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Research article

Exploration and development of large gas fields in China since 2000

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Abstract

Fifty-one large gas fields had been proved in China until 2013. Specifically, exploration characteristics of those discovered since 2000 are as follows: (1) Large gas fields are only found in basins with sedimentary area larger than 10×10^4 km^2; (2) Large gas fields have been proved in 9 basins, with total proved reserves of 27085.88×10^8 m^3 before 2005, much less than that after 2005, which reached 81683.77×10^8 m^3 by the end of 2013; (3) The reserve abundance of large gas fields varies a lot. The Kela2 gas field has the largest reserve abundance of 59.05×10^8 m^3/km^2, which is 86 times that of the smallest reserve abundance, i.e. 0.684×10^8 m^3/km^2 of the Jingbian gas field; and (4) The reservoirs of large gas fields between 3000 m and 4500 m share a large proportion of proved reserves, accounting for 46.11% of the total. Development characteristics of the large gas fields in China are as follows: (1) The yield of large gas fields is essential to the natural gas industry of China. In 2013, the total yield was 922.72×10^8 m^3, accounting for 76.3% of the nation's total natural gas yield; (2) The yield is dominated by coal-derived gas, which reached 710.13×10^8 m^3 in 2013, accounting for 77.0% of the total yield of large gas fields in China; and (3) The yield of key large gas fields (Sulige, Jingbian, Daniudi, Puguang, and Kela2) is fundamental in making China a major gas producer.

Keywords: China; Large gas field; Coal-derived gas; Exploration; Development; Reserves; Yield

In China, a large gas field refers to one with proved gas in place (GIP) equal to or more than 300×10^8 m^3. The current number of proved large gas fields is different from that mentioned in previous literatures [1,2], because some large gas fields approaching this threshold (e.g. Qianmiqiao, Mahe and Panyu 30-1) have been removed from the list after their GIPs were graded down in reserves estimation. Figs. 1 and 2 show the geographic location and discovery year of 51 proved large gas fields in China by the end of 2013.

1. Exploration (geologic) features

The geologic features of large gas fields in China, including forming conditions, distribution regularity, main controlling factors, reservoir lithology and geologic ages, gas geneses and sources, traps and gas accumulation stages, have been widely discussed by the previous researchers [3−8], which will not be described in this paper. This paper only deals with the features rarely studied.

1.1. Large gas fields are discovered in the basins with an area of more than 10×10^4 km^2

There are 417 sedimentary basins in China, including 18 basins with an area larger than 10×10^4 km^2, 67 basins with an area ranging in $(1-10) \times 10^4$ km^2, and 332 basins with an area smaller than 10000 km^2 [9]. As is shown in Fig. 1, large gas fields have been discovered in 9 basins like Sichuan, Ordos, Tarim, Qaidam, Junggar, Songliao, Yingqiong, East China Sea and Pearl River Mouth of China (although Tiezhenshan Gas Field has been discovered in Taiwan Basin, it is not included in them due to its undefined reserves, the same below). Specifically, the Tarim Basin has the largest area (about 56×10^4 km^2) and the Qaidam Basin has the smallest area (about 10.4×10^4 km^2). No large gas field has been

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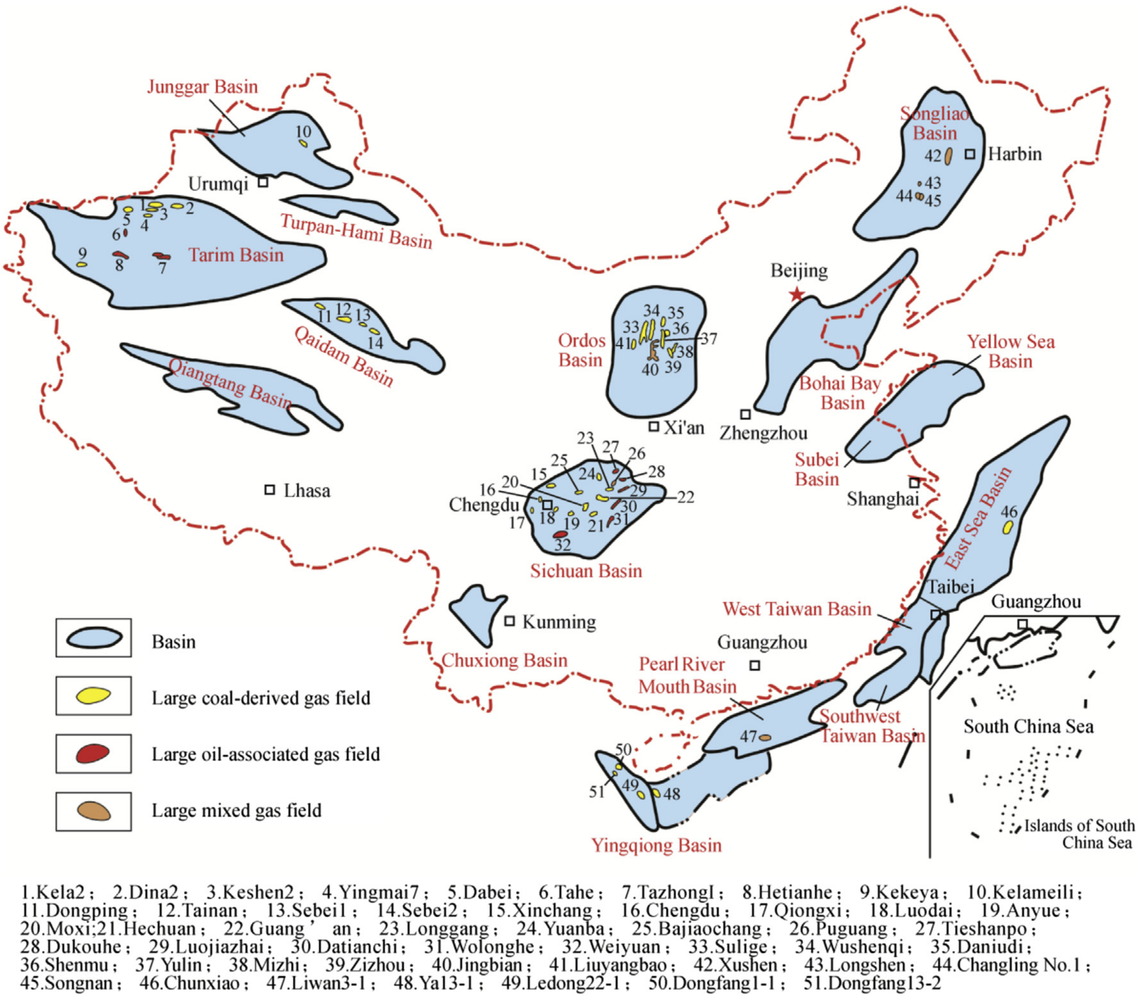

Fig. 1. Distribution of major sedimentary basins and large gas fields in China (by the end of 2013).

discovered in the basins with an area smaller than 10×10^4 km^2 up to now.

In the 18 basins with an area larger than 10×10^4 km^2 in China, only 9 basins have been found with large gas fields, while the remaining 9 basins are prospective for discovering large gas fields. Apart from further operations in the former 9 basins, attention will be paid to the remaining 9 basins where the potential is also large. Therefore, more large gas fields can be proved one after another in the future in China.

A larger sedimentary basin often corresponds to a larger area of source rocks, more horizons and stable structures, which provide the formation of a large gas field with two

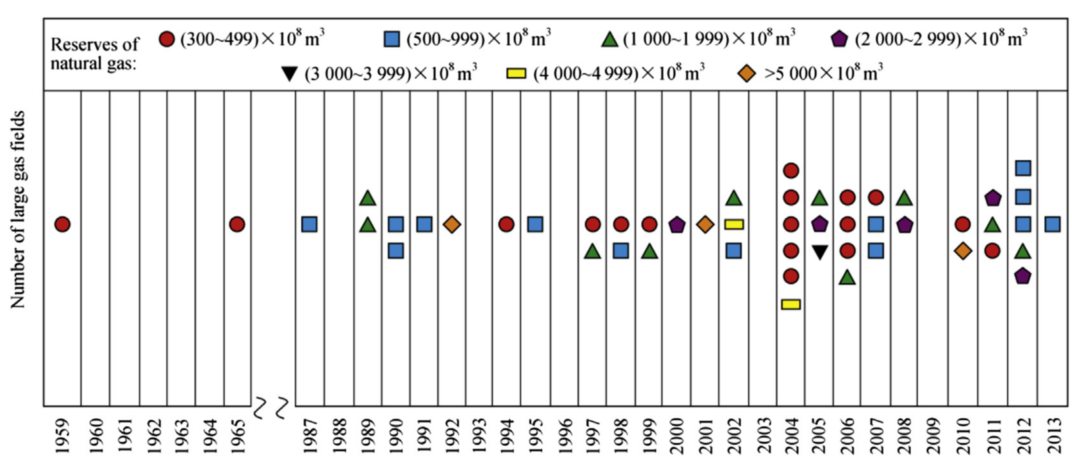

Fig. 2. Large gas fields proved in different years in China.

critical conditions, i.e. sufficient gas source and good preservation. Therefore, a large basin usually means multiple large gas fields with large reserves and high flow rates.

The Tarim Basin, the largest one in China, has 9 large gas fields discovered up to now. Typically, Kela2 Gas Field has the largest gas reserve abundance in China, and it is also the first gas field with an annual output exceeding $100 \times 10^8\ m^3$ in the country (2007). In this gas field, Well Kela2-7 records the maximum cumulative gas production − up to $101.7776 \times 10^8\ m^3$ by the end of August in 2014. The Ordos Basin, the third largest one in China, with an area of $25 \times 10^4\ km^2$, has 9 large gas fields discovered. Specifically, Sulige Gas Field contained reserves up to $12725.8 \times 10^8\ m^3$ and achieved an annual gas production of $212.2 \times 10^8\ m^3$ in 2013, making it a gas field with the maximum reserves and the highest annual gas production in China. In addition, the Ordos Basin produces the most gas in China ($379.63 \times 10^8\ m^3$ in 2013), contributing 31.4% to China's total annual gas production.

In the world, there are four basins with a respective area of more than $100 \times 10^4\ km^2$, namely, the Persian Gulf Basin, the West Siberian Basin, the Gulf of Mexico Basin and the Alberta Basin, where a great number of large gas fields and giant gas fields have been discovered. The Persian Gulf Basin is the largest one with an area of $256.5 \times 10^4\ km^2$, where 41 large gas fields have been proved with reserves of more than $1000 \times 10^8\ m^3$, including seven giant gas fields with proved reserves of more than $1.0 \times 10^{12}\ m^3$. The North-South Pars Field, the largest gas field in the world with reserves of $42.52 \times 10^{12}\ m^3$, is just in the Persian Gulf Basin. The West Siberian Basin ranks the second with its area of $250 \times 10^4\ km^2$, where at least 24 gas fields have been proved with reserves of more than $1000 \times 10^8\ m^3$, including 10 giant gas fields with proved reserves of more than $1.0 \times 10^{12}\ m^3$. The Urengoy Gas Field, the second largest one in the world with its reserves of $13.5 \times 10^{12}\ m^3$, is just in the basin, and its annual gas production was $3300 \times 10^8\ m^3$ in 1989 [10], accounting for 41.4% and 15.7% of gas production of the former Soviet Union (Russia) and of the world in the same year respectively.

1.2. Reserves of large gas fields

The reserves of large gas fields discovered in the nine basins of China are different to some extent in time and gas type. As is shown in Fig. 3, in time, 2005 implies an inflection point. Prior to 2005, large gas fields were only discovered in the Ordos Basin, Sichuan Basin, Tarim Basin, Qaidam Basin, Yingqiong Basin and East China Sea Basin, with relatively small total reserves of $27085.88 \times 10^8\ m^3$; during 2005−2013, large gas fields were further discovered in the Songliao Basin, Junggar Basin and Pearl River Mouth Basin, increasing greatly the total reserves of large gas fields to $81683.77 \times 10^8\ m^3$. Also as is shown in Fig. 3, there are two obvious features in gas types of large gas fields. Firstly, coal-derived gas predominates. The coal-derived gas accounted for 74.6% of the total reserves of large gas fields of China in 2013. Secondly, although coal-derived gas reserves exist in the large gas fields of all the nine basins in China, the contribution of each basin is different. The Ordos Basin, Sichuan Basin and Tarim Basin have the most maximum coal-derived gas reserves in China, with proved total reserves of $28614.15 \times 10^8\ m^3$, $14819.89 \times 10^8\ m^3$ and $7936.51 \times 10^8\ m^3$ respectively in 2013.

1.3. Reserve abundances of large gas fields

The reserve abundances of large gas fields differ greatly in China. For instance, the reserve abundance of Kela2 Gas Field is the maximum, about $59.05 \times 10^8\ m^3/km^2$, which is 86 times more than that of the Jingbian Gas Field (only about $0.684 \times 10^8\ m^3/km^2$). The reserve abundances of the nine large gas fields discovered in the Ordos Basin all are low, among which, the reserve abundance of the Daniudi Gas Field is the highest, but it is only $2.289 \times 10^8\ m^3/km^2$, and the three large gas fields (Jingbian, Mizhi and Zizhou) with reserve abundance of less than $1 \times 10^8\ m^3/km^2$ in China are all in this basin, which is obviously related to the fact that the reservoirs of large gas fields in the Ordos Basin are tight sands [11,12].

Although the smallest reserve abundance of large gas field is $0.684 \times 10^8\ m^3/km^2$ in China, there are large gas fields with

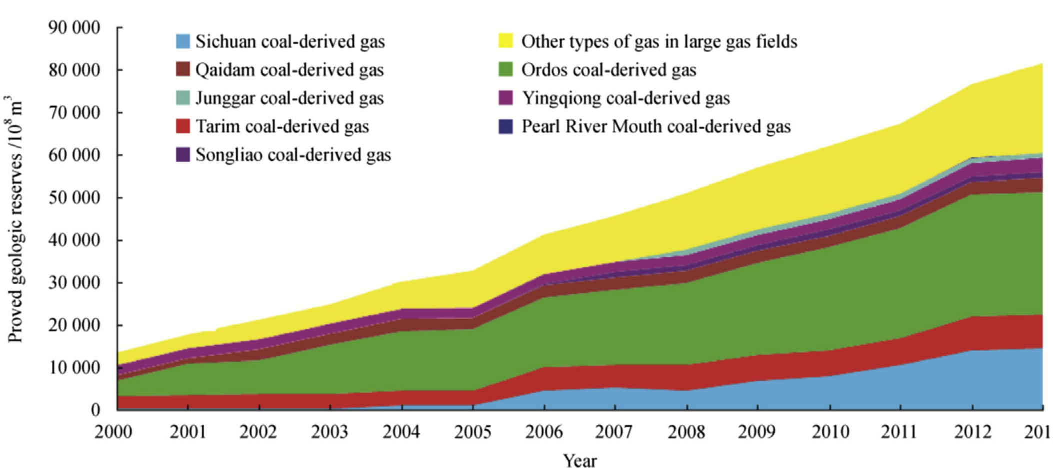

Fig. 3. Coal-derived gas and other types of gas in place proved in different basins of China during 2000−2013.

smaller reserve abundances abroad. For example, the reserve abundance of Elmworth Gas Field in Canada is only 0.37×10^8 m^3/km^2. The gas field with the maximum reserve abundance in the world is the Loekrige Gas Field in the USA, which is up to 102.2×10^8 m^3/km^2.

In view of reserve abundances, large gas fields in China have similarity with those abroad (Fig. 4). As is shown in Fig. 4, the large gas fields with $(1-5) \times 10^8$ m^3/km^2 reserve abundances come first, then those with $(5-10) \times 10^8$ m^3/km^2 reserve abundances; the proportion of large gas fields with reserve abundances of less than 1×10^8 m^3/km^2 is small. However, differently, the proportion of large gas fields with reserve abundances of more than 30×10^8 m^3/km^2 is low in China, but high in other countries.

1.4. Depths of large gas fields

Among 51 large gas fields proved in China by the end of 2013, the Keshen2 Gas Field of the Tarim Basin has the largest buried depth of gas zone, about 6550−6987.3 m, whereas the Sebei2 Gas Field of the Qaidam Basin shows the smallest buried depth, about 400−1420 m. As is shown in Fig. 5, the buried depths of gas zones in large gas fields of China mainly range in 3000−4500 m. Statistics of the relation between reserves and buried depths of large gas fields with reserves of more than 1000×10^8 m^3, 500×10^8 m^3 and 300×10^8 m^3 abroad were conducted by Zhang Zishu in 1990 (Table 1) [3]. As is shown in Table 1, among the 236 large gas fields with reserves of more than 300×10^8 m^3 and the 293 large gas fields with reserves of more than 500×10^8 m^3 abroad, the reserves at buried depths of 1500−3000 m account for 49.9% and 56.2% of the total reserves respectively, which are the “gold” buried depths of reserves of large gas fields; whereas the “gold” buried depths of the 114 large gas fields with reserves of more than 1000×10^8 m^3 are smaller, i.e., the reserves at buried depths of less than 1500 m account for 52.8% of the total reserves. In contrast, the “gold” buried depths of reserves of large gas fields in China are deeper than those abroad, i.e., the reserves at buried depths of 3000−4500 m (Fig. 5) account for 46.11% of the total reserves of China. As a result, the difficulties and costs of exploring large gas fields in China are all higher than those abroad.

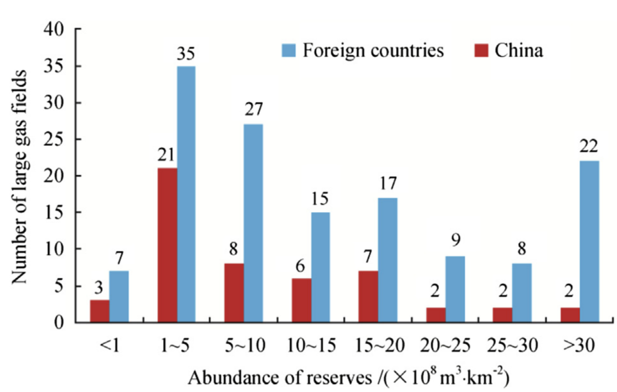

Fig. 4. Reserve abundance distribution of large gas fields in the world.

With drilling engineering increasingly improved and the demand for petroleum growing day by day, the petroleum exploration is gradually conducted from shallow to deep layers. Therefore, the petroleum exploration and discovery show a characteristic of deepening with years and being from easy to difficult. Nowadays, deep petroleum exploration is a trend. Definitions and criteria for deep zones vary among different scholars and in different countries and institutions. The depth at which the generation of a great deal of liquid hydrocarbon comes to an end and the generation of gaseous hydrocarbon commences is usually regarded as the boundary of a deep zone. However, because the geothermal gradients are different in all basins, the depths of deep zones also vary. The depths of deep zones are smaller in the basins with higher geothermal gradients, and vice versa. The depth criterion of deep zones in both the Bohai Bay Basin and the Songliao Basin with higher geothermal gradients is defined as being more than 3500 m [13,14]. Li Xiaodi believed that a deep zone refers to a zone with buried depth of more than 4000 m [15]; while Zhou Shixin et al. took the zone with buried depth of more than 4000 m or 4500 m as a deep zone [16]. The zone with buried depth of more than or equal to 15000 ft (4500 m) is classified as a deep zone in the world. The Calculation Specifications for Petroleum Reserves (2005) issued by the National Commission of Mineral Reserves defines the zone with buried depth ranging in 3500−4500 m as a deep zone and that of more than 4500 m as an ultra-deep zone. Whereas, the deep zone criteria adopted in China drilling engineering are as follows: 4500−6000 m: deep zone; more than 6000 m: ultra-deep zone. The 4th Symposium on Progress of Basic Research in Petroleum Geology took the deep and ultra-deep petroleum geology and accumulation as the subject, and the scholars participated in the conference regarded the zone of more than or equal to 4500 m as a deep zone. From the above, it is the mainstream understanding of all parties to take the zone with buried depth of more than or equal to 4500 m as a deep zone.

As is shown in Fig. 5, most deep large gas fields in China are proved after 2000. Later, the number of proved deep large gas fields has been increased; a total of 11 deep large gas fields have been proved in the 21st century in China, among which, the first deep large gas field — Dina2 Gas Field (4750−5590 m) was proved in 2002. Currently, the buried depths of reservoirs of two large gas fields (Keshen2, Yuanba) exceed 6000 m, namely 6550−6987.3 m and 6480−6880 m respectively. The Mills Ranch Field (7663−8083 m) in the USA is the deepest gas field in the world, with proved reserves of 365×10^8 m^3 and single well production of 6×10^4 m^3/d [17]. Therefore, the potential for exploring deep gas in China is still very great.

2. Development features

The features of development techniques, methods, engineering and technologies of large gas fields are not dealt with in this paper. It only focuses on the features like the produced gas type and volume of large gas fields and their significances in the gas industry of China.

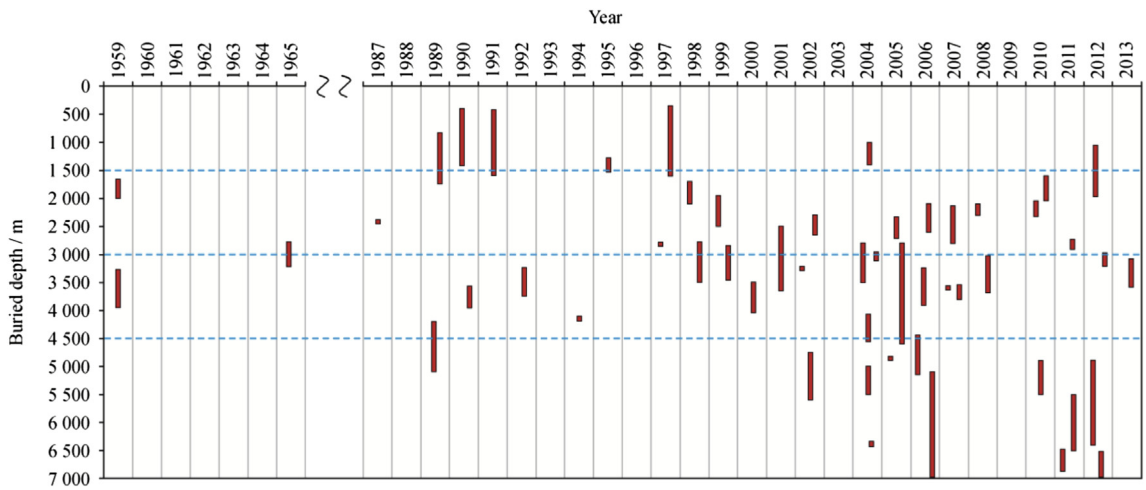

Fig. 5. Buried depth vs. discovery year of large gas fields in China.

As is shown in Fig. 6, the total annual yield of large gas fields in China increases over time. The yield was 90.92×10^8 m^3 in 2000, accounting for 34.33% of total gas production in China; the yield was 922.72×10^8 m^3 in 2013, accounting for 76.3% of total gas production of China. It indicates that large gas fields are a main contributor to the gas industry in China.

2.1. Coal-derived gas predominates in the yield of large gas fields

As is shown in Figs. 6 and 7, the coal-derived gas dominates in the yield of large gas fields in China. In 2000, the total yield of large gas fields was 90.92×10^8 m^3, among which, the yield of coal-derived gas was 70.62×10^8 m^3, accounting for 77.7%. In 2013, the total yield of large gas fields was 922.72×10^8 m^3, among which, the yield of coal-derived gas was 710.13×10^8 m^3, accounting for 77.0%. As is shown in Fig. 7, the proportion of yield of coal-derived gas in the total yield of large gas fields in China came to a peak, i.e., 90%, in 2008 and 2009.

2.2. The yield of key large gas fields is the cornerstone for a gas producer

Several key gas fields usually play an important role in supporting China as a gas producer [18]. The so-called key large gas fields refer to those with a majority of reserves or very large reserve abundance in a country. In China, Sulige, Jingbian, Daniudi and Puguang Gas Fields rank respectively the first, second, fourth and fifth in terms of reserves, and the Kela2 Gas Field contains the maximum reserve abundance. They are regarded as the five key large gas fields of China. Their proportion in the total gas production of China went up from nearly 11% to 38.0% year by year during 2001–2013 (Fig. 8). Specifically, the Sulige Gas Field produced 212.2×10^8 m^3 gas in 2013, accounting for 17.6% of total gas yield of the country. Qatar, Holland and Russia become major gas producers relying on the key large gas fields like the North Field, the Groningen Gas Field and the Urengoy Gas Field respectively. With the three key large gas fields like Urengoy, Yamburg and Zapolyarnoye, Russia provided an annual gas production within $5000–6200 \times 10^8$ m^3 during 1995–2012 (Fig. 9); the total gas production of the three key gas fields was 4582.3×10^8 m^3 in 2004, accounting for 75.4% of total gas production of Russia [18].

3. Prospects of gas development in China

The prospects of natural gas development in a country depend mainly on resource potentials, which are based on the quantity of resources, and the development/production potentials, which are based on reserves.

Table 1
Distribution of gas reserves in depths [3].

Depth (m)	Gas fields with reserves of more than $1000 \times 10^8 m^3$		Gas fields with reserves of more than $500 \times 10^8 m^3$		Gas fields with reserves of more than $300 \times 10^8 m^3$	
	Reserves ($\times 10^8$ m^3)	%	Reserves ($\times 10^8$ m^3)	%	Reserves ($\times 10^8$ m^3)	%
<1500	327710	52.8	311750	35.7	291185	38.8
1500–3000	268118	43.3	490180	56.2	373743	49.9
3000–4500	17929	2.9	55670	6.3	79012	10.5
>4500	5996	1	15510	1.8	6060	0.8
Total	(114 gas fields) 619753	100	(293 gas fields) 873110	100	(236 gas fields) 750000	100

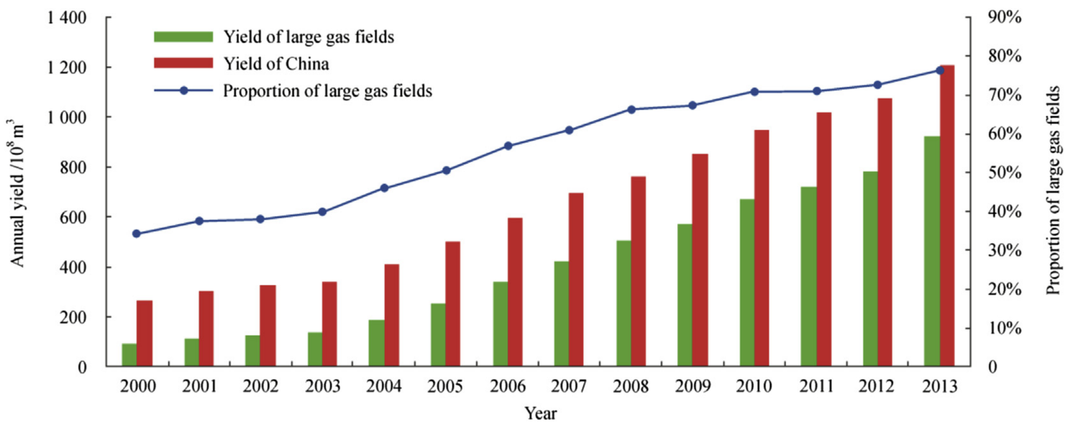

Fig. 6. Yield and its proportion variation of large gas fields during 2000−2013.

3.1. Gas resources

3.1.1. Conventional gas resources

Conventional gas geological resources in China have risen from (5.4−7) × 10^{12} m^3 [19] in 1981 to 63 × 10^{12} m^3 in 2010, which have been assessed by various scholars and divisions over the past thirty years and thus are trustworthy [20]. China recorded (39.0−39.2) × 10^{12} m^3 [21] recoverable conventional gas resources which is as immense as that in other major gas producers (Table 2) [22]. In a word, that will provide a solid foundation for the sustainable development of China's gas industry.

3.1.2. Unconventional gas resources

Unconventional gas may refer to the following sources of natural gas production: tight sandstone, shale, Coal Bed Methane (CBM), and gas hydrate. This paper discusses the implications of tight sandstone gas, shale gas and CBM in the recent development of gas industry because they are playing an important role in current production. Some scholars suggest that there is an average 921.9 × 10^{12} m^3 of global tight sandstone gas, shale gas and CBM, but others believe there is (800−6521) × 10^{12} m^3, approximately 1.7−13.8 times that of conventional gas resources [23]. This indicates a promising prospect of unconventional gas. Extensive development of tight sandstone gas (1980s), CBM (1990s) and shale gas (2000s) have begun in America, the leader in unconventional gas research, exploration and development, so it has become the largest gas producer in recent years.

In contrast to America, China is slow in unconventional gas research, exploration and development. However, a comparison of their recoverable resources and reserves of tight sandstone gas, shale gas and CBM (Table 3) suggests that China has similar recoverable resources with America, although the production in 2013 was much less. This indicates that China has a great potential for development of tight sandstone gas, shale gas and CBM, which will support the sustainable development of China's gas industry.

3.2. Recoverable gas reserves

Recoverable gas reserves of a country provide a foundation for assessing its production potential and national prosperity.

3.2.1. Remaining recoverable reserves of conventional gas

Remaining recoverable reserves, annual production and the ratio of reserves to production of conventional gas in 2013 in six major gas producers (Russia, America, China, Iran, Canada

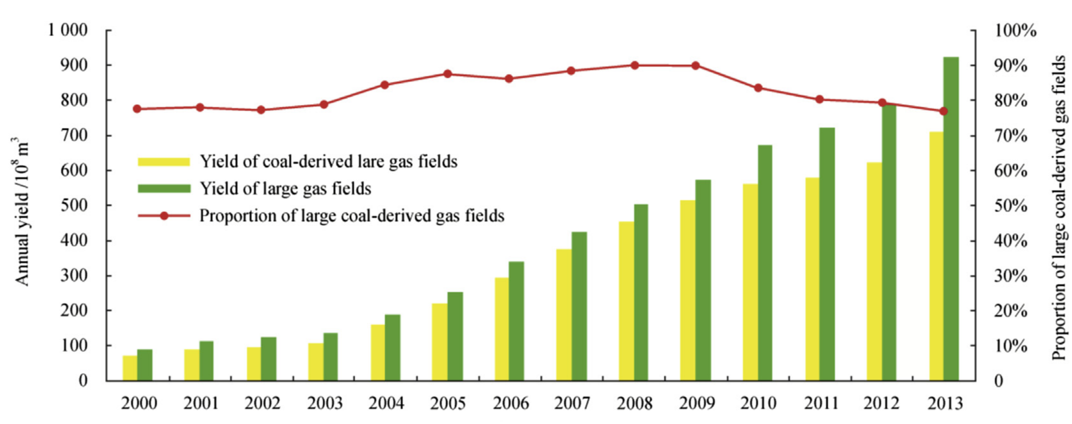

Fig. 7. Total annual yield vs. coal-derived gas yield of large gas fields in China during 2000−2013.

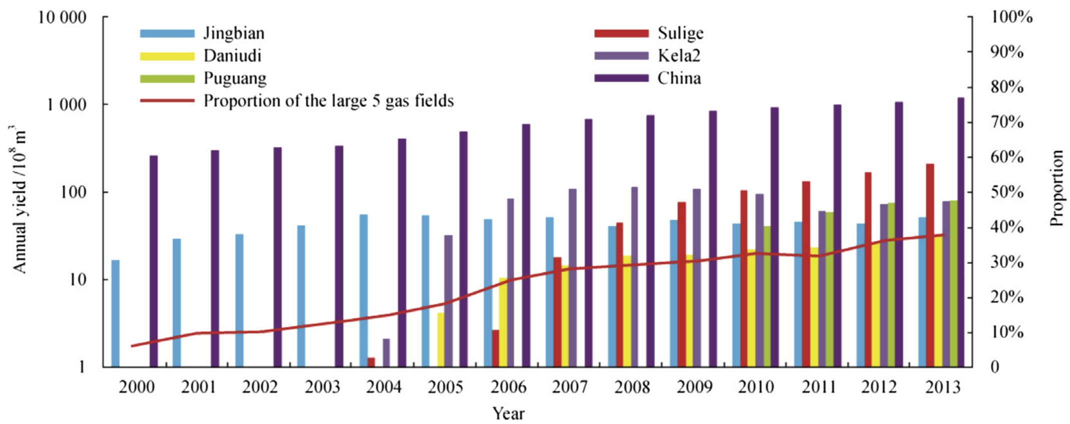

Fig. 8. Total annual yield of key large gas fields during 2001−2013 and its proportion in gas production of China.

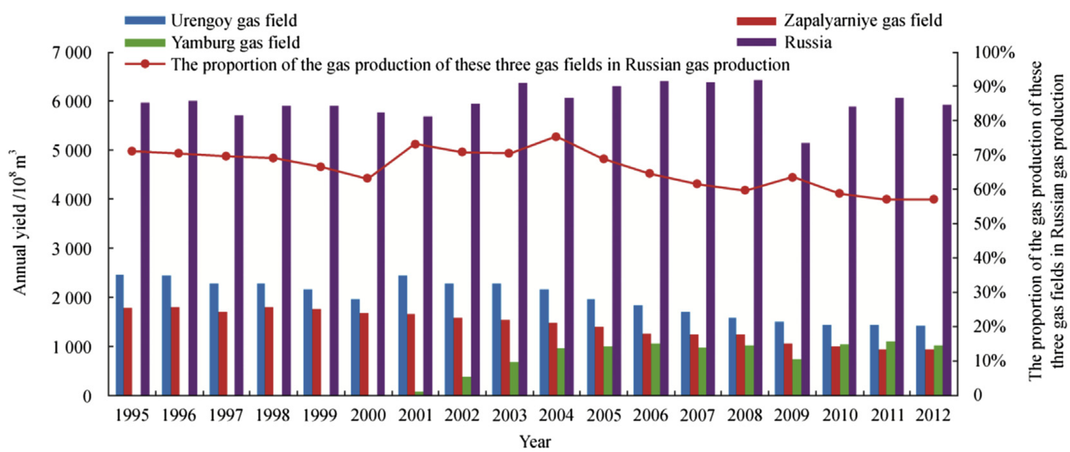

Fig. 9. Total annual yield of key large gas fields and its proportion in gas production of Russia (the annual yield of key large gas fields is taken from the Wood database).

and Saudi Arabia) are listed in Fig. 2. With a higher ratio of reserves to production, Russia, Iran and Canada may not only maintain a long-term stable production per year but also has the potential of further enhancement. America and Canada, which have a 13+ of that ratio, is difficult to maintain their production per year and they lack the potential of further enhancement. With a ratio of 26, China, however, has the potential of maintaining the present annual production and enhancing the future production.

3.2.2. Remaining recoverable reserves of unconventional gas

As is indicated in Table 3, China and America are quite similar in recoverable resources of tight sandstone gas, shale gas and CBM, as well as significant remaining reverses, and America's recoverable reserves, however, are about four times the number of China. This difference is also reflected in their gas production in 2013. This suggests that: (1) contribution of the present production of shale gas and CBM in China to its

Table 2
Summary of conventional gas resources & reserves and unconventional gas resources in China and other major gas producers.

Country	Recoverable / 10^{12} m^3		Remaining reserves of recoverable conventional resources in 2013 / $10^{12}m^3$	Gas production in 2013 / 10^8m^3	Ratio of reserves to production
	Conventional resources	Unconventional resources			
Russia	107.24	8.07	31.3	6048	51.7
America	40.43	32.88	9.3	6876	13.6
China	39.00−39.20	31.57	3.3	1171	28.0
Iran	35.37		33.8	1666	202.9
Canada	13.75	16.23	2.0	1548	13.1
Saudi Arabia	13.73		8.2	1030	79.9

Table 3
Comparison of recoverable resources, reserves and production of unconventional gas in China and America.

Gas type	Recoverable resources / 10^{12} m^3		Recoverable reserves / 10^{12} m^3		Production in 2013 / $10^8 m^3$	
	China	America	China	America	China	America
Tight sandstone gas	9–13	13	1.15	5	420	1370
Shale gas	31.57	32.88	0.0267	4.51	2	3228
CBM	10.9	3.46	0.2025	0.35	30	ca.415

gas industry is very limited; (2) China has a significant potential of shale gas and CBM production, which may greatly support the development of China's gas industry in the future.

4. Conclusions

A total of 51 large gas fields had been proved in China by the end of 2013. The exploration and development of large gas fields in China during 2000–2013 are characterized by:

1) Exploration: large gas fields are discovered in the basins with a depositional area larger than 10×10^4 km^2; large gas fields are proved in nine basins, with smaller proved reserves before 2005; the reserve abundances of large gas fields differ as much as 86 times at both sides of range; the proved reserves of large gas fields at buried depths of 3000–4500 m account for 46.11% of total reserves in China.
2) Development: the yield of large gas fields is the main contributor to the gas industry in China; coal-derived gas predominates in the yield of large gas fields; the yield of key large gas fields like Sulige, Jingbian, Daniudi, Puguang and Kela2 is the cornerstone for China to become a major gas producer.

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