



Major progress in the natural gas exploration and development in the past seven decades in China

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Abstract: China has made significant progress in the exploration and development of natural gas in the past 70 years, from the gas-poor country to the world's sixth largest gas production country. In 1949, the annual gas output in China was $1.117 \times 10^4 \text{ m}^3$, the proved gas reserves were $3.85 \times 10^8 \text{ m}^3$, and the average annual gas consumption and available reserves of per person were 0.0206 m^3 and 0.7107 m^3 , respectively. By 2018, the average domestic annual gas production per person was 114.8576 m^3 and the reserves were 12.01108 m^3 , and the average domestic annual gas production and reserves per person in the past 70 years increased by 5575 times and 16900 times, respectively. The exploration and development of large gas fields is the main way to rapidly develop the natural gas industry. 72 large gas fields have been discovered in China so far, mainly distributed in three basins, Sichuan (25), Ordos (13) and Tarim (10). In 2018, the total gas production of the large gas fields in these three basins was $1.03926 \times 10^8 \text{ m}^3$, accounting for 65% of the total gas production in China. By the end of 2018, the cumulative proved gas reserves of the 72 large gas fields had amounted to $124.504 \times 10^8 \text{ m}^3$, accounting for 75% of the total national gas reserves ($16.7 \times 10^{12} \text{ m}^3$). New theories of natural gas have promoted the development of China's natural gas industry faster. Since 1979, the new theory of coal-derived gas has boosted the discovery of gas fields mainly from coal-measure source rocks in China. In 2018, the gas production of large coal-derived gas fields in China accounted for 50.93% and 75.47% of the total national gas production and total gas production of large gas fields, respectively. Guided by shale gas theories, shale gas fields such as Fuling, Changning, Weiyuan and Weirong have been discovered. In 2018, the total proved geological reserves of shale gas were $10.45567 \times 10^8 \text{ m}^3$, and the annual gas production was $108.8 \times 10^8 \text{ m}^3$, demonstrating a good prospect of shale gas in China.

Key words: China; natural gas; coal-derived gas; shale gas; gas production; gas reserves; exploration and development progress

Introduction

Since the founding of the People's Republic of China 70 years ago, China has made great progress in natural gas exploration and development, and has changed from a gas poor country to the sixth largest gas producing country in the world. The sharp increase in gas reserves and per capita gas reserves is enough to explain China's process of changing from a gas poor country to a large gas producing country. China's annual gas production in 1949 was $1.117 \times 10^4 \text{ m}^3$ ^[1-2], the annual gas consumption per capita was 0.0206 m^3 . The annual gas consumption per capita in 2018 was $1602.7 \times 10^8 \text{ m}^3$ ^[3], and the annual gas consumption per capita was 114.8576 m^3 . The annual gas consumption per capita had increased by 5575 times in 70 years. China's proved geological reserves of natural gas in 1949 were $3.85 \times 10^8 \text{ m}^3$ ^[4], the per capita geological reserves of natural gas were 0.7107 m^3 , and the total proved geological reserves of natural gas in 2018 were $167.60024 \times$

10^8 m^3 , the per capita geological reserves of natural gas were 12.01108 m^3 , which had increased by 16900 times in 70 years. In 1949, China only discovered Ziliujing, Shiyougou and Shengdengshan gas fields in the Sichuan Basin, and small gas fields such as Jinshui, Zhudong, Niushan and Liuchongxi in Taiwan^[5]. In 2018, China discovered 313 gas fields, including 5 shale gas fields, 24 coalbed gas fields and 3 carbon dioxide gas fields. Among them, 72 large gas fields had reserves more than $300 \times 10^8 \text{ m}^3$. The geological reserves of the Sulige and Anyue gas fields are both over $1 \times 10^{12} \text{ m}^3$, and the current annual gas production of these two gas fields are both over $100 \times 10^8 \text{ m}^3$.

In the past 70 years, China has made brilliant achievements in gas production, reserves and number of discovered gas fields, which was mainly attributed to the rapid development of seismic exploration and drilling technology. In 1951, China established the first seismic team, and carried out the first PetroChina seismic exploration^[6-7] in the Yanchang mining

Received date: 27 Aug. 2019; **Revised date:** 30 Sep. 2019.

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Foundation item: Supported by the PetroChina Science and Technology Project (2013B-0601).

[https://doi.org/10.1016/S1876-3804\(19\)60266-1](https://doi.org/10.1016/S1876-3804(19)60266-1)

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area of the Ordos Basin. By 2018, China had established 191 petroleum exploration seismic teams. The development of China's seismic exploration technology can be divided into four stages: (1) Stage of light spot earthquake (1964-1971), using "51" light spot seismograph, recording seismic wave information with light spot photography on sensitive paper. It's characterized with single point reception, non playback, discovery only anticlinal traps and uplifts, and low efficiency and accuracy. (2) Stage of analog earthquake (1965-1981), using analog tape seismograph. It is mainly used for structural interpretation, trying to identify special lithologic bodies with velocity spectrum data. (3) Stage of digital earthquake (1974-1997), using digital seismograph. At this stage, the technology enjoyed increased coverage times and full digital processing interpretation to expand the application field, and was mainly used for the comprehensive evaluation of structure, petrology and petroliferous properties. (4) Stage of "two wide and one high" (2000 to now), which refers to wide frequency band, wide azimuth and high density. It's used to increase azimuth seismic information, and to solve the anisotropic problems caused by fractures and stresses, which is applied to the fields from conventional reservoir to unconventional reservoir, such as prediction of source rock quality and engineering quality, optimization deployment and field tracking of horizontal wells. It's characterized by full digital 3D visualization plus virtual reality, letting you see all that you get.

In 1949, there were only 8 shallow and medium-sized drilling rigs in China^[5]. However, in 2018, there were 2719 oil drilling rigs in China, mainly medium and deep drilling rigs, as well as ultra-deep drilling rigs. In recent years, with the help of the ultra-deep drilling with a depth of 6000 m, the Keshen, Dabei and Tazhong-1 large gas fields have been found in the Tarim Basin, and the Yuanba and Longgang large gas fields^[8] have been found in the Sichuan Basin, plus, the first deep well in Asia (8 882 m)^[9] has been completed in the Tarim Basin. Drilling technology developed from vertical well

to horizontal well and acid fracturing operation. The horizontal well technology ensures shale gas production and enables the development of the Fuling, Changning and Weiyuan shale gas fields in China.

1. From gas-poor country to gas-rich country

China's natural gas industry was very poor in the early days of the founding of the People's Republic of China. After a long and arduous exploration, it has embraced a fast development, making China's proved reserves of natural gas rise from negligible to the forefront of the world, and its natural gas production rise from negligible to the sixth largest gas producing country in the world.

1.1. The formation of a major country of natural gas resource

In 1949, China's proved natural gas reserves were only $3.85 \times 10^8 \text{ m}^3$ ^[1]. In the following decades, the growth of natural gas reserves was slow, but it increased significantly in the 40 years after 1979, especially in the late 20 years. From 1949 to 1993, it took 45 years for China's total proved natural gas reserves to rise to $1 \times 10^{12} \text{ m}^3$ (excluding Taiwan, the same for the following figures), while for the reserves to rise to $2 \times 10^{12} \text{ m}^3$, it took only six years. In 2009, the total proved reserves of natural gas exceeded $7 \times 10^{12} \text{ m}^3$ ^[10], and in 2014, the proved reserves of natural gas exceeded $10 \times 10^{12} \text{ m}^3$. In 2018, the total proved reserves of natural gas exceeded $15 \times 10^{12} \text{ m}^3$ (excluding shale gas, coalbed gas and other unconventional gas) (Fig. 1). It can also be seen from Fig. 1 that the rapid growth of China's natural gas reserves is closely related to the growth of coal-derived gas reserves, which is the main force of China's natural gas reserves growth. In 1999, the cumulative proved reserves of coal-derived gas exceeded $1 \times 10^{12} \text{ m}^3$, after only two years, the reserves reached $2 \times 10^{12} \text{ m}^3$, and by 2018, the cumulative reserves exceeded $9 \times 10^{12} \text{ m}^3$.

In China, 188 coal-derived gas fields (including 24 coalbed

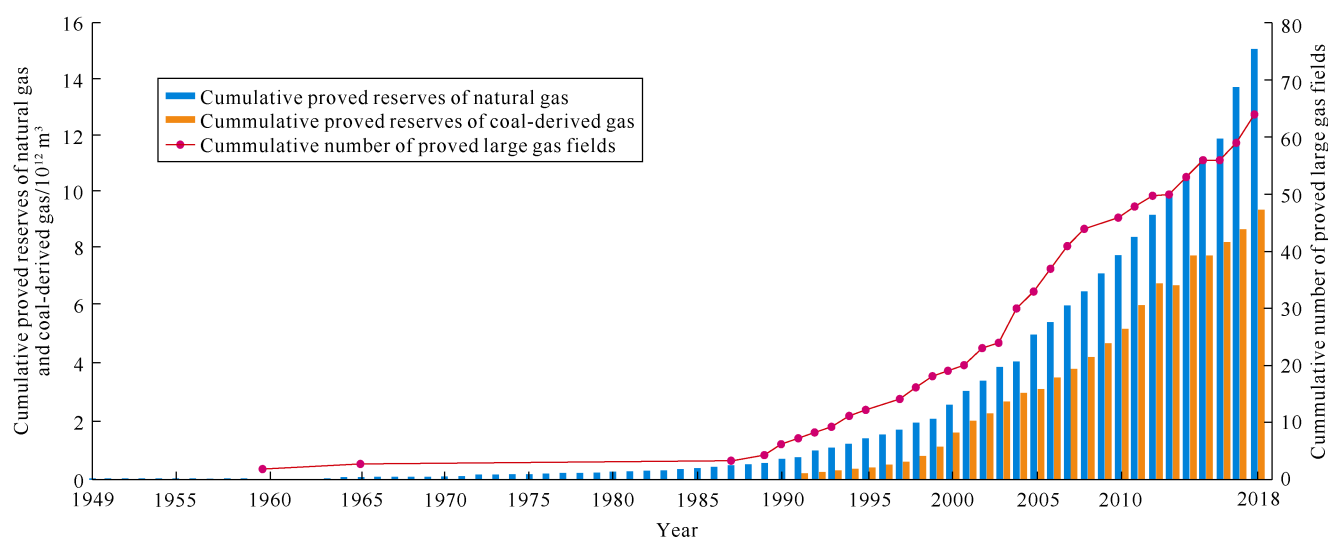


Fig. 1. The cumulative proved reserves of natural gas and coal-derived gas in China from 1949 to 2018 and their relationship with large gas fields.

gas fields) were discovered, accounting for 60.1% of 313 gas fields in total. By the end of 2018, the total proved reserves of coal-derived gas fields in China were $92.556 \times 10^8 \text{ m}^3$, accounting for 61.4% of the total proved reserves of gas reservoirs ($150.622.6 \times 10^8 \text{ m}^3$) in China in that year, which is consistent with the conclusion that the number of gas fields and proved reserves in previous studies in China are mainly coal-derived gas^[11–18].

1.2. The formation of a major country in natural gas production

In 1949, China's natural gas production was only $1117 \times 10^4 \text{ m}^3$ ^[1–2], and up to 1957, China's annual natural gas production was less than $1 \times 10^8 \text{ m}^3$; in 1958, the annual gas production reached $1.0643 \times 10^8 \text{ m}^3$, and in 1976, the annual production of natural gas exceeded 10 billion cubic meters ($100.9501 \times 10^8 \text{ m}^3$). In 1998, the annual production of gas was $222.8 \times 10^8 \text{ m}^3$, and the gas consumption per capita was only 17.9 m^3 , which indicates China as a country poor in natural gas. The standard of a major gas producing country is a country with an annual gas production of $500 \times 10^8 \text{ m}^3$ or more^[19]. In 1929, the United States produced $541 \times 10^8 \text{ m}^3$ of gas, which made it the first major country in producing natural gas; in 1960, Russia (former Soviet Union) produced $452.8 \times 10^8 \text{ m}^3$ of gas, becoming the second major country of natural gas production. From 1929 to 2003, there were only 11 major gas producing countries with an annual production of $500 \times 10^8 \text{ m}^3$ or more. Based on analysis, two basic conditions were found for a country to become a major gas producing country: (1) the recoverable resource of natural gas is more than $13 \times 10^{12} \text{ m}^3$; (2) the minimum remaining recoverable reserves are $1.2462 \times 10^{12} \text{ m}^3$ ^[19]. In 2003, China's recoverable natural gas resources were 13.32×10^{12} – $17 \times 10^{12} \text{ m}^3$, and the remaining recoverable reserves were $2.0894 \times 10^{12} \text{ m}^3$. Based on this data, Dai Jinxing^[19–20], Jia Wenrui^[21], Zhang Kang^[22] and Zhao Xianzheng^[23] concluded that China could become a major gas producing country in 2005. As expected, in 2005, China's annual gas production was $499.5 \times 10^8 \text{ m}^3$ (including $261.16 \times 10^8 \text{ m}^3$ of coal-derived gas, accounting for 52.3% of the total production), becoming the 11th major gas producing country in the world (Fig. 2), and there were 12 major gas producing countries in the world. According to Fig. 2, it can be seen that: (1) before becoming a major gas producing country in 2005, the proportion of coal-derived gas production in China's natural gas in each year was lower than 50% or even lower; after 2005, the proportion of coal-derived gas production in each year was higher than 50%, with an average annual rate of 56.5%, of which the largest proportion was 66.2% in 2008; (2) after 2005, the annual gas growth rate increased.

From 1949 to 2010, after 61 years, China's cumulative gas production reached $1 \times 10^{12} \text{ m}^3$ ($1.017 \times 10^{12} \text{ m}^3$), and then after 8 years from 2010 to 2018, the cumulative production increased to $2 \times 10^{12} \text{ m}^3$ ($2.068 \times 10^{12} \text{ m}^3$), which shows that

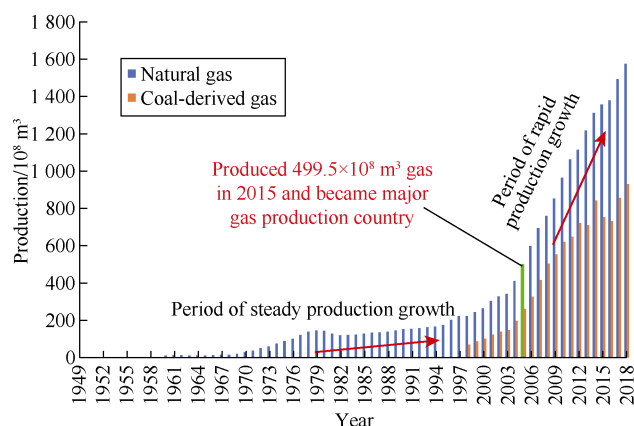


Fig. 2. Annual production of natural gas (including coal-derived gas) in China from 1949 to 2018.

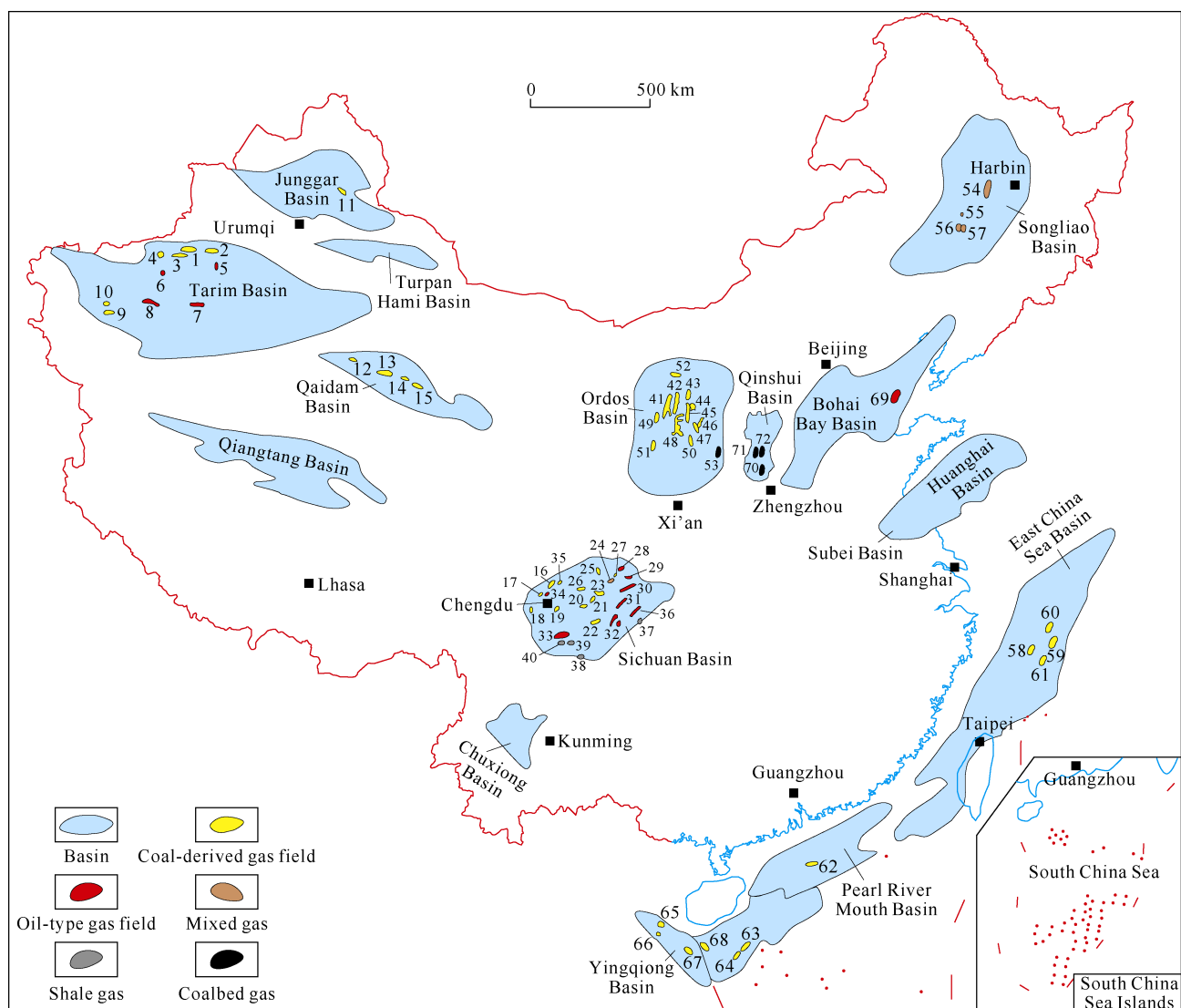
China's annual gas production has been increasing.

2. Exploration and development of large gas fields is the main way to the rapid development of natural gas industry

2.1. Large gas fields are the backbone of natural gas industry

By the end of 2018, 72 large gas fields (including 4 shale gas fields and 4 coalbed gas fields) had been discovered in China. The first large gas field in China, Wulonghe Gas Field, was discovered in 1959, with geological reserves of $380 \times 10^8 \text{ m}^3$ ^[19]. The distribution of China's large gas fields is shown in Fig. 3. It can be seen from Fig. 3 that China's large gas fields are mainly distributed in three basins: 25 (4 shale gas fields) in Sichuan Basin, 13 (1 coalbed gas field) in Ordos Basin and 10 in Tarim Basin. Meanwhile, these three basins are also China's main gas producing areas^[24]. In 2018, the natural gas production of large gas fields in Ordos Basin was $408.69 \times 10^8 \text{ m}^3$, that of Sichuan Basin is $399.15 \times 10^8 \text{ m}^3$, and that of Tarim Basin was $231.42 \times 10^8 \text{ m}^3$, with production of large gas fields accounting for 87.9%, 92.9% and 85.4% of the total production of each basin respectively. The total production of these three basins is $1.039.26 \times 10^8 \text{ m}^3$, accounting for 65% of China's total natural gas production. Therefore, these three basins play a dominant role in China's natural gas production.

Super large gas fields with reserves more than $1 \times 10^{12} \text{ m}^3$ are playing significant roles in large gas producing countries. The Sulige and Anyue gas fields in China are both super large gas fields, with annual gas production of over $100 \times 10^8 \text{ m}^3$ with a total gas production of $302.8 \times 10^8 \text{ m}^3$ in 2018, accounting for 18.9% of the total national gas production. Presently, both Russia and the Netherlands, the two largest gas producing countries in the world, are exploring and developing large gas fields to help them change from gas poor countries to large gas producing countries. In 1958, the recoverable reserves of natural gas in the Netherlands were less than $740 \times 10^8 \text{ m}^3$, and the annual production of natural gas was only $2 \times 10^8 \text{ m}^3$. However, in 1959, Groningen super-large gas



10 in Tarim Basin: 1. Kela 2; 2. Dina 2; 3. Kelasu; 4. Dabeji; 5. Tahe; 6. Yudong; 7. Tazhong #1; 8. Hetianhe; 9. Keke; 10. Akemomu. 1 in Junggar Basin: 11. Kelameili. 4 in Qaidam Basin: 12. Dongping; 13. Tainan; 14. Sebei 1; 15. Sebei 2. 25 in Sichuan Basin: 16. Xinchang; 17. Chengdu; 18. Qiongxixi; 19. Luodai; 20. Anyue; 21. Moxi; 22. Hechuan; 23. Guang'an; 24. Longgang; 25. Yuanba; 26. BAJIAOCHANG; 27. Puguang; 28. Tieshanpo; 29. Dukou River; 30. Luojiashai; 31. Datianchi; 32. Wolong River; 33. Weiyuan; 34. West Sichuan; 35. Zhongjiang; 36. Dachigan; 37. Fuling; 38. Changning; 39. Weiyuan (shale gas); 40. Weirong. 13 in Ordos Basin: 41. Sulige; 42. Wushen Banner; 43 Niudi, 44 sacred trees; 45. Yulin; 46. Mizhi; 47. Zizhou; 48. Jingbian; 49. Liuyangbao; 50. Yan'an; 51. Qingyang; 52. Dongsheng; 53. Eastern Ordos. 4 in Songliao Basin: 54. Xushen; 55. Longshen; 56. Changling 1; 57. Songnan. 4 in East China Sea Basin: 58. Chunxiao; 59. Ningbo 22-1; 60. Ningbo 17-1; 61. Taiwaitian C. 1 in Pearl River Mouth Basin: 62. Liwan 3-1; 6 in Yingqiong Basin: 63. Lingshui 17-2; 64. Lingshui 25-1; 65. Oriental 1-1; 66. Oriental 13-2; 67. Ledong 22-1; 68. YA13-1. 1 in Bohai Bay Basin: 69. Bohai Sea. 3 in Qinshui Basin: 70. Panzhuang District of Qinshui; 71. Qinshui; 72. Shizhuang South District of Qinshui.

Fig. 3. Distribution of large gas fields in China.

field with a recoverable reserve of nearly $3 \times 10^{12} \text{ m}^3$ was discovered, and the annual production of natural gas reached $828.8 \times 10^8 \text{ m}^3$ in 1975. Therefore, the Netherlands exported natural gas to Germany, France and Belgium, becoming a large gas producing country^[19]. In the early 1950s, Russia (the former Soviet Union) was a gas poor country with natural gas reserves of less than $2.230 \times 10^8 \text{ m}^3$ and annual gas production of only $57 \times 10^8 \text{ m}^3$. From 1960 to 1990, with the discovery of more than 40 large gas fields, the reserves of natural gas reached $453.069 \times 10^8 \text{ m}^3$, and the annual gas production increased from $453 \times 10^8 \text{ m}^3$ to $8.150 \times 10^8 \text{ m}^3$, making it the largest country in natural gas in the world at that time^[19].

2.2. The peak period of large gas field discovery is also a period of rapid growth of reserves and production in China

In 1949, China's total proved natural gas geological reserves and annual gas production were extremely low. Until 1990, China's total proved natural gas reserves were only $7.045 \times 10^8 \text{ m}^3$, with an annual production of $152 \times 10^8 \text{ m}^3$. In that 40 years (1949-1990), China's natural gas reserves and production increased slowly. The main reason is that the number of large gas fields discovered during this period was very small, and only six large gas fields were discovered in China^[25], and none of them was found to have reserves over

$1\ 000\times 10^8\ \text{m}^3$ ^[26]. However, from 1991 to 2018, over 28 years, 2.4 large gas fields on average were discovered every year, and the reserves of a single large gas field were also large, with 33 large gas fields exceeding $10\ 000\times 10^8\ \text{m}^3$, and the reserves of the Sulige and Anyue gas fields exceeding $10\ 000\times 10^8\ \text{m}^3$. The discovery of these large gas fields enhanced the rapid growth of China's natural gas reserves and production (Fig. 1). By the end of 2018, the total proved natural gas geological reserves of 72 large gas fields in China reached $124\ 504\times 10^8\ \text{m}^3$, accounting for 75% of the national proved natural gas reserves of $16.7\times 10^{12}\ \text{m}^3$.

Based on comparison of Fig. 1 and Fig. 2, it can be seen that from 1991 to 2000, there is a significant positive correlation between the number of discovered gas fields and the growth rate of natural gas reserves, but the positive correlation between the number of discovered gas fields and the annual production growth rate of natural gas in the same period is not significant. This is because of the time needed for the development of the gas field and the construction of the transportation pipeline. This lag has subsided since 2001, and the data shows a significant positive correlation between the discovery rate of large gas fields and the gas reserve and production.

2.3. Research on the main controlling factors and forming conditions for large gas fields accelerates the discovery of large gas fields

Since the “sixth five year plan” period, with the help of national natural gas science and technology research projects, Chinese scholars have continued to carry out research on the main controlling factors of the formation of large gas fields^[27–34], and summed up seven quantitative and semi-quantitative main controlling factors of the formation of large gas fields^[32], and predicted the favorable exploration fields of China's gas fields, which accelerated the discovery of a large number of large gas fields. The quantitative and semi-quantitative main controlling factors for the formation of large gas fields are summarized as follows^[32]: (1) The zone with gas intensity greater than $20\times 10^8\ \text{m}^3/\text{km}^2$ in the gas center and its periphery is favorable for the formation of the gas field. (2) The gas field is formed late, mainly in the Cenozoic era, if it is formed many times, it then refers to the last formation period. (3) There are paleouplift traps in the effective gas source area. (4) The large gas fields are mostly formed in coal measures or in traps above or below. (5) In the gas area of the large gas field, pore reservoirs are dominating reservoirs. (6) The low gas potential area is favorable for the accumulation of large gas fields. (7) Outside (between) or inside the abnormal pressure storage box, it is favorable for the formation of large gas fields. Based on the above listed research results on the main controlling factors for the formation of the large gas field, the distribution of the large gas field in China is predicted in advance, which provides a theoretical basis for the discovery and exploration of the large gas field in China and accelerates the exploration and development of the large gas

field. Fig. 4 is a comparison of the natural gas favorable area or gas accumulation zone in Ordos Basin predicted by natural gas research project since the “sixth five year plan” and the proved large gas fields in different periods later on. The early research results successfully predicted favorable natural gas areas in the Ordos Basin. By the end of 2018, 12 large gas fields (excluding coalbed gas fields) have been found in the Ordos Basin, with proved geological reserves of $43\ 461.89\times 10^8\ \text{m}^3/\text{km}^2$, including 9 large gas fields of more than 100 billion cubic meters. These gas fields are distributed in the range of favorable natural gas exploration areas predicted in the early stage, and basically located in the gas generating zones where the gas intensity is more than $20\times 10^8\ \text{m}^3/\text{km}^2$. The gas generation intensity controls the distribution of the large gas fields.

3. New theory of natural gas enhances faster development of natural gas industry

Different natural gas theories can be divided according to different classification principles. As per organic genesis and inorganic genesis of natural gas atoms, there formed the theories of organic genesis and inorganic genesis of natural gas; as per whether the alkane gas comes from sapropelic kerogen or humic kerogen, there formed the theories of oil-associated gas and coal-derived gas; as per the separation or community of reservoir sources, there formed conventional natural gas theory and unconventional natural gas theory, and the latter also includes reservoir source separation such as tight sandstone gas.

Oil-associated gas theory and coal-derived gas theory are meritorious theories that have guided the development of natural gas industry. Promoted by the “shale gas revolution”, unconventional gas theory shows great potential in guiding the natural gas industry for better development in the future.

3.1. The coal-derived gas theory enables China to develop from a gas poor country to a major gas producing country

In the 1870s, the theory of marine oil generation began to sprout in the world, and has been developing and improving since then; in the 1920s, the theory of terrestrial oil generation began to form attributed to Chinese scholars' efforts^[35–36]. Both marine and terrestrial oil generation theories admit that sapropelic shale and carbonate rock are the source rocks of oil and gas. The difference in between is that for the former the source rocks are marine facies, while for the latter the source rocks belong to terrestrial facies. Therefore, both theories can be identified as oil-gas theory. It can be seen that the earliest traditional theory guiding natural gas exploration in the world is oil-associated gas theory.

In the 1940s, German scholars proposed that coal measures can form abundant natural gas, and can accumulate into industrial gas fields^[37], but they did not pay attention to whether coal measures can form oil and established a simple coal to gas theory. The emergence of this new theory and its

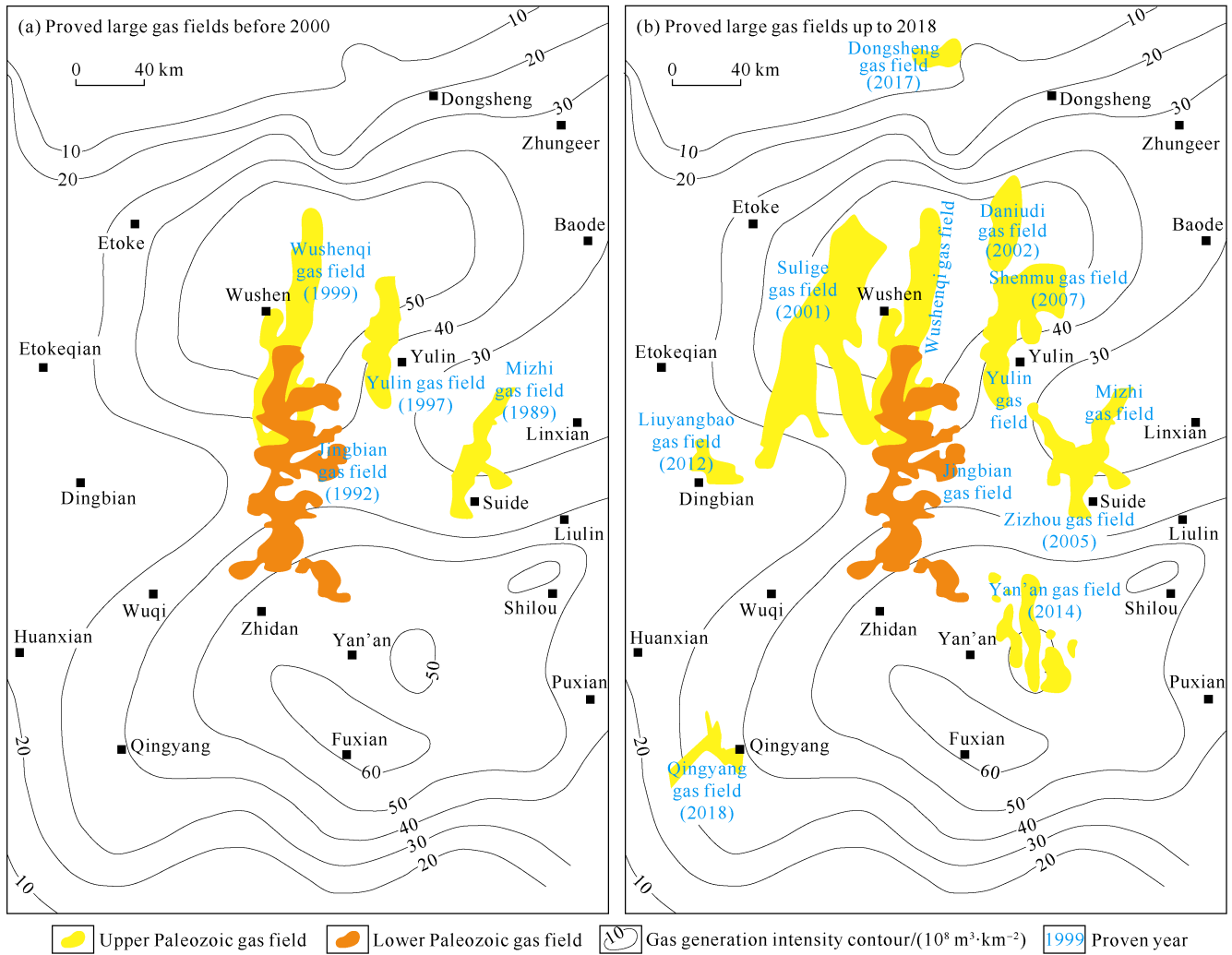


Fig. 4. Proved large gas fields in Ordos Basin at different times.

guidance for natural gas exploration in Western Europe have achieved great success: a large number of coal-derived gas fields such as Groningen super large gas field have been found in the Northwest basin of Germany^[17], and at least 455 coal-derived gas fields have been found in the England-Netherlands basin^[38].

China's modern petroleum industry started in 1878 and has been guided by the theory of oil-associated gas, i.e. "monism", for 100 years till 1978^[19]. The natural gas industry was extremely weak, and the reserves and production of natural gas were very small. The research on coal-derived gas in China began in the late 1970s. In 1979, the article "Petroleum and Natural Gas Generation during Coalification"^[39] pointed out the primary and secondary relationship for gas and oil formed by coal measures, stating that coal measures were the source rocks, while the hydrocarbon generation of coal measures were dominated by gas and supplemented by oil^[17, 40]. The emergence of the new theory of coal-derived gas made China's natural gas exploration theory develop from "monism" of oil-associated gas to a "dualism" theory of both coal-derived gas and oil-associated gas. The coal-derived gas theory has opened up a new field for China's natural gas exploration and promoted the fast development of China's natural gas industry.

It can be seen from the following aspects: (1) Coal-derived gas has promoted China to become a major gas producer, and China became the 11th largest gas producer in the world in 2005. As is well known, reserves are the basis of production. Only when the reserves and production of coal-derived gas exceed 50% of total natural gas, can China become a major producer of natural gas. In 2005, the above two proportions were 62.4% and 52.3% respectively, which indicates that the reserves and production of coal-derived gas are the basis for China to become a major producer of natural gas in the world. (2) Coal-derived gas fields are the backbone of major gas producing countries. By the end of 2018, China had discovered 64 conventional gas fields (with a total proved natural gas reserves of 109 425.21×10⁸ m³, excluding 4 shale gas fields and 4 coalbed methane gas fields), including 45 large coal-derived gas fields, with total proved natural gas reserves of 82 912.42×10⁸ m³. The national total proved natural gas reserves were 167 600.24×10⁸ m³ in China. Therefore, the reserves of coal-derived gas field accounted for 49.47% of national natural gas reserve and 75.77% of total reserve of large gas field. In 2018, the national natural gas production was 1 602.7×10⁸ m³, and the large gas field production was 1 081.56×10⁸ m³, among which the production of coal-derived

gas fields was $816.27 \times 10^8 \text{ m}^3$, so the production of coal-derived gas field accounts for 50.93% and 75.47% of the national gas production and the large gas field gas production respectively. (3) The new theory of coal-derived gas guides the exploration and development of natural gas and helps to build the largest gas producing areas in China. The Ordos Basin is the first oil field in China to use modern drilling rigs to explore oil and gas. From well Yan-1 in 1907 to the end of the 1970s, it had been guided by the theory of marine and terrestrial oil generation. The coal-bearing strata of Carboniferous to Permian were not regarded as gas source rocks, and there was no progress in natural gas exploration. At the beginning of 1980, especially the launch of the “Sixth Five Year Plan” and “Coal-derived Gas Development and Research” natural gas scientific and technological research projects, Changqing oil field and many scholars^[41–46] pointed out that Carboniferous–Permian coal series were good source rocks for natural gas, which is still an important target for natural gas exploration in Changqing oil field. Great progress has been made in Ordos Basin in natural gas exploration and development, making it the first large gas producing area in China. Its annual gas production in 2018 was $464.96 \times 10^8 \text{ m}^3$, which was the first basin with annual gas production exceeding $400 \times 10^8 \text{ m}^3$ in China, accounting for 29% of the total national gas production. The Sulige gas field, a gas field with the highest reserves and production in China, has a proved natural gas reserves of $18\,598 \times 10^8 \text{ m}^3$ and an annual gas production of $188.68 \times 10^8 \text{ m}^3$ in 2018, accounting for 11.77% of the national gas production. 12 large gas fields had been found in the whole basin (Fig. 4). Except for the Jingbian gas field, which has mixed source of coal-derived gas and oil-associated gas, all others are coal-derived gas fields, 9 of which have reserves exceeding $1000 \times 10^8 \text{ m}^3$. The Ordos large gas producing area plays an important role in improving environmental pollution in Beijing-Tianjin-Hebei and the eastern part of Northwest China. (4) The discovery and development of coal-derived gas field Kela 2 gave birth to the construction of the West-to-East natural gas transmission project pipelines and the Tarim gas area, the third large gas producing area in China. Although at that time there was an opinion holding that the annual natural gas transmission of the West-to-East natural gas transmission project pipelines was $120 \times 10^8 \text{ m}^3$, the reserve guarantee of Tarim Basin was not enough, and the reserve production ratio was only 28, which was not suitable for the construction of the pipeline; there was another opinion contending that the project could be built^[46], because there was the “three most” Kela 2 Gas Field as the basis for the geological and development advantages of natural gas: the largest reserve abundance ($59.05 \times 10^8 \text{ m}^3/\text{km}^2$), the highest gas column height (468 m) and the largest single well (Kela 2-7 well) yield ($495.6 \times 10^4 \text{ m}^3/\text{d}$). At the same time, Kuqa depression has great potential in coal-derived gas, and more reserves can be found. Later, a number of large coal-derived gas fields were discovered in Dina 2, Dabei and Keshen, which made

the reserves for the West-to-East natural gas transport project more sufficient. In addition, Tarim Basin has now become the third large gas producing area in China, which proves that coal-derived gas theory is of great significance to the development of China’s natural gas industry.

3.2. The shale gas theory adds new driving force to the faster development of China’s natural gas industry

Shale gas is a kind of source-reservoir integration natural gas produced from a dark and organic rich shale formation system with very low porosity and permeability, which is mainly accumulated in adsorption or free state, and is essentially a continuously generated biogenic gas, thermogenic gas or a mixture of both^[47–49]. Shale gas, with its wide distribution and large reserves, had risen rapidly in the past decade and attracted attention of more and more countries. Since the drilling of the first shale gas well with a depth of only 8 m in 1821, it took the United States nearly 200 years to develop the technology, which can mainly be divided into four stages^[50]: the first stage (1821-1978), the stage of accidental discovery; the second stage (1978-2003), the stage of understanding innovation and technological breakthrough; the third stage (2003-2006), the stage of horizontal well and hydraulic fracturing technology promotion and application (the stage of great development); the fourth stage (from 2007 till now), the stage of globalization. The United States is the only country in the world to achieve large-scale commercial exploitation of shale gas. In 1981, George Michel, known as the father of Barnett shale gas, realized large-scale fracturing of shale section of well C.W.Slay No.1, which made Barnett shale the first large-scale commercial shale gas field in the United States. This triggered the vigorous development and major breakthrough of shale gas exploration and development in the United States, and set off an upsurge of shale gas exploration and development in the world^[51]. At present, great development has been achieved in the United States, China, Canada and Argentina (Fig. 5). In 2018, the shale gas production of the United States was $6072 \times 10^8 \text{ m}^3$ ^[52], and the proved shale gas reserves accounted for 66% of the total proved natural gas reserves^[53], making the United States change from a major gas producing country that imports natural gas to a major gas producing country that exports natural gas.

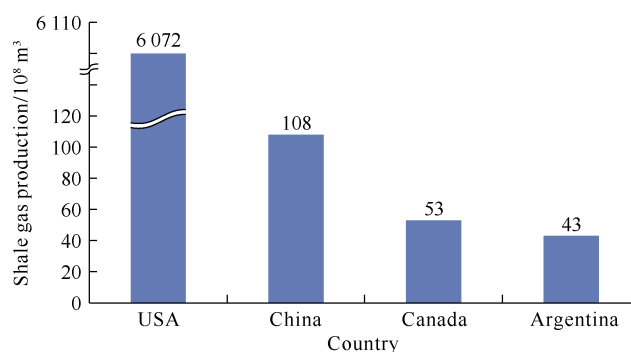


Fig. 5. Production of shale gas from countries in 2018 in the world^[52].

Marine shale is widely developed in China and North America, while transitional facies and continental shale are also developed in China. The types of marine shale organic matter in China and North America are mainly type I or type II₁^[54]. The marine shale in China is old and deeply buried (1500–5000 m), with high thermal maturity (R_o value is 2.0%–3.5%). The reservoir formation conditions are complex, and it has experienced multiple stages of structural movement, with poor preservation conditions and high exploration risk. The burial depth of continental shale in China is big, but its thermal maturity is low (R_o value is 0.4%–1.3%)^[55]. There are a lot of brittle minerals in shale reservoirs in China, with a brittleness coefficient of 46.15%^[56]. The brittleness coefficient of North America is 38.27%^[57]. In general, as per brittleness, the shales in China are better than those of the USA.

Compared with American shale, Chinese shale has poor preservation conditions due to its deep burial, multi-stage tectonic movement. The marine shale is old and its maturity is high; while the continental shale is new and its maturity is low and most of them are in the stage of oil generation window. The geological conditions of shale gas in China are worse than those in the United States. In 1980, the United States launched the theoretical and technological research project of shale gas development, while China was about 30 years late. Shale gas exploration and development in China has roughly gone through three stages^[58]: (1) Stage of learning (2003–2008); (2) Stage of evaluation of selected area and implementation of well exploration (2009–2012); (3) Stage of large scale construction and production (2013–present). In 2008, with international cooperation, China completed the first shale gas well, Changxin-1. In 2009, PetroChina implemented shale gas vertical well Wei-201. In 2010, two sets of shale gas target intervals, Wufeng-Longmaxi and Qiongzhusi formations were discovered, and industrial shale gas flow was obtained. As a result, since 2013, Fuling, Weiyuan, Changning, Qirong and other shale gas fields have been discovered and developed successively in the south of Sichuan Basin. By the end of 2018, the total proved geological reserves of shale gas in China were $10\,455.67 \times 10^8 \text{ m}^3$, including economic recoverable reserves of $313.29 \times 10^8 \text{ m}^3$, and cumulative gas production was $335.24 \times 10^8 \text{ m}^3$. As the geological resources of shale gas in China are $(83.3\text{--}166.0) \times 10^{12} \text{ m}^3$, and the technical recoverable resources are $(10.0\text{--}36.1) \times 10^{12} \text{ m}^3$, China has abundant shale gas resources in general, which has a good development prospect^[59]. At present, China has become the second largest shale gas producer in the world, and shale gas is also a new driving force for the development of China's natural gas industry.

3.3. Coalbed methane

There are 74 countries with CBM resources in the world, 90% of which are distributed in 12 major coal producing countries. Countries with relatively early development of coalbed methane industry include the United States, Russia,

Germany, Australia, Britain, India, etc., among which the United States is the country with the most successful coalbed methane development and the largest production^[60]. The development of coalbed methane resources in China can be divided into three stages: the stage of mine drainage (1952–1989), the stage of coalbed methane development technology introduction (1989–1995) and the stage of coalbed methane industry formation (1996 to present)^[61]. Since 1995, China has established the national coalbed methane development and utilization engineering research center and coal mine gas control research center. In 1997, the first coalbed methane well was drilled in Zaoyuan, Qinnan. By 2015, 10 coalbed methane industry demonstration project bases, including Qinshui, Eastern Ordos and Yangmei, had been built.

China is rich in coalbed methane resources. The results of “a new round of coalbed methane resource evaluation” organized by the Ministry of Land and Resources in 2006 shows that the total geological resources of shallow coalbed methane with a burial depth of 2000 m in China is $36.81 \times 10^{12} \text{ m}^3$, and the recoverable resources are $10.87 \times 10^{12} \text{ m}^3$. According to the results of “dynamic evaluation of coalbed methane resources” organized by the oil and gas strategy research center of the Ministry of Land and Resources in 2015, the total resources of shallow coalbed methane with a burial depth of 2000 m in China is about $30 \times 10^{12} \text{ m}^3$, and the recoverable resources are about $12.5 \times 10^{12} \text{ m}^3$, ranking the third in the world (Table 1). By the end of 2018, the total proved geological reserves of coalbed methane in China were $6521.9 \times 10^8 \text{ m}^3$, the technical recoverable reserves were more than $3253 \times 10^8 \text{ m}^3$, and the economic recoverable reserves were more than $2625 \times 10^8 \text{ m}^3$.

China's coalbed methane resources are geologically characterized by “multiple coal ranks, multiple burial depths, multi-stage gas generation, multi-source superposition and multi-stage transformation”. It is characterized by various types of coal in each coal rank, large span of burial depth, various coal forming conditions, multiple coal forming stages, superposition of coal metamorphism and multiple episodes of structural change, which lead to complex coalbed methane reservoir formation and various types of gas reservoirs^[63]. The overall characteristics of CBM occurrence can be summarized as “four lows and one high”, that is, low gas saturation, low permeability, low resource abundance, low reservoir pressure and high metamorphic degree. Compared with the reservoir characteristics of the main producing areas of coalbed methane in the United States, Australia and other countries,

Table 1. Reserve of CBM resources and coal of different countries^[62].

| Country | CBM Resources/ 10^{12} m^3 | Coal Reserve/ 10^{12} t |
|-----------|--------------------------------------|-----------------------------------|
| Russia | 17.0–113.0 | 6.50 |
| Canada | 6.0–76.0 | 7.00 |
| China | 30.0–36.8 | 5.60 |
| USA | 21.0–28.0 | 3.95 |
| Australia | 8.0–14.0 | 1.70 |

China's coalbed methane reservoir has not only favorable characteristics such as large coal seam thickness, high gas content and moderate burial depth, but also unfavorable factors such as late formation age, complex structure, low pressure coefficient and low permeability^[64]. Therefore, China's coalbed methane development is difficult, and its conditions and production are not as good as that of the United States. In 2018, only $51.5 \times 10^8 \text{ m}^3$ of coalbed methane was produced.

4. Conclusions

In the past 70 years since the founding of the People's Republic of China, great progress has been made in natural gas exploration and development. China has changed from a gas poor country to the sixth largest gas producing country in the world. In 1949, China's annual gas production was $1117 \times 10^4 \text{ m}^3$, the proved natural gas reserves were $3.85 \times 10^8 \text{ m}^3$, and the annual domestic gas consumption and reserves per capita were 0.0206 m^3 and 0.7107 m^3 respectively. However, by 2018, the annual domestic gas consumption per capita was 114.8576 m^3 , and the natural gas reserves per capita were 12011.08 m^3 , with domestic gas consumption and reserves per capita increased by 5575 times and 16900 times respectively.

Exploration and development of large gas field is the main way to rapidly develop the natural gas industry. By the end of 2018, 72 large gas fields had been discovered in China, of which the proved geological reserves of Sulige and Anyue gas fields were more than $1 \times 10^{12} \text{ m}^3$, and the annual gas production was more than $100 \times 10^8 \text{ m}^3$. Large gas fields are mainly distributed in the Sichuan (25), Ordos (13) and Tarim (10) basins. In 2018, the total gas production of the three basins was $1039.26 \times 10^8 \text{ m}^3$, accounting for 65% of China's total natural gas production. It can be seen that the large gas fields play dominant roles in China's gas production. By the end of 2018, the total proved natural gas reserves of 72 large gas fields in China were $124504 \times 10^8 \text{ m}^3$, accounting for 75% of the national proved natural gas reserves of $16.7 \times 10^{12} \text{ m}^3$, which is enough to show that the large gas fields are very important in the natural gas industry.

The new theory of natural gas enhances China's natural gas industry to develop better and faster. Before 1979, the traditional oil-associated gas theory, i.e. "monism", guided the exploration of natural gas. Since 1979, coal-derived gas theory has become a new theory to guide the exploration of natural gas. It helped China's natural gas exploration theory to develop from "monism" to "dualism" (oil-associated gas and coal-derived gas), enabling China's natural gas industry to develop rapidly. Coal-derived gas is the main gas that made China a major gas producer. In 2018, China's natural gas production was $1602.7 \times 10^8 \text{ m}^3$, and the gas production of large gas field was $1081.56 \times 10^8 \text{ m}^3$, including $816.27 \times 10^8 \text{ m}^3$ of coal-derived gas field, which accounted for 50.93% and 75.47% of China's total gas production and large gas field's gas production respectively; by the end of 2018, China's total

proved reserves of coal-derived gas field were $92556 \times 10^8 \text{ m}^3$, accounting for 61.4% of the total proved reserves of the year of $150622.6 \times 10^8 \text{ m}^3$. Shale gas theory appeared in China at the beginning of the 21st century, but it had made important progress by 2018. At present, the annual production of shale gas is $108.8 \times 10^8 \text{ m}^3$, and shale gas fields in Fuling, Changning, Weiyuan and Weirong have been explored and developed. The total proved geological reserves of natural gas are $10455.67 \times 10^8 \text{ m}^3$, and the cumulative production of gas is $335.24 \times 10^8 \text{ m}^3$. Among the four countries (USA, China, Canada, Argentina) that produce shale gas, the production amount of shale gas in China is only second to that of the United States, which shows that shale gas in China has a good prospect.

Acknowledgements

We are grateful for Academician Su Yinao, Professor He Zhiliang and Professor Zhang Gongcheng who have provided the data of drilling crew and seismic crew.

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