tilley (Jenden et al., 1993; Tilley et al., 2013).

The carbon isotope reversal ratio in the Sulige gas field is up to 78% because of multiple charging and accumulation. The alkane gas carbon isotope reversal in the Hechuan and Anyue gas fields of the Sichuan Basin was caused by the mixing of coal-derived gas that was charged and accumulated, respectively, in the Late Jurassic and Late Cretaceous (Zhao et al., 2010). The alkane gas carbon isotope reversal in the Dabei gas field of the Tarim Basin was caused by the mixing of abundant coal-derived gas that was charged 5 Ma and a small amount of coal-derived gas charged between 3 and 1 Ma (Wu Yongping et al., 2011). In summary, the alkane gas carbon isotope reversals in China’s large tight sandstone gas fields is mainly caused by the mixing of gases with different maturities, which were charged during different stages.

4.3 Origin and source of coal-derived tight sandstone gas

(1) Origin of coal-derived tight sandstone gas

Natural gas compositions and their carbon isotopes directly reflect origin types. The $\delta^{13}\text{C}_1$, $\delta^{13}\text{C}_2$, and $\delta^{13}\text{C}_3$ of tight sandstone gases in the Ordos, Sichuan, and Tarim basins shown in Table 2 are interpolated into the $\delta^{13}\text{C}_1$ - $\delta^{13}\text{C}_2$ - $\delta^{13}\text{C}_3$ chart distinguishing alkane gases of different origins proposed by Dai Jinxing (Fig. 9). The natural gas of major tight sandstone gas fields in China is distributed in the chart’s coal-derived gas regions, suggesting that the natural gas of China’s major tight sandstone gas fields is coal-derived gas from coal-bearing strata. Whiticar (1999) prepared a chart distinguishing natural gas origin based on $\delta^{13}\text{C}_1$ - $\text{C}_1/\text{C}_{2+3}$ parameters (Fig. 10). When the compositions and carbon isotope of tight sandstone gas in the Ordos, Sichuan, and Tarim basins are interpolated into this chart (Fig. 10), we see that natural gas in China’s large tight sandstone gas fields is a coal-derived gas generated by Type III kerogen.

Figure 10 shows that the $\delta^{13}\text{C}_1$ - $\delta^{13}\text{C}_2$ regression line of alkane gas in the Ordos, Sichuan, and Tarim basins is similar to that of coal-derived gas generated by Type III source rocks in the Sacramento Basin (Jenden, 1988) and the Niger delta (Rooney, 1995). This indicates that the tight sandstone gas in China is in the coal-derived gas category (Fig. 11).

(2) Source of coal-derived tight sandstone gas

Using the gas composition and isotope geochemistry of coal-derived gas, together with the geochemistry, accumulation, and time-space coupling characteristics of source rocks, we verified that the gas in China’s large tight sandstone gas fields is generated by coal-measure source

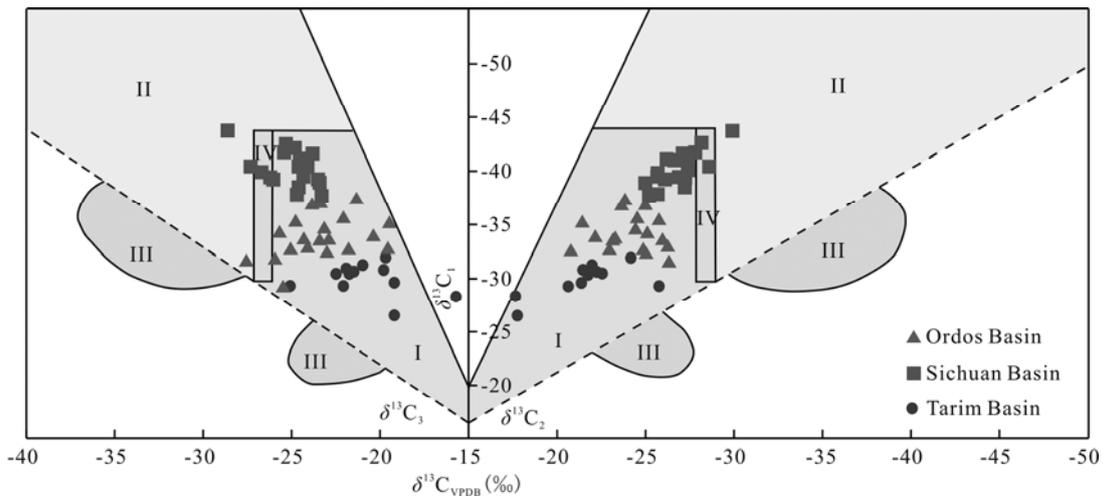


Fig. 9. Correlation diagram of $\delta^{13}C_1$, $\delta^{13}C_2$, and $\delta^{13}C_3$ (from Dai Jinxing, 1992, 2014).

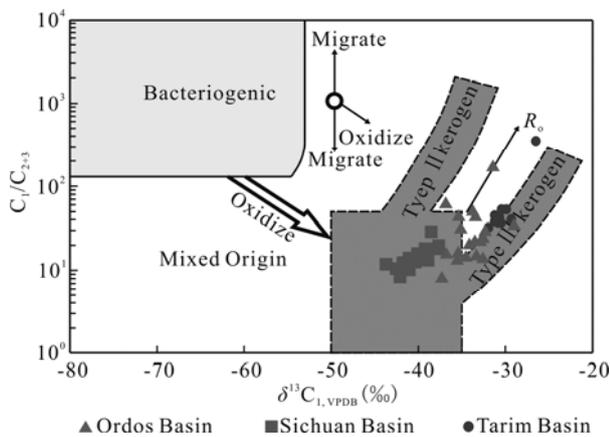


Fig. 10. $\delta^{13}C_1$ - C_1/C_{2+3} distinguishing chart (from Whiticar, 1999).

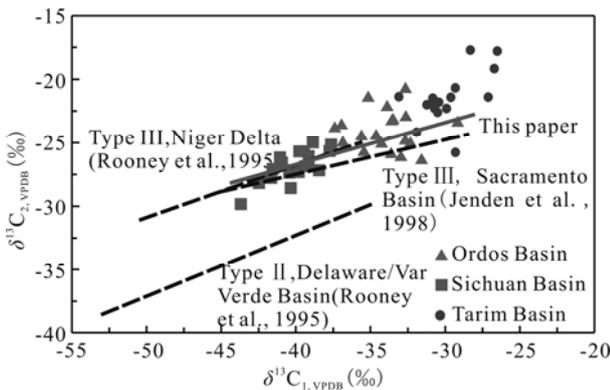


Fig. 11. Compositional correlation of $\delta^{13}C_1$ and $\delta^{13}C_2$.

rocks.

Upper Paleozoic strata in the Ordos Basin were deposited in a marine-terigenous environment. The Shanxi, Taiyuan, and Benxi formations are typical coal-measures in northern China, and their maceral consists mostly of vitrinite. The vitrinite content is 43.8%–90.2%

(average 73.6%; Table 3) in the Shanxi Formation, 21.2%–98.8% (average 64.2%) in the Taiyuan Formation, and 72.0%–93.3% (average 87.2%) in the Benxi Formation. Fusinite is dominant in mudstones, with contents of 51.8%–87.0% (average 72%), in the Shanxi Formation, 15.3%–89.3% (average 53.3%) in the Taiyuan Formation, and 12.3%–59.8% (average 44.0%) in the Benxi Formation. The Xujiahe Formation in the Sichuan Basin has a dominantly continental sedimentation environment and is divided into six members. The first, third, and fifth members (T_3x^1 , T_3x^3 , and T_3x^5) consist mainly of dark gray and gray mudstones and shales with interbedded coal of plain swamp facies and occasional slight quartz sandstones and siltstones. These members also contain source rocks, which are humic, with organic maceral composed of vitrinite-inertinite assemblages with less exinite and sapropel. In the Kuqa Depression, the Mesozoic source rocks are mainly developed, predominantly in the Jurassic (including partial Triassic), and are dominantly composed of extensively distributed thick coal-measures. Type III organic matter is dominant in the Kuqa Depression; therefore, its gas-generating potential is immense, and the presence of humic source rocks provides a substantial basis for forming coal-derived gas.

Tight sandstone gas is developed and coal-measure source rocks are extensively distributed in China. Xujiahe Formation source rocks are distributed throughout the whole Sichuan Basin, and source rocks with thicknesses greater than 10 m cover more than 75% of the basin. Source rocks are generally thicker in the west and thinner in the east. Dark mudstones are 10–1500 m thick, with an average thickness of 232 m, and the organic abundance of coal-measure source rocks is higher. Based on statistical analyses of 863 samples, the *TOC* of mudstone is 0.5%–

Table 3 Geochemical parameters of Upper Paleozoic source rocks in the Ordos Basin (He Zixin et al., 2003)

Item	Organic carbon (%)	Chloroform bitumen A (%)	Total hydrocarbon (ppm)	Maceral (%)		
			Max./Min. Average	Vitrinite	Fusinite	Inertinite
Mudstone	<u>19.29/0.07</u>	<u>0.5/0.0024</u>	<u>524.96/519.85</u>	<u>47/8</u>	<u>87/51.8</u>	<u>20.3/0</u>
	2.25	0.037	163.76	20.5	72	7.4
Coal	<u>83.2/3.83</u>	<u>1.96/0.03</u>	<u>4463/222</u>	<u>98.8/21.2</u>	<u>63.7/1.3</u>	<u>15.1/0</u>
	74.7	0.61	1757.1	64.2	32.1	3.7
Taiyuan Fm. Mudstone	<u>23.38/0.1</u>	<u>2.95/0.003</u>	<u>1904.64/15</u>	<u>82/8.3</u>	<u>89.3/15.3</u>	<u>34.5/0.3</u>
	3.33	0.12	361.6	38	53.3	8.4
Limestone	<u>6.29/0.11</u>	<u>0.43/0.0026</u>	<u>2194.53/88.92</u>			
	1.41	0.08	493.2			
Benxi Fm. Coal	<u>80.26/55.38</u>	<u>0.97/0.41</u>		<u>93.3/72</u>	<u>25.2/6.7</u>	<u>2.8/0</u>
	70.8	0.77		87.2	16	1.4
Mudstone	<u>11.71/0.05</u>	<u>0.44/0.0024</u>	<u>1466.34/12.51</u>	<u>47.8/12.3</u>	<u>59.8/12.3</u>	<u>39.5/0.3</u>
	2.54	0.065	322.73	24.5	44	18.2

6.5%, with most samples higher than 1.0%. The R_o of the source rocks was commonly greater than 1.5% in the western Sichuan Basin and less than 1.3% in the central Sichuan Basin. In the Kuqa Depression of the Tarim Basin, Mesozoic coal-measure source rocks are mainly developed, with coal-bearing source rocks covering 12000–14000 km², with a total thickness of about 1000 m, thus presenting immense gas-generating potential.

In the Ordos Basin, coal bed thickness is generally 10–15 m, with some locally thicker than 40 m. The cumulative thickness of coals and mudstones in the Ordos Basin is about 200 m. The average *TOC* of coals is 60% and the *TOC* of dark mudstones is 1%–5%, with most around 2%–4% and mudstones showing a maximum greater than 10%. Type III kerogen is dominant; therefore, the Ordos Basin is composed of good gas source rocks (Dai, 1980; Zhang Shiya, 1994; Huang, 1996). The Benxi, Taiyuan, and Shanxi formations are marine-terrigenous, with limestones of 2–5 m and 20–40 m thick, respectively. Their *TOC* values are generally in the range of 0.5%–5%, and Type II₁ kerogen is dominant. Black coal is the thickest in the Jingbian gas field and is thinning or absent outwards. In the Sulige gas field, black coal acts as secondary source rocks of oil-type gas in a limited area, and generally less than 10 m thick. It is only in the Jingbian gas field where oil-type gas or a mixture of coal-derived and oil-type gases is found. The underlying formation of this coal-measure consists of Lower Ordovician Majiagou Formation argillaceous dolomites that were formed during palaeo-karstification for 140 Ma, and is occasionally interbedded with gypsum. Based on an organic carbon analysis of 449 samples taken from the Majiagou Formation argillaceous dolomite, the maximum, minimum, and average *TOC* values are 1.81%, 0.04%, and 0.24% respectively. We thus conclude that the Majiagou Formation is a non-source rock. Therefore, the gas in this coal-measure and its overlying purple, red, or parti-colored lower Shihezi Formation (P_{2x}), upper Shihezi Formation (P_{2sh}), and Shiqianfeng Formation (P_{3s}) can only be generated by the coal-measures of the Benxi,

Taiyuan, and Shanxi formations.

Tight sandstone gas discovered in China is all derived from coal-measure source rocks. The deep-basin tight sandstone gas in the Cordillera Mountains and eastern Rocky Mountains of North America was also derived from coal-measure source rocks. Nevertheless, it is possible that a small amount of this tight sandstone gas is an oil-type gas generated by sapropel source rocks. Why coal-derived gas dominates China's large tight sandstone gas fields? The answer is the low porosity and permeability of tight sandstones. Humic coal-measures are "all-weather" gas source rocks and can generate natural gas at each coal ranking from lignite to anthracite. Thus, the gas source is sufficient over the long term, supplying tight sandstones with abundant natural gas. Sapropel source rock is at an "oil-generating window" to generate oil for a lengthy period during the middle stage of thermal evolution, so it is considered a "discontinuous gas source rock." Therefore, sapropel source rocks cannot provide tight sandstones with sufficient gas over the long term. As a result, tight sandstone gas is mostly coal-derived rather than oil-type.

5 Discussions: "Sweet Spot" Selection and Exploration Potential of Coal-derived Tight Sandstone Gas in China

Tight sandstone gas is the most reliable target for promoting reserves and production of unconventional gas in China. In the following section, it is discussed from the aspects of "sweet spot" selection, technically recoverable reserves, proven reserves, production, and exploration prospect.

5.1 Selection principle of "sweet spot" in tight sandstone gas

"Sweet spot" is a term for the preferential exploration and development target of tight sandstone gas. Evaluating and selecting a sweet spot plays a crucial role in economically and effectively exploiting tight sandstone

gas. A sweet spot should satisfy the following four conditions.

The effective source rocks should generally be more than 10 m. Additionally, coal-bearing strata should have higher cumulative thickness and thermal evolution maturity R_o value should be greater than 1.1%. Otherwise, the cumulative thickness of Type I and II source rocks with TOC greater 5% should be larger and R_o value should be greater than 1.3% (Zou Caineng, 2014).

Reservoirs should be thicker and have better physical properties or fractures and microfractures. The reservoir matrix should have air permeability greater than $0.5 \times 10^{-3} \mu\text{m}^2$ and its porosity should be higher than 8%. Tight sandstone reservoirs where fractures or microfractures are more developed should have a cumulative thickness greater than 20 m and low-amplitude structures may exist locally.

Gas saturation and reserve abundance should be higher. The difference between the sweet spot's gas saturation and that of the average of the tight sandstone gas zone in this area should be greater than 5%, and the reserve abundance should be twice the size of the average one in this area.

A tight sandstone gas zone satisfying the above conditions should be distributed over a larger area. One or more adjacent regions should be large enough to economically satisfy production construction.

For example, the Sulige tight gas field is in the western portion of the Shanbei slope in the Ordos Basin. Paleozoic strata in this field are characterized by gentle dip angles, short natural gas migration distances, and near-source accumulated reservoirs. The He 8 member of the lower Shihezi Formation and the Shan 1 member of the Shanxi

Formation provide the majority of gas production for the whole reservoir and are the sweet spots (Zhang et al., 2016).

5.2 Technically recoverable resources of tight sandstone gas

In China, there is a large amount of technically recoverable tight sandstone gas resources distributed extensively both onshore and offshore. Onshore coal-derived tight sandstone gas is concentrated in the Ordos, Sichuan, and Tarim basins (Fig. 12). Based on research by many scholars in recent years, the recoverable tight gas, coalbed methane (CBM), and shale gas resources are almost the same, and the technically recoverable tight gas, CBM, and shale gas resources are $11 \times 10^{12} \text{ m}^3$, $12 \times 10^{12} \text{ m}^3$, and $11 \times 10^{12} \text{ m}^3$, respectively (Qiu Zhongjian et al., 2012). However, the credibility of recoverable tight sandstone gas is the highest, because the recoverable resources of tight sandstone gas are mainly in the Ordos and Sichuan basins and have been verified by three rounds of national resource evaluation and the efforts of many research organizations and scholars over a 40 year period (Dai, 2003). Technically recoverable CBM resources have also been evaluated several times, but have been studied less than tight sandstone gas. Additionally, CBM production has not been good in recent years. Therefore, the credibility of technically recoverable CBM resources needs to be further verified. Tight gas and shale gas have the same technically recoverable resources ($11 \times 10^{12} \text{ m}^3$), but research on shale gas in China began in 2003, thus the credibility of its technically recoverable resources is lower than that of tight sandstone gas.

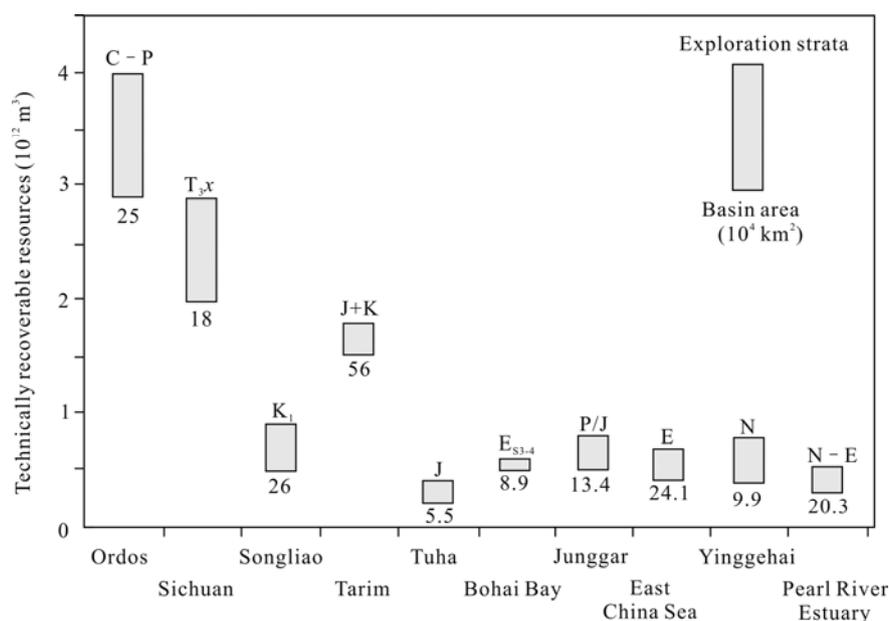


Fig. 12. Technically recoverable tight sandstone gas resources in some basins in China.

5.3 Proven reserves of tight sandstone gas

In China, tight sandstone gas is the unconventional gas with the largest reserves. Based on the latest statistics, by the end of 2014, the cumulative proven coal-derived tight sandstone gas in place in the Sulige gas field in the Ordos Basin, the eastern Ordos Basin, the Xujiahe Formation in the Sichuan Basin, and the Kuqa Depression in the Tarim Basin was $3.018 \times 10^{12} \text{ m}^3$. In the United States, yearly gas production grew from 1990 to 2010, mainly due to an increase in tight sandstone gas production. Among the top 100 gas reservoirs in the United States, based on reserves, 58 are tight sandstone gas reservoirs (Baihly et al., 2009). In China, 18 large gas fields with reserves of more than $1000 \times 10^8 \text{ m}^3$ were discovered by the end of 2010, of which nine are large tight sandstone gas fields with total proven gas in place of $25777.9 \times 10^8 \text{ m}^3$, accounting for 53.5% of the 18 large gas fields (Dai, 2003).

In summary, tight sandstone gas reserves in China is similar to those in the United States. Tight sandstone gas makes up a predominant share of the state's natural gas reserves. It is thus inevitably the first target for future unconventional gas exploration and development in China.

5.4 Production of tight sandstone gas

Tight sandstone gas contributes about 30% of China's total natural gas production. Over the past 20 years, conventional gas dominated China's natural gas production, but its share had been gradually declining. In contrast, unconventional gas production, which is dominated by tight sandstone gas, increased over that same period. Shale gas was in the early stages of massive industrial production and CMB production was very low. In 1990, conventional gas production accounted for 95.1% of China's total gas production, and tight sandstone gas, produced only in the Sichuan Basin, accounted for 4.9% ($7.48 \times 10^8 \text{ m}^3$ annually). In 2000, conventional gas accounted for 84.7% of total production and tight sandstone gas accounted for 15.3%. In the same year, tight sandstone gas production in the Sichuan and Ordos basins was $20.5 \times 10^8 \text{ m}^3$ and $20.2 \times 10^8 \text{ m}^3$, respectively. In 2010, tight sandstone gas production increased significantly in China, reaching $232.96 \times 10^8 \text{ m}^3$ (including $222.5 \times 10^8 \text{ m}^3$ in 15 large tight sandstone gas fields and $10.46 \times 10^8 \text{ m}^3$ in medium and small tight sandstone gas fields), which accounted for 24.6% of total gas production (Dai, 2003).

In 2013, tight sandstone gas production was $340 \times 10^8 \text{ m}^3$, accounting for 29% of total gas production, and it has played crucial role in the rapid increase in China's natural gas production in recent years. The increasing prevalence of tight sandstone gas production in the United States allows us to infer that tight sandstone gas will serve as a stable support for rapid total gas production increases in China over at least the next 10 years. Khlaifat et al. pointed out that tight sandstone gas accounted for nearly 70% of global unconventional gas production in recent years (Khlaifat, 2011); therefore, tight sandstone clearly gas plays a vital role in the natural gas industry.

5.5 Development prospect of tight sandstone gas

Tight sandstone gas is currently taking a leading role in expanding onshore natural gas reserves and production in China, and is the most reliable unconventional gas development target (Zou et al., 2013). Based on preliminary evaluation, total reserves reach about $5.0 \times 10^{12} \text{ m}^3$ in six large tight sandstone gas regions (eastern and southwestern Ordos Basin, the Xujiahe Formation in the Sichuan Basin, deep layers in the Songliao Basin, and Paleogene strata in the Bohai Bay Basin) in China (Table 4). In the future, tight sandstone gas will remain a leading contributor to China's natural gas industry. Tight oil and gas have been innovatively explored in China over the past decade. Tight gas is now a critical way to increase natural gas reserves and production. During the past ten years, the average amount of proven tight gas in place was $2760 \times 10^8 \text{ m}^3$, accounting for 45% of proven gas reserves over the same period. In 2013, tight gas production increased to $340 \times 10^8 \text{ m}^3$, accounting for 29% of China's total gas production, and the Sulige tight gas region was discovered, which with proven tight gas in place of $3.9 \times 10^{12} \text{ m}^3$ and a yearly production of $212 \times 10^8 \text{ m}^3$ is the largest in China. It is predicted that proven tight gas in place will grow to more than $4.0 \times 10^{12} \text{ m}^3$ within the next 20 years and that tight gas production will reach $1500 \times 10^8 \text{ m}^3$ by 2035. In summary, tight sandstone gas is a promising resource in China.

6 Conclusions

(1) In China, coal-derived sandstone gas dominates tight sandstone gas deposits, and is mainly distributed in the

Table 4 Predictive evaluation on China's large tight sandstone gas regions with 500-1000 billion m^3 reserves

No.	Large oil/gas region	Area (km^2)	Resources (10^{12} m^3)	Reserves (10^{12} m^3)
1	Eastern Ordos Basin	35000	2.2	1.0
2	Southwestern Ordos Basin	14500	0.8-1.2	0.5
3	Xujiahe, Sichuan Basin	21000	1.5	0.8-1
4	Deep layers in Songliao Basin	23000	1.3-2.5	0.7-1
5	Paleogene in Bohai Bay Basin	89000	1.5-2.5	0.8-1
6	Deep layers in Kuqa, Tarim Basin	36000	5	2-2.5

Ordos, Sichuan, and Tarim basins. Tight sandstone gas was mainly deposited in continental lake basin delta and marine-terrigenous facies environments. Being associated with coal-measure strata, tight sandstone gas is mostly buried more than 2000 m deep and has a formation pressure of 20–30 MPa, with pressure coefficients varying from overpressure to negative pressure. There are multiple oil-gas-water relationships and water is common in these formations.

(2) We proposed six conditions for the formation of coal-derived tight sandstone gas. The following three conditions are crucial. ① Effective mature source rocks that extend over a large area. These source rocks are dominantly Type III rocks in coal-bearing strata, with a thermal evolution maturity, R_o , greater than 1.0%. ② Tight sandstone reservoirs with nano-scale pore throats. Reservoirs with air permeability values lower than $1 \times 10^{-3} \mu\text{m}^2$ are distributed over a large area, accounting for more than 80% of the reservoirs. ③ Source rocks integrated or in close contact with reservoirs. Effective source-reservoir assemblages are formed inside high-quality mature source rocks or are composed of high-quality mature source rock and close-contact tight sandstones.

(3) We revealed the geochemical characteristics of coal-derived tight sandstone gas in China. In China, the hydrocarbon content of coal-derived tight sandstone gas is mostly higher than 95% and CH_4 content is dominant at more than 90%. Additionally, the dry coefficient is higher. The $\delta^{13}\text{C}_1$ and $\delta^{13}\text{C}_2$ values of three large tight sandstone gas regions mainly ranged from -42‰ to -28‰ and from -28‰ to -21‰ , respectively. Carbon isotope series analyses indicated that local isotope reversals were mainly caused by the mixing of natural gas generated at different stages. Further analysis showed that the reversal tendency becomes more apparent with increasing maturity, and that Type III coal-measure source rocks that coexist closely with tight reservoirs are developed extensively in all large gas regions. The organic petrology of source rocks and carbon isotope compositions of gas demonstrate that the tight sandstone gas in China is a coal-derived gas generated by coal-measure strata.

(4) In China, coal-derived tight sandstone gas presents a greater exploration prospect. The average incremental proven tight gas in place over the past decade was $2760 \times 10^8 \text{ m}^3$, accounting for 50% of incremental proven gas reserves. Two major tight gas regions have formed, the Sulige gas field in the Ordos Basin and the Xujiache Formation in the Sichuan Basin. Breakthroughs in tight gas exploration have also been made in the Tarim, Tuha, Songliao, and Bohai Bay basins, which have become important targets for increasing reserves and production. By the end of 2014, the cumulative proven coal-derived

tight sandstone gas in place in China had reached $3.018 \times 10^{12} \text{ m}^3$.

It is predicted that China's large tight oil and gas regions with 500–1000 billion m^3 in reserves are mainly distributed in the eastern Ordos Basin, the Xujiache Formation in the Sichuan Basin, the deep layers of the Songliao Basin, and Paleogene strata of the Bohai Bay Basin, and their reserves could reach as high as $5.0 \times 10^{12} \text{ m}^3$. In the future, coal-derived tight sandstone gas, will play a leading role in increasing natural gas reserves and production as the first target for unconventional gas development.

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