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Original research paper

Suggestions on the development strategy of shale gas in China☆

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Abstract

From the aspects of shale gas resource condition, main exploration and development progress, important breakthrough in key technologies and equipment, this paper systematically summarized and analyzed current situation of shale gas development in China and pointed out five big challenges such as misunderstandings, lower implementation degree and higher economic uncertainty of shale gas resource, and still no breakthrough in exploration and development core technologies and equipment for shale gas buried depth more than 3500 m, higher cost and other non-technical factors that restrict the development pace. Aiming at the above challenges, we put forward five suggestions to promote the shale gas development in China: (1) Make strategies and set goals according to our national conditions and exploration and development stages. That is, make sure to realize shale gas annual production of 20×10^9 m^3, and strives to reach 30×10^9 m^3. (2) Attach importance to the research of accumulation and enrichment geological theory and exploration & development key engineering technologies for lower production and lower pressure marine shale gas reservoir, and at the same time orderly promote the construction of non-marine shale gas exploration & development demonstration areas. (3) The government should introduce further policies and set special innovation funds to support the companies to carry out research and development of related technologies and equipment, especially to strengthen the research and development of technology, equipment and process for shale gas bellow 3500 m in order to achieve breakthrough in deep shale gas. (4) Continue to promote the geological theory, innovation in technology and management, and strengthen cost control on drilling, fracturing and the whole process in order to realize efficient, economic and scale development of China's shale gas. (5) Reform the mining rights management system, establish information platform of shale gas exploration and development data, and correctly guide the non-oil and gas companies to participate in shale gas exploration and development.

Keywords: Organic black shale; Shale gas resources; Exploration and development; Development strategy; Key technology; Challenge

1. Introduction

Shale gas refers to the natural gas being exploited from black shale formations, which is rich in organic matter. Shale formations are extremely tight and self-production cannot be realized after drilling. Effective production can be acquired only after the formation of network volumetric fractures in the

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shale beds with the adoption of special technique, such as high pressure [1]. The exploration and development of shale gas are characterized by tight reservoir, high technology demand, rapid production decrease, and long investment recovery period. Through near 30 years of practice and technology research of exploration and development, large-scale developments in USA only began in the recent ten years. The American shale gas production of shale gas in 2015 exceeded 4200×10^8 m^3 [2,3], accounting for 50% of America's total natural gas production, effectively promoting the implementation of "energy independence" of America and also resulting in significant influence on global energy patterns and geopolitics.

By referring the American experience, China initiated exploration and development of shale gas in 2010, and the geological selection, drilling valuation and development testing, have preliminarily proved the abundant shale gas resource in domestic China, with large potentials of exploration and development [4–7]. For five years of exploring, industrial development of marine shale gas have basically realized in Sichuan Basin, and key exploration and development technology and equipment targeting horizons shallower than 3500 m have basically realized domestication. However, even though some findings and tracers at the regions outside of Sichuan Basin have been acquired, no material breakthrough has been realized. In the meantime, with the promotion of exploration and development, the exploration and development potential predication is not yet consistent with the formulation advice of development targets. The current technology and equipment of exploration and development is not adapted to the exploration and development targeting shale gas at deep horizons, with continuously high single-well costs, and the conflicts and challenges, such as the deficiency of management and operating mechanism, are becoming more and more prominent. In order to promote the ordered, healthy and sustainable development, this paper basically clarifies the exploration and development status of shale gas based on the investigation and research of exploration and development of shale gas in China, determining the key problems for the development of shale gas, and development strategy suggestions have been put forward accordingly.

2. Basic characteristics of shale gas in China

2.1. Three types of shale developed in China, with the most types of shale gas in the world, and marine shale gas is the most realistic type

Organic-rich shale types in China are various, including marine, transition, and terrestrial types [4–9] (Fig. 1). Marine shale rocks are mainly distributed in Sichuan Basin and its periphery, the Southern area, is dominated by Middle-Lower Yangtze Region, and the Central and Western area is dominated by Tarim Basin. Upper Ordovician Wufeng Formation to Lower Silurian Longmaxi Formation (Wufeng–Longmaxi Formation) stratum sequence is the focused horizon; transition-phase shale rocks are mainly distributed in Carboniferous-Permian strata in the sedimentary basins, such as Ordos, Jungar and Tarim basins in the Central and Western regions, and in the Permian strata in the Southern regions; terrestrial shale rocks are mainly distributed in the sedimentary basins such a as Songliao, Bohai Bay, Ordos, and Sichuan basins, with the focused strata in Qingshankou, Shahejie and Yanchang Formation and Triassic-Jurassic strata. The exploration and development practice gradually proved that the three types of organic-rich shale rocks are all characterized by basic geologic conditions for the accumulation of shale gas, with relatively big discrepancies. The accumulation conditions of marine shale gas are favorable, with the most realistic exploration and development potential of shale gas.

2.2. Shale gas resources in China is relatively abundant, among which the volume of marine shale gas resources is the largest

Since 2011, different organizations [5–7] carried out predictions on resource potential of shale gas in China (Table 1). In 2011 and 2013, US Energy Information Agency (EIA) evaluated shale gas resources of China twice, and the shale gas resources in place are 144.50×10^{12} m^3 and 134.40×10^{12} m^3, respectively, and recoverable resources are 36.10×10^{12} m^3 and 31.57×10^{12} m^3, respectively, which was ranked the 1st and 2nd place worldwide in the current period. In 2012, the resources in place of shale gas in China is 134.42×10^{12} m^3 and a recoverable resources are 25.08×10^{12} m^3, which is evaluated by *China Ministry of Land and Resource.* The resources s in place evaluated by *China Ministry of Land and Resource* is the same as that of EIA (2013) and an obvious discrepancy as to the recoverable resources. In 2012, with emphasis on southern marine shale gas resources, the shale gas recoverable resources in China evaluated by *Chinese Academy of Engineering* is 11.50×10^{12} m^3. In 2015, based on the latest development, the shale gas resources in place in China evaluated by the author (*PetroChina Research Institute of Prtroleum Exploration and Development*) is up to 80.45×10^{12} m^3, and 12.85×10^{12} m^3 for recoverable resources. By combination of all prediction results (Table 1), the shale gas resources in place in China is ranged from 80.45×10^{12} to 144.5×10^{12} m^3, and 11.5×10^{12} to 36.1×10^{12} m^3 for recoverable resources.

Judging from Table 1, shale gas resources is China are relatively abundant. However, due to low degree of both exploration and development and understanding degree, the resource prediction discrepancies are relatively big, which is in accordance with the characteristic of oil and gas resources as a matter of fact. Generally, oil and gas resource potential will not be completely determined in one resource evaluation, and may receive continuous improvement with the deepening exploration and development, then gradually being settled. Based on the current exploration and development status of shale gas in China, a total of three agreements may be basically acquired.

Firstly, the marine shale gas resource is relatively determined. The distribution area of marine shale rocks in Wufeng Formation–Longmaxi Formation in southern China is ranged from 10×10^4 km^2 to 20×10^4 km^2, which is characterized

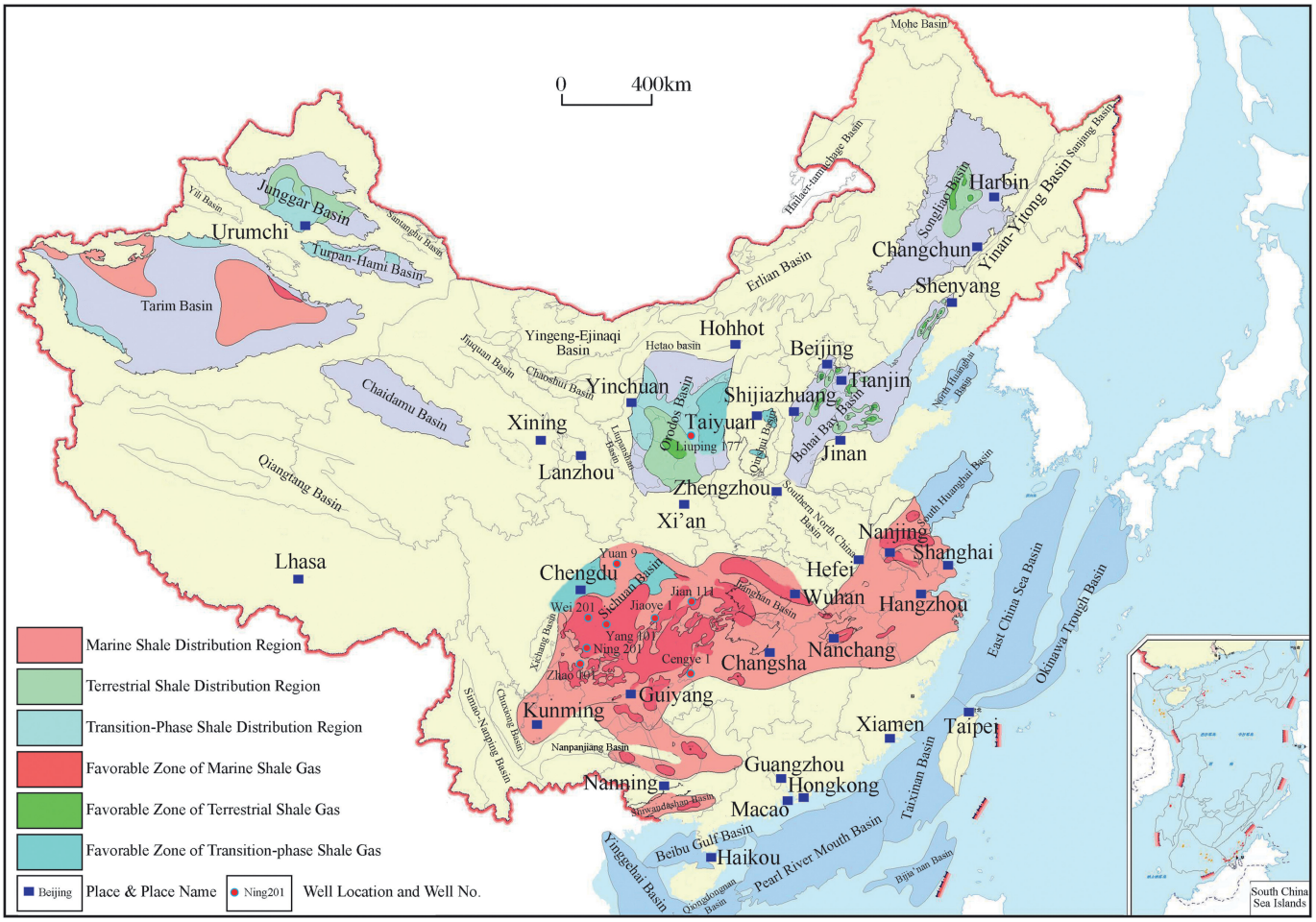

Fig. 1. Distribution of different types of shale and prediction of favorable shale gas zones in China.

Table 1
Statistics of China's shale gas resource volume prediction (unit: $\times 10^{12}$ m^3).

Agency	Evaluation time	Resources category	Marine	Transition	Terrestrial	Total
US Energy Information Agency (EIA)	2011	Gas in place	144.5	/	/	144.50
		Recoverable	36.10	/	/	36.10
Ministry of Land and Resource	2012	Gas in place	59.08	40.08	35.26	134.42
		Recoverable	8.19	8.97	7.92	25.08
Chinese Academy of Engineering	2012	Recoverable	8.80	2.20	0.50	11.50
US Energy Information Agency (EIA)	2013	Gas in place	93.6	21.64	19.16	134.40
		Recoverable	21.12	6.54	1.91	31.57
PetroChina Institute of Exploration and Development	2015	Gas in place	44.1	19.79	16.56	80.45
		Recoverable	8.82	2.37	1.66	12.85
Total	2011–2015	Gas in place	44.1–144.5	19.79–40.08	16.56–35.26	80.45–144.5
		Recoverable	8.80–36.10	2.2–8.97	0.5–7.92	11.50–36.10

by large thickness, abundant organic matter, high air-bearing content, and strong brittleness, which are favorable geologic conditions for shale gas accumulation. Through 5 years of exploration and development practice, the accumulation and enrichment geologic theory of marine shale gas has been preliminarily established, with determination of two Wufeng–Longmaxi Formation strata, Sichuan Basin, Upper-Middle Yangtze region, as the "dessert" zones. The determined favorable shale gas bearing are is about 10×10^4 km^2, and a recoverable resources of 8.8×10^{12} m^3.

Secondly, the potential of transition-phase shale gas resources is not clear. The research found that the transition-phase shale rocks are mainly associated with coal seams, and are inter-bedded with tight sandstone, with characteristics of shale gas accumulation such as small thickness of high-quality shale, poor continuity, obvious gas-bearing content variations and ordinary brittleness. Although the distribution area of transition-phase shale is predicted to be ranged from 15×10^4 km^2 to 20×10^4 km^2, potential resource volume evaluation varies greatly, with a suspicious prospect, a

minimum resources of 2.2×10^{12} m^3, and a maximum resources of 8.97×10^{12} m^3.

Thirdly, the resources prospect of terrestrial shale gas is generally limited. The terrestrial shale is characterized by relatively large thickness, high organic matter abundance, main oil generation, small gas generation potential, low gas-bearing content value and poor brittleness. The distribution of terrestrial shale area is about 20×10^4 km^2 to 25×10^4 km^2, and the potential resources evaluation is relatively small with large variations. The minimum and maximum recoverable resources are 0.50×10^{12} m^3 and 7.90×10^{12} m^3, respectively.

3. The progress in exploration and development of shale gas in China

3.1. Industrial development of shale gas has been preliminarily realized in Sichuan Basin, and exploring and preparation stage as to other regions

By the end of 2015 (Table 2, Table 3) [5–11], a total of accumulated 54 terrestrial exploration rights of blocks have been established (among which 21 blocks are tendering blocks), with an area of 17×10^4 km^2. Three marine shale gas industrial development demonstration regions have been established in Fuling, Weiyuan, and Changning-Zhaotong; a terrestrial shale gas development demonstration region of Yanchang and Fushun-Yongchuan cooperated development region (Fig. 2). The accumulated investment is near 30 billion RMB; more than 400 drilled shale gas wells, 280 of them have been put into operation; the accumulated productivity reaches 75×10^8 m^3; installed pipeline length of 235 km; the proved geologic reserves of shale gas amount are up to 5441.29×10^8 m^3, and the production of shale gas in 2015 is 44.6×10^8 m^3, with an accumulated production of more than 60×10^8 m^3. The proved geologic reserves and production are all from marine Wufeng Formation–Longmaxi Formation in Sichuan Basin. In addition, three types of shale gas are discovered in other regions in the south, as well as the north areas of Southern China Basin, Qaidam Basin, and Ordos Basin, but the production was not able to form in large capacity, and the exploration prospect is under exploring.

Table 3
Overview of the marine shale gas industrial production demonstration regions/cooperation zones in Sichuan Basin.

Demonstration/Cooperation	Fuling Jiaoshiba	Changning-Zhaotong	Weiyuan	Fushun-Yongchuan
Area/km^2	545	3450	4216	3500
Geological resources/($\times 10^8$ m^3)	4044	6318	6680	3600
Proved reserves/($\times 10^8$ m^3)	3805.98	1361.8	273.5	/
Completion/well	256	68	60	23
Production/well	180	47	488	16
Accumulated production/($\times 10^8$ m^3)	43.26	10.65	4.5	2.0
Total production/($\times 10^8$ m^3)	60.41			

3.1.1. Sichuan Basin

Sichuan Basin is a significant region of shale gas exploration and development in domestic China, where two sets of marine shale gas generation strata, Qiongzhusi Formation and Wufeng Formation–Longmaxi Formation, have been discovered [7,10,11]. Due to the characteristics of large burial depth, low production and high technique required as to Qiongzhusi Formation, the current exploration and development work is mainly focused in Wufeng Formation–Longmaxi Formation, with shallow burial depth and high production. The preliminarily determined favorable exploration area at horizons shallower than 4500 m is 4.0×10^4 km^2, with a recoverable resource of 4.5×10^{12} m^3; the completed wells amount to 384, with 0.4×10^{12} m^3 giant shale gas field, namely Fuling Jiaoshiba of Chongqing, Changning-Zhaotong, Weiyuan, and Fushun-Yongguan of Sichuan, have been discovered. The determined geologic reserves exceeded 1.0×10^{12} m^3, and the proved reserves amount is up to 5441.29×10^8 m^3 (Table 3); the number of accumulated production wells is 291, with an established productivity of 75×10^8 m^3 in 2015 and accumulated production of 60.55×10^8 m^3.

3.1.2. Other regions

In addition to those blocks in the Sichuan Basin, the Ministry of Land and Resource sets 20 blocks for bidding [5,6]. Local governments, such as Yunnan, as well as Guizhou, Chongqing, Jiangxi and Inner Mongolia, and Yangchang oil

Table 2
Statistics of shale gas exploration and development work in China (modified as footnote[a]).

Company name	2D Seismic/km	3D Seismic/km^2	Drilling well/well	Pipeline construction/km	Production of 2015/($\times 10^8$ m^3)	Investment/($\times 10^8$ RMB)
PetroChina	6076	757	220	93.7	12.15	103.15
Sinopec	4793.61	999.5	256	141.3	32.45	155.25
Yanchang oilfield		103.76	59		0.0144	10.95
CNOOC	316.18		5			1
China CBM	2178.65	272	14			1.4
Companies winning the bid	7503.9		43			16.2
Ministry of land and resource	210		66			7.2
Local governments	739.82		45			5.1
Total	21818.16	2133.85	708	235	44.61	300

[a] China Geological Survey, Oil & Gas Resources Research Center, *China Shale Gas Resources Survey Report (2014), 2015.5.*

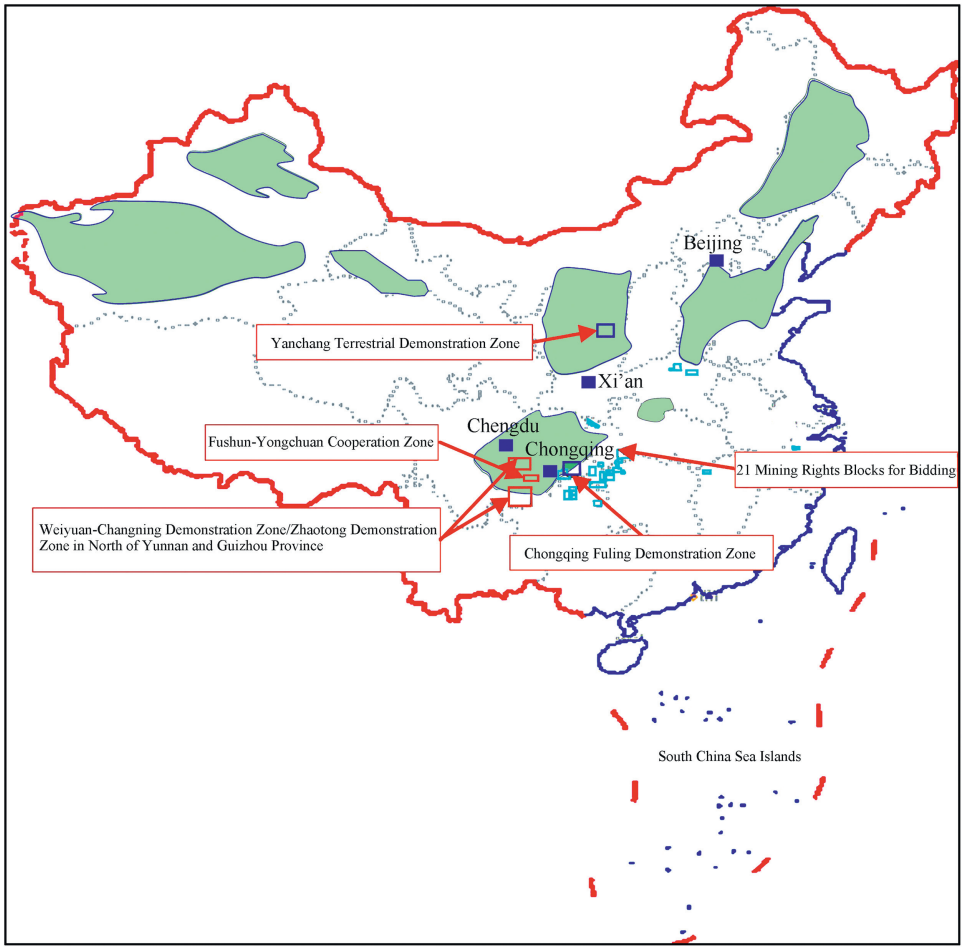

Fig. 2. Distribution of shale gas exploration and development blocks in China.

fields have carried out independent exploration evaluation as to respective bidding blocks, with completion of 150 wells and discovery of some good tracer. Since 2011, Shaanxi Yanchang Petroleum Corporation discovered shale gas in 40 wells in the southeastern part of Ordos Basin and established the first terrestrial shale gas industrial production demonstration zone, with an accumulated investment of RMB 1.1 billion and 60 completed wells. The preliminarily determined shale gas geological reserves amount to 677×10^8 m^3 and a constructed productivity of 1.2×10^8 m^3. The single-well gas rate is ranged from 0.17×10^4 m^3/d to 4.0×10^4 m^3/d.

Besides, some achievements have also been acquired in the exploration of marine shale gas in the regions out of terrestrial, transition-phase, and Sichuan Basin. In respect to exploration and development of terrestrial shale gas, SINOPEC had drilled near 20 wells in different terrestrial shale horizons during 2011–2012, with a gas rate range from 0.26×10^4 m^3/d to 51.7×10^4 m^3/d; In 2013, *China Geologic Survey* drilled Well Chaiye 1 in the north margin of Qaidam Basin, and discovered terrestrial shale gas in Jurassic strata. Through rough statistic, a total of 50 terrestrial shale gas wells have got gas production. With testing production of several wells, the general production of terrestrial shale gas is low, with large production variations and rapid depletion. As a result, no valuable industrial productivity has been established, and resource potentials need further determination. As to the exploration and development of transition-phase shale gas, good tracers have been discovered in Northern China. Gas rate after fracturing of Well Eye 1 in Ordos Basin is 1.95×10^4 m^3; gas rate after fracturing of Well Yunyeping 1 is 2.0×10^4 m^3; gas rate after fracturing of Well Shenmu 0–5 is 6695 m^3, and shale bed with thickness of 465 m and air-bearing content of 4.5 m^3/t. The number of transition-phase shale gas is limited, with extremely unstable shale gas production. Without production wells and development blocks, the resource prospect is unclear. During the exploration and development of marine shale gas outside of Sichuan Basin, a gas rate ranged from 2.0×10^4 m^3 to 5.0×10^4 m^3 was achieved in Devonian Luofu Formation of Liuzhou (Guangxi Province) and Carboniferous Datang Formation of Liupanshui (Guizhou Province), and the prospect of exploration and development have be a bright future.

In general, in the regions out of Wufeng Formation–Longmaxi Formation in Sichuan Basin, the wells with disclosure of gas are relatively popular, with low single-well production and unstable gas rate, without formation of actual productivity, which demonstrated that the abundant shale gas

resources at other regions and strata need further determination, and the realization of industrial development needs lots of work.

3.2. Basicly localization of key technology and equipment for the depth less than 3500 m

Since the beginning of the shale gas exploration and development in China, after technology introduction, absorption and independent innovation, China has basically mastered the key techniques, such as geophysics, as well as drilling, completion and fracturing stimulation, which are used for exploration and development of shale gas. Some independently developed equipment types, such as movable drill, 3000 fracturing truck and drillable bridge plug, have realized large-scale production and application [5−7,11]. The completion period of horizontal well has decreased to 60 d from 150 d, with a minimum period of 35 d. The stages of staged fracturing have increased to an average of 15 from original value of 10, with a maximum value of 29, which completely fulfills the requirements of drilling, completion, and staged fracturing of horizontal wells shallower than 3500 m. The factory-like production mode of platform well groups has been preliminarily established, and the comprehensive costs of single wells have decreased to about 65−75 million RMB from 100 million RMB.

4. The main challenges for the development of shale gas in China

Currently, the exploration and development of natural gas in China is mainly conventional gas type. Some achievements have been received in the exploration of shale gas in Sichuan Basin, while it is still in exploring stage in other regions. The shale gas in China has its unique characteristics, which differ greatly with the shale gas of North America [5−13]. The shale gas of North America is characterized by marine gas, with characteristics such as large distribution area of "desert", lateral stability of reservoir thickness, as well as easy formation of fracture network system after fracturing, appropriate burial depth, flat surface, and abundant water resource; the marine shale gas in China is characterized by relatively large burial depth, strong damage, small area of favorable "desert" and hard fracturing. The air-bearing content of non-marine shale is low, with relatively small thickness; the surface is usually characterized by mountain and desert, and water resource is generally inadequate.

4.1. Misunderstanding of the development stage of shale gas

With the breakthroughs in Fuling Jiaoshiba, Changning-Zhaotong, and Weiyuan shale gas field, the over optimistic mood as to the potential of shale gas in China is rapidly spreading. The cause is lack of understanding with regard to the specialty of shale gas resources. The biased understanding that "the existence of shale rocks means the existence of shale gas", "the existence of shale gas means successful industrial development", and "shale gas could be developed with application of conventional techniques; the huge discrepancy between marine and terrestrial shale gas is not recognized, with the false understanding that as the accumulation conditions of marine and terrestrial shale gas are the same, the technology of exploration and development should be similar; the emphasis and attentions have been mainly focused on the breakthroughs of processing technology, such as drilling and staged fracturing stimulation, resulting in many embarrassing cases of "successful processing technology and low production", which in the end neglected the evaluation and optimization of "deserts" [6]. The deviations of understanding and imbalance of operations result in the subjective targeting of the development stage of shale gas in China. Some agencies even admitted that the development of shale gas in China has entered massive development stage, with over expectations in respect to production prediction, which results in compilation of unachievable development targets, where a quick success is eager for operations development.

Both of American shale gas and Chinese coal related gas did great contributions to respective national natural gas industry development. In 2015, shale gas accounted for 50% of the total natural gas production in America [2], and Coal related gas accounted for 64% of total natural gas production in domestic China, both of which are geologic exploration and development projects [14]. The success of the geologic exploration and development project cannot be achieved overnight, which needs exploring for a rather long period before some effectiveness could be acquired. The development of shale gas in North America has undergone four stages, namely technical research, piloting testing, technical breakthrough, and large-scale development [15] (Fig. 3). Since 1981, it had taken more than 20 years for the breakthroughs of the key technologies, such as horizontal well drilling, staged fracturing for stimulation and "factory-like" operation, and large-scale development only initiated after 2005, with the number of drilling wells more than 100 thousand. With the introduction of the American pattern, it took more than 10 years before the commercial development of shale gas in Canada. As to coal related gas industry, with the establishment of the theory of Chinese coal-related gas in 1979, more than 30 years of improvements resulting in the industrial development (Fig. 3). The exploration of shale gas in domestic China initiated from the drilling of Well Wei 201 in Sichuan Basin in 2010. The exploration period in China is less than six years, with a total number of drilling wells less than 600 and the exploration time of the gas fields under construction in less than 2 years. The distribution zones of favorable resources have not been determined; the main controlling factors of enrichment and the production mechanism of gas field are still not clear; the key technologies of development have not been completely mastered; the "factory-like" development mode is not sophisticated enough. All the problems aforementioned are pending, which means the realization of large-scale development still needs a long way to go.

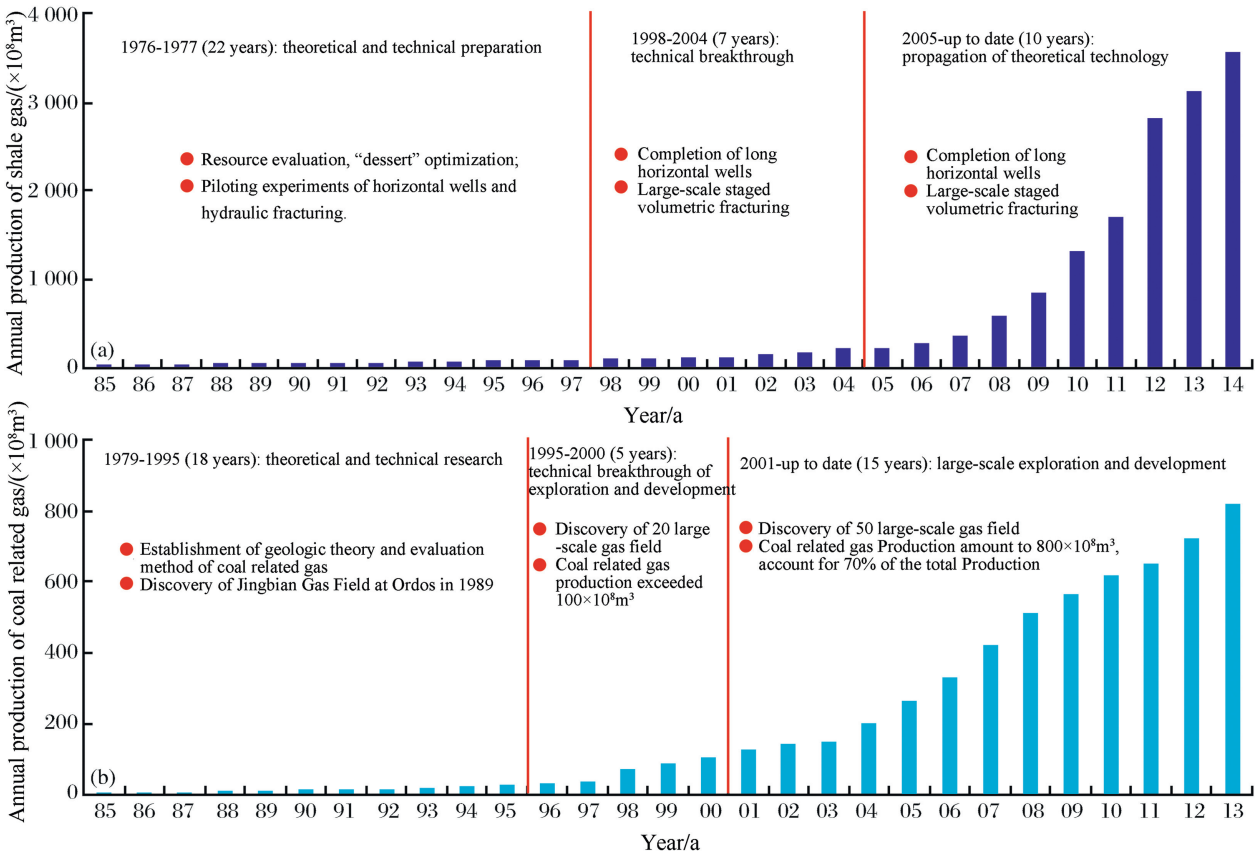

Fig. 3. Production growth histogram of shale gas in America (top) and coal related gas in China (bottom).

4.2. High uncertainty of shale gas resources and its economics of non-marine (transition phase and terrestrial) shale gas

Non-marine shale gas is a typical characteristic and an important constituent of shale gas in China, which is widely distributed in some basins or regions, namely Bohai Bay, Sichuan, Ordos, Jungar, Tarim, and Tuha. Although the distribution area is as high as (30–40) × 10^4 km^2, with a recoverable resource of 4.03 × 10^{12} m^3, the resource endowment is generally worse than that of marine phase, which is characterized by poor gas storage capacity, only 1/4 to 1/2 of that of marine phase. As to the development of this sort of resource, there are no successful examples overseas. Exploration experiment is only initiated in Ordos Basin. Although 59 wells have been completed and half of them have got gas rate, the gas rates of a single well are all lower than 5 × 10^4 m^3. Based on current exploration practice and understanding degree, the economy and exploration & development prospect of this type resource could not be determined.

4.3. Breakthrough of no key technologies and equipment for the depth more than 3500 m

Horizontal well drilling, staged fracturing stimulation, and "factory-like" operation are the three key technologies for the exploration and development of shale gas. Shale gas that occurred shallower than 3500 m is mainly developed in North America, while the shale gas that occurred deeper than 3500 m accounts for 65% in China, for which no mature technologies or equipment are available for reference. The three main technical problems are: firstly, the burial depth of the target shale is large, with complex structures and it is hard for prediction of "desert"; secondly, the drilling accidents are frequent, it is hard for the controlling of the wellbore trajectory, it is difficult for the staged stimulation with poor effect; thirdly, the formation breakthrough pressure is high, resulting in operation conditions of high temperature and high pressure which cannot be fulfilled by current matching tools and equipment. The wells deeper than 3500 m in Sichuan Basin, such as Wei 204H1-2 and Dingye 2HF, have good surface conditions, while wellbore collapse is serious during drilling, the wellbore trajectory deviations are big and the power of fracturing truck is insufficient, resulting in less perforation stages, small stimulated volume and poor single-well production.

4.4. Continuously higher costs of exploration and development of shale gas in China

As to the four shale gas development zones, the exploitation effect of Chongqing Fuling Jiaoshiba zone is the best one, where an average drilling depth is 2300 m, horizontal well stage is 1500 m, and an average single-well gas rate is over

10×10^4 m^3/d. The single well costs are ranged from 70 to 85 million RMB, and the exploitation costs of shale gas is RMB 1.85 yuan/m^3. At Weiyuan-Changning–Zhaotong zone, the average drilling depth is 2500 m, the horizontal well stage is 1500 m, the average single-well gas rate is over 6×10^4 m^3/d, the single well costs are ranged from 65 to 75 million RMB and the exploitation costs of shale gas is RMB 2.03 yuan/m^3, which is categorized into inefficiency to low-inefficiency level. Taking Barnett shale of America for comparison, the average drilling depth is 2500 m, horizontal well stage is 1000 m, the average single-well gas rate is over 6×10^4 m^3/d, the single well costs are about 35 million RMB and the exploration costs of shale gas is RMB 0.81 yuan/m^3. The data aforementioned proved that, under similar conditions, the exploration and development costs of shale gas in China is twice to triple than that of America's. Decreasing the costs and improving the efficiency is critical for the realization of large-scale and effective development.

4.5. The non-technical factors seriously constrained the rapid development of shale gas

4.5.1. Complicated surface conditions

Compared with North America, shale gas resources regions in China are mainly located at harsh environments, such as mountain areas, deserts, and loess plateau, with inconvenient transportation, complex terrain, rare network, and high exploration difficulty, which greatly adds up to the non-technical cos. The gas fields, such as Fuling Jiaoshiba and Changning-Zhaotong are both located at remote mountain areas of Sichuan Basin, with obviously rugged terrains and being far away from gas transportation pipelines, resulting in the enormous difficulty for "factory-like" operation and deployment of well platforms. The investment of surface facilities is huge and the construction period is long.

4.5.2. Insufficient water sources

With the current technology, the development of shale gas needs consumption of large amounts of water. Statistically, the average single-well (drilling and fracturing) water consumption quantity in North America is ranged from 1.5×10^4 m^3 to 3.2×10^4 m^3, while the average single-well (drilling and fracturing) water consumption quantity in Sichuan Basin is ranged from 1.8×10^4 m^3 to 4.3×10^4 m^3. The increasing and stable production of shale gas depend on large amounts of drilling and fracturing. Production of 100×10^8 m^3 shale gas needs 800 to 1500 production wells. The available data shows the renewable water resource per capita in China is 2100 m^3, which is only 1/10 of that of America and 1/42 of that of Canada. Annual precipitation is unevenly distributed in most parts of China and long droughts even often happen in the south areas, such as Chongqing and Sichuan, where the annual precipitation is relatively high. Shortage of water resource in the middle and western parts in the north is more serious. The shale gas exploration zones in Ordos Basin and Xinjiang are located at loess plateau, gobi and desert areas, where water resource is in severe scarcity, resulting in the impossible large-scale construction of current fracturing stimulation technology and large-scale development.

4.5.3. Impacts on environmental ecology

Large amounts of fracturing fluid are consumed during exploitation of shale gas. The fracturing fluid is mainly composed of a series of additives, including thickener, cross-linker, and high-temperature stabilizer. During the construction process, the residual fracturing fluid in the formation may jeopardize the underground water resource. The flow black waste fracturing fluid, with newly added materials from the formations, have more complicated components compared with the original fluid. The disposal of the waste fracturing fluid without treatment will cause damage to the human and natural environment. After a series of procedures of fracturing and water injection, many artificial fracture networks were formed, which broke the original balance in the formation. The structure changes may induce potential hazards, such as surface collapses, micro (small) seisms and landslides. During shale gas production, large amounts of drilling work is adopted for production growth and stability, which produced lots of noise, large-area vegetable destruction, and impact on the habitat environment of animals. The unqualified equipment, intentional venting, and fracturing may also result in methane leakage risk. The leaked methane may pollute formation water after dissolving and jeopardize human health after venting into the air, which also increases the possibility of ozone damage.

4.5.4. The limited promotion capabilities for non-petroleum enterprises

Under flexible operating and innovation mechanism, with a long period of exploring, the middle to small enterprises in America contributed a lot to the large-scale development of shale gas. However, the shale gas development in China is right in the starting stage, which is characterized by large investment, high risk, and high technological demand. The non-petroleum enterprises know little about the characteristics of petroleum exploration and do not get enough understanding of technical features and economic risks of exploration and development of shale gas, which result in blind participation of exploration and development of shale gas to some extent.

Judging from the operating conditions of the 20 blocks acquired by the non-petroleum enterprises, although large amount of investment has been spent, the advancement of most projects are slow, with low exploration efficiency against to the expectations, which heavily frustrated the ambitions of non-petroleum enterprises, resulting in relatively negative impact to the industry's development.

4.5.5. Difficult coordination between enterprise and community

The population density is high inside the shale development block in Sichuan Basin, and the construction well site is close to the residential area. Although the enterprise has reached agreement in terms of land requisition, safety production, and environmental protection, the local residents still request

additional compensation during actual construction, with the excuse of noise, water consumption, and fracturing induced earthquake. The residents initiated this additional request by means of blocking the road. The stalemate severely influence the construction progress, resulting in great economic loss. For example, at the four platforms of Zhaotong demonstration zone in north of Yunnan and Guizhou province, the fracturing operation was postponed by three months for road blockage, and merely the compensation for the rent of fracturing equipment of Schlumberger and Chuanqing Underground Company reached near 100 million RMB. At Changning-Weiyuan Demonstration Zone, the pre-drilling work of 23 platforms was impacted by road blockage, postponed by 17 d to 96 d, with an average postponed period of 46 d for each platform.

5. Suggestions on the development strategy of shale gas in China

5.1. Some "misunderstandings" exist for the status of shale gas development

The exploration and development of shale gas of China only acquired some breakthroughs at the pioneering testing zone in Sichuan Basin and is still in starting stage nationwide, with great distance away from the development in North America [16]. Development stages out of the reality are not recommended; impractical production target is not recommended; blind development regardless of effectiveness is not recommended. It is suggested that development strategy and targets should be established [5,6] according to the national conditions of China. Around 2020, the development stage, development strategy, and target should be set as follows:

(1) Until 2020, the total shale gas production upper capability is up to 300×10^8 m^3, and make sure the lower capability is 200×10^8 m^3. The conventional and unconventional gas production totals $(550-600) \times 10^8$ m^3, with the establishment of "gas-Daqing".
(2) During the period from current time and the following 5−10 years, the shale gas development stage in China is still dominant by preliminary exploring and industrial production should be realized in some regions in Sichuan Basin.
(3) Set development strategy "based on the marine shale gas in Sichuan Basin, stressing theory innovation, tackling key technologies, getting breakthrough on the three theoretical and technological bottleneck of non-marine, deep horizon and water-less fracturing, and realizing the production leap of shale gas". A series of exploration and development experiment areas will be established in Sichuan Basin, realizing the overall exploration and development of southern shale gas, and promoting the nation-wide terrestrial shale gas exploration. The successful experience and effective approaches acquired at the shallow and over-pressure areas will be promoted to deep horizons and normal-low pressure areas, which will gradually formulate the geologic theory, self-dependent core technologies, and localization of the main equipment, as to marine shale gas.

5.2. High uncertainty of economic resources as to shale gas at lower-production and lower-pressure zones and non-marine shale gas

(1) Pay attention to the geologic theory and engineering technical research for the shale gas at low-production and low-pressure zones. Focus on the optimization and evaluation of the resource "desert", optimize exploration and development technologies, improve organization and management, and gradually realized effective exploration and development of shale gas at low-production and low-pressure zones.
(2) Focus on resource evaluation and "desert" preferred selection. Due to the relatively low exploration degree of shale gas in domestic China, and no available exploration work in the most areas, it is recommended that, the *Ministry of Land and Resource*, shall lead the establishment of the national shale gas exploration fund, with emphasis on Sichuan Basin, Ordos Basin, and Middle-Lower Yangtze Region. Targeting at non-marine shale gas, according to different types, 20 to 30 shale gas scientific evaluation wells should be drilled, with data being sampled completely and accurately. The "desert basin" with abundant non-marine shale gas, the "desert intervals" with resource enrichment and the "desert zones" with favorable construction and production conditions should then be determined.
(3) Promote the construction of non-marine shale gas demonstrations sequentially. After the year 2015, the non-marine shale must contribute to the large-scale development of shale gas, and the establishment of non-marine shale gas demonstration zone is essential. By introduction of successful experience of the current four marine shale gas demonstration zones, two to three non-marine shale gas favorable zones in Sichuan and Ordos Basin will be selected for construction of demonstration zones. Experiment research will be initiated, and the geologic theory of non-marine shale gas accumulation, key technologies and equipment will be innovatively developed, with forming of some production scale.

5.3. Breakthrough of no key technologies and equipment as to depth more than 3500 m

Focus on systematic research of technology, equipment and processing for the shale gas deeper than 3500 m, which will promote scale production breakthrough of deep shale gas. It is recommended that the government should formulate policy and establish special innovation fund to support the enterprises for relevant research of technology and equipment. The *Ministry of Science and Technology of the People's Republic of China* should support the research and

manufacturing of 4000 and above large-scale fracturing pump truck in *China National Major Special Projects*. It is also recommended that the government should formulate policy and establish special innovation funds to support the enterprises for research of technologies and equipment, such as high-temperature fracturing fluid, high-strength prop-pant, and rotating and piloting, which will resolve the pressure deficiency of the current fracturing truck and the bad performance of the current fracturing fluid system, promoting the development and utilization of shale gas for the horizons deeper than 3500 m.

5.4. Continuously high costs of shale gas exploration and development

During the research on shale gas in America, the government offered a subsidy as high as 51% of the gas price, with a time period of more than 20 years, which effectively promoted the preliminary development stage of shale gas in America. The currently high development costs of shale gas in China are relatively high and will be maintained for a long period. In the year 2013, the central government initiated a fiscal subsidy of RMB 0.4 yuan/m^3; RMB 0.3 yuan/m^3 during 2016 and 2018 and RMB 0.2 yuan/m^3 during 2019 and 2020. To further promote the exploration and development of shale gas, it is suggested that the enterprises participating into shale gas exploration and development should continuously promote technology and management innovation, emphasizing on costs control mechanism during drilling and fracturing, and making an effort for the economically scale development of shale gas.

5.5. Handling the non-technical factors severely impacting the rapid development of shale gas

(1) Based on the technical characteristics of exploration and development of shale gas, the mining right management system should be reformed. Exploration stages and development stages are set for conventional gas. The purpose of exploration stage includes discovery, evaluation, and putting forward proven reserves; the purpose of development stage involves in productivity construction and gas production, which offers possibility for the separate management of exploration right and mining right. However, draining while exploring is common for shale gas, as there is one to two years of testing production period, even longer, before putting forward proven reserves. The current permitting testing production period is only one year, which results in the common gas production without mining right. It is suggested that the *Ministry of Land and Resource* shall initiate the integration of exploration right and mining right, extending the testing production period and improving development effects.
(2) Rigorous management measures should be stipulated by the government, and the potential impacts on environmental ecology during exploration and development of shale gas should be monitored. Based on adequate understanding of geologic conditions of shale gas exploration and development, with adoption of advanced technology and process equipment, the leakage of fracturing fluid and methane should be rigorously controlled; waste water, waste gas, and waste solid residue should be well treated; stress recycling and reusing of water resource and the integrated utilization of waste residue. Decrease formation damage, water resource pollution, and surface vegetable destruction; monitor and motivate the enterprises for development of water-less or non-water fracturing technology. Within the exploration and development zones of shale gas, monitoring of geologic hazards should be strengthened, such as earthquakes and landslides. Treatment measures should be suggested in time according to the monitored results.
(3) Definite policies should be stipulated by the government, piloting the non-petroleum enterprises into participation of shale gas development. During the relatively high exploration stage, the non-petroleum enterprises should not be involved in or less involved in; during the relatively low-risk development stage, the non-petroleum enterprises may participate in various ways.
(4) Shale gas development data and information platforms should be established under the leadership of a relevant government department, and shale gas exploration data management should be unified for information sharing. Connect the offering of relevant shale gas exploration and development data to mining right, establish the system of data acquisition, storage and informatization of shale gas exploration, which constitutes the data and information platforms of covering shale gas exploration both at home and abroad, realizing the management of shale gas mineral rights and data sharing.

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Conflict of interest

The authors declare no conflict of interest.

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