Chapter 4

Current Technologies and Prospects of Shale Gas Development in China

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Additional information is available at the end of the chapter

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Abstract

Shale gas in China has realized the great-leap-forward development because of the significant strides of development technique for marine shale resource, becoming the second largest shale gas producer only to the USA. Benefits from the progress of technique advance, a complete technique series for the development of shale resource buried less than 3500 m has been established by operating technique research and field trail, including five main key techniques of geological evaluation, optimum and fast drilling, multi-stage hydraulic fracturing, productivity evaluation, and development parameters optimization. At present, shale resource in China has not been fully exploited besides the marine shale resource (<3500 m). It would be the future development trend to enhance ultimate recovery of shale gas (<3500 m). Moreover, two-thirds of recoverable resource are stored in the formation (>3500 m). With the further process of development technique for marine shale, shale gas is expected to the single type of gas reservoir contributing to the highest annual production rate in the near future. Therefore, based on the success in shale industry, this work is organized by reviewing the advances and challenges of current evaluation techniques, and then discussing the possible development trend of shale gas performance evaluation in the future.

Keywords: shale gas, reservoir characteristics, productivity evaluation, horizontal section length, fracture parameter, development well spacing, production system

1. Introduction

China has abundant organic-rich shale resource, and there is 31.6×10^{12} m^3 technically recoverable reserves (predicted by EIA [1]), ranking the second only to the USA. China has already become one of few countries besides North America making breakthrough in the aspect of shale gas development. Especially for the last 2 years, China has greatly promoted the shale gas development, annual production rapidly increasing from 2×10^8 m^3 in 2013 to 45×10^8 m^3 in 2015, and become the second largest shale gas producer only to the USA [2, 3]. In the structure of total natural gas output in China, shale gas has surpassed the coalbed methane (CBM) and becomes the second largest gas reservoir type only to tight gas.

Shale gas industry in China has realized the great-leap-forward development because of the significant strides of development technique for marine shale resource. Encouraged by government investment and subsidy policy during the 12th five-year plan, a complete technique series for the development of shale resource buried less than 3500 m has been established by operating technique study and field trail, including five main key techniques of geological evaluation, optimum and fast drilling, hydraulic fracturing, productivity evaluation, and development parameters optimization (**Figure 1**). These technique trials and applications result in enhancing production rate of gas well and reducing investment costs on single well, which has laid the technical foundation of large-scale development of shale resource.

Although shale gas enjoys vast development prospects in China, shale resource in China has not been fully exploited besides the marine shale resource buried less than 3500 m, a very low development degree. Considering the supply–demand relation in the natural gas market in China, it would be the future development trend to enhanced ultimate recovery of shale gas. Moreover, two-thirds of recoverable resource are stored in the formation buried more than 3500 m [4, 5]. With the process of development technique for marine shale and the breakthrough of development technique for land and transitional shale with large areas in the northern China, shale gas is expected to the single type of gas reservoir contributing to the highest annual production rate in the near future.

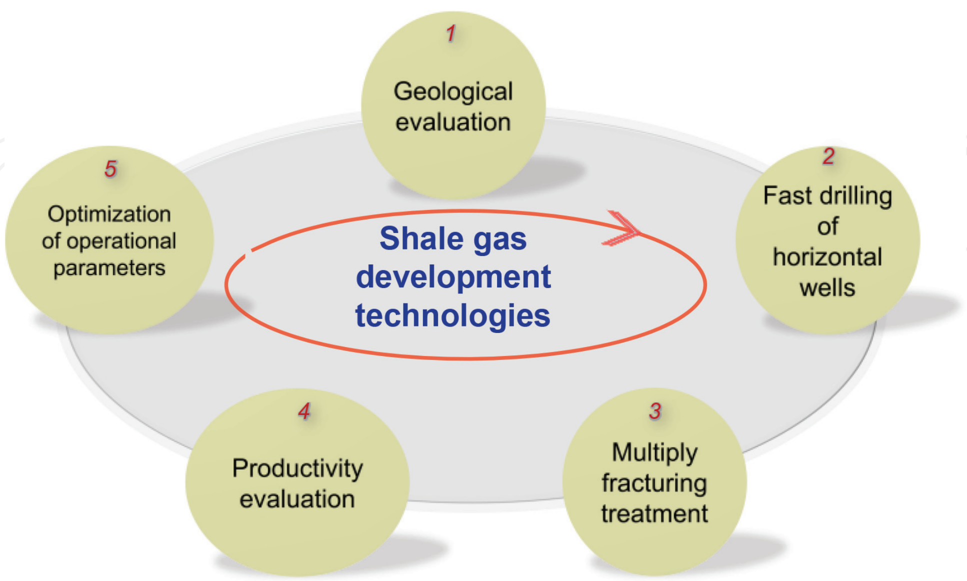

Figure 1. Schematic diagram of shale gas development technologies.

This chapter compares the shale gas developing conditions between China and the United States, reviews the developing practice and technological innovations and gives a summary of progress in key technologies of evaluating shale gas development in the past few years, in the hope of providing instructive references for the development of China's shale gas industry.

2. Development status of China's marine shale gas

Shale gas exploration and development in China have made a great breakthrough during the 12th five-year plan period. A series of major theories, systematic innovations and technology progresses fueled commercial development of China's shale gas from 2014 to 2015. By the end of 2015, 198 evaluation wells, 393 horizontal wells of marine shale gas had been finished, 267 wells had been fractured and put into production, with the productivity of 77×10^8 m^3, and three marine shale gas demonstration areas, Fuling, Changning-Weiyuan and Zhaotong had been built [2, 6].

The selection of "sweet spot," optimized and accelerated drilling and volume artificial fracturing technologies have made major progress through research and test during the 12th five-year plan, which has supported the transition of invalid resource to effective production, lowered the total investment of single well from 100 million Yuan in the early days to 7 0 million Yuan now, and brought about the rapid increase of shale gas production from 12.8×10^8 m^3 in 2014 to 44.6×10^8 m^3 in 2015. How to translate effectively production into scale production is the most important research direction in the 13th five-year plan period.

According to the characteristics of marine shale gas in southern China, CNPC and SINOPEC have come up with the four modes of efficient exploration and development, "well deployment on wellpad, factory drilling and fracturing, skid-mounting of production and storage equipment, and integrated organization and management." They have also worked out "cooperative evaluation, development test stage, and scale development stage" three kinds of scale development regimes for shale gas, which have promoted the technical progress, lowered cost and increased efficiency.

- In the stage of cooperative evaluation stage (2007–2011), the main work was focus on explorating technologies for shale gas development, and building out shale gas development strategies.
- In the stage of development test stage (2012–2015), the main technologies for shale gas development were developed, tested and determined rapidly, and single well production and EUR were increased rapidly.
- In the stage of scale development stage (2016-), single well production and EUR kept increasing steadily, and development technologies were optimized continuously. As a result, annual production is increased rapidly.

In summary, the shale gas production has increased rapidly in China since 2013, similar to the historic period of tight gas from 2005 to 2008 [7], as shown in **Figure 2**. As a consequence,

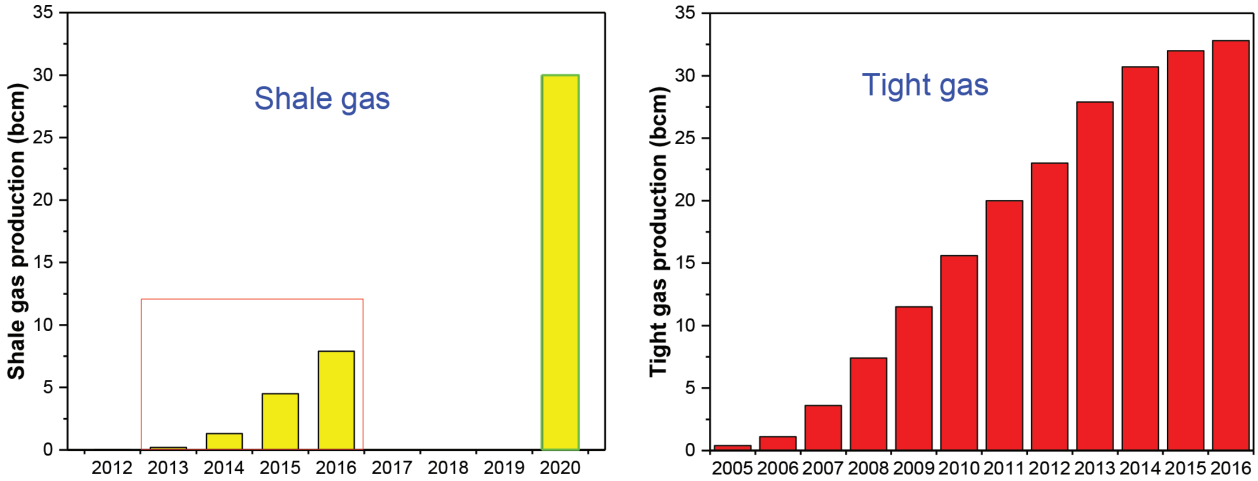

Figure 2. Comparison of annual production and forecast of shale gas and tight gas in China.

recoverable resources have been proved, daily production of single well almost doubled, and the development costs declined.

3. Current status of applied techniques in shale gas development

3.1. Geologic evaluation of marine shale gas in China

Shale reservoir description is characterized by acquiring, processing and interpreting 3D seismic and logging data from shale in mountainous area. As a result, high-quality shale interval in vertical distribution and sweet spot in lateral distribution are recognized by integrating comprehensive geological evaluation technology with outcrop, core, geochemical data and sedimentary setting model. These techniques provide guidance for the target optimization of drilling horizontal well and the mass arrangement of multiwell pad.

Seismic survey. An integrated technique has been established to conduct 3D seismic acquisition, process and interpretation as shown in **Figure 3**. Here, 2D seismic technique is used to perform structure evaluation and predict reservoir-characterized parameters [8]. After using this integrated technique, the consistency of parameters prediction with actual parameters is up to 80% in 3D seismic acquisition areas.

Well logging. China has conducted independent development of LWF (Logging While Fishing) technologies, as shown in **Figure 4**. As a result, the interpretation of parameters such as TOC, porosity and gas content has the consistency of up to 90%.

Reservoir evaluation. Geological evaluation is performed on the basis of flow unit appraisal (**Figure 5**). The gas bearing layer is the lower part of the Longmaxi Formation with thickness of 30 m. The drilling target has been optimization to the lower zone with thickness of 15 m. Reserve abundance is reevaluated: the development zone has average abundance of 0.45 bcm/km^2, the lower unit is 1.2 bcm/km^2.

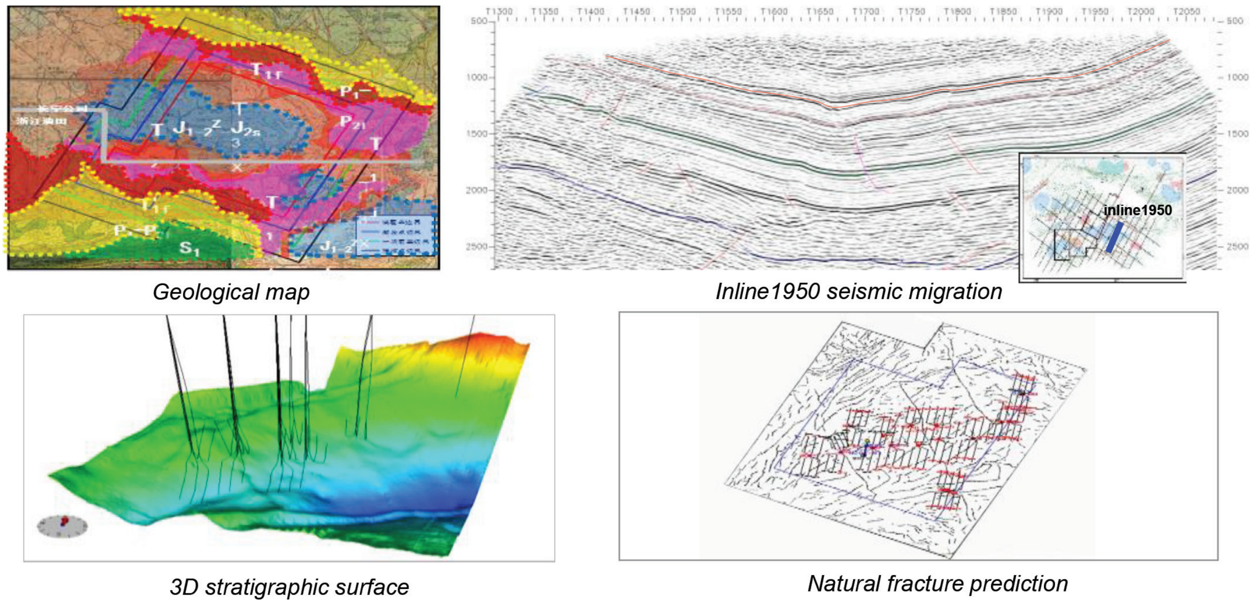

Figure 3. Technical frame of integrated 3D seismic interpretation.

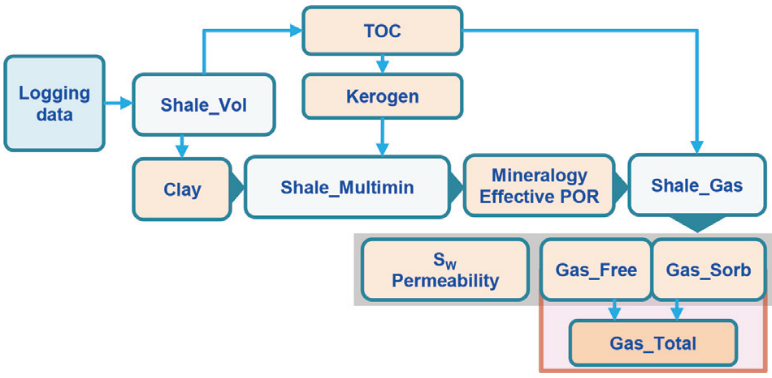

Figure 4. Shale gas well logging interpretation flow chart.

As a result, stratigraphy was correlated by using logging and core data, and Longmaxi Formation is divided into three members according to the characteristics of lithology, fossils and logging curves [9, 10]. We find that Longmaxi Formation and its favorable reservoirs are stable in thickness, which make good targets for horizontal wells; the good seal condition leads to an abnormal high pressure, which is the key to high production; The carbonaceous or siliceous shale with abundant organic matters, which deposited in restricted or semi-restricted sea basin, is ideal as favorable reservoirs (sweet spots). In addition, geological factors such as TOC, gas content, porosity and pressure coefficient control the quantity of resources (geological sweet spots), and engineering factors such as brittleness, Young modulus and Poisson ratio control the fracturing efficiency (engineering sweet spots), seen in **Figure 6**.

3.2. Fast drilling of horizontal well

It was not until 2013 that there was a total shit to horizontal wells for developing shale in the Changning-Weiyuan shale as well as other China shale basins that followed. Now that the

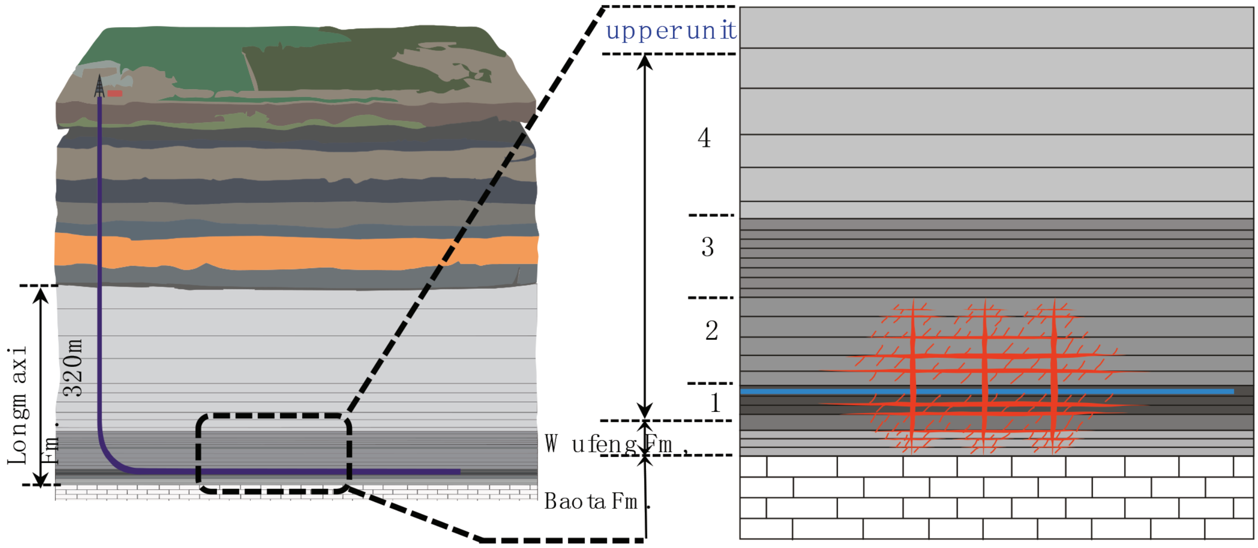

Figure 5. Stratigraphy structure and OGIP evaluation for producing layers in Changning area.

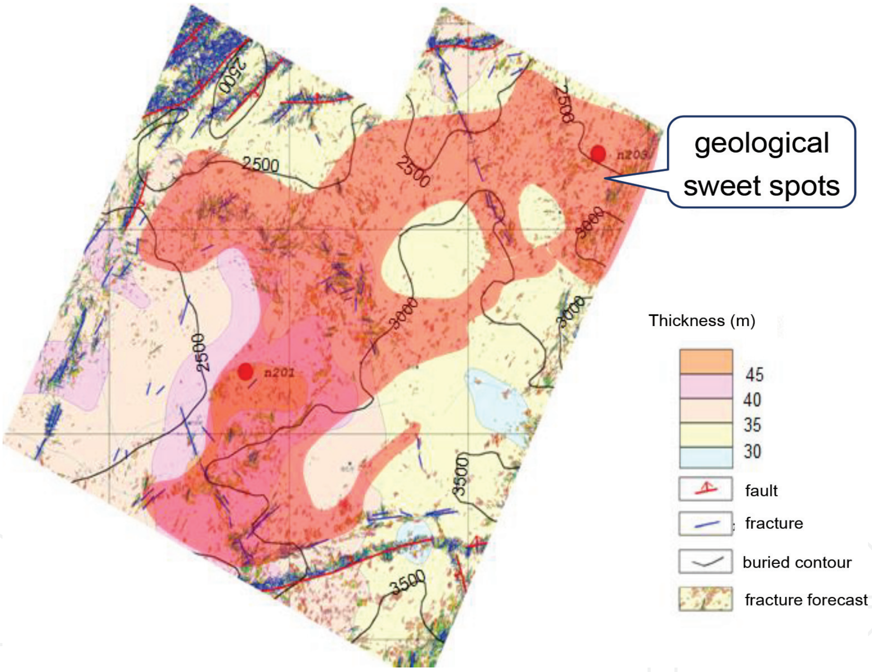

Figure 6. Sweet spots prediction based on 3D seismic interpretation.

template has been set for shale gas drilling in China, service companies have been successfully reducing drilling costs through optimized drilling and new technology [11]. The advance of drilling technique makes the drilling cycle reduce from 139 to 69 days with the help of hole structure optimization, straight hole high-efficiency motor, individualized PDC bits, rotary steerable drilling system, gas factory drilling progress management (**Figure 7**).

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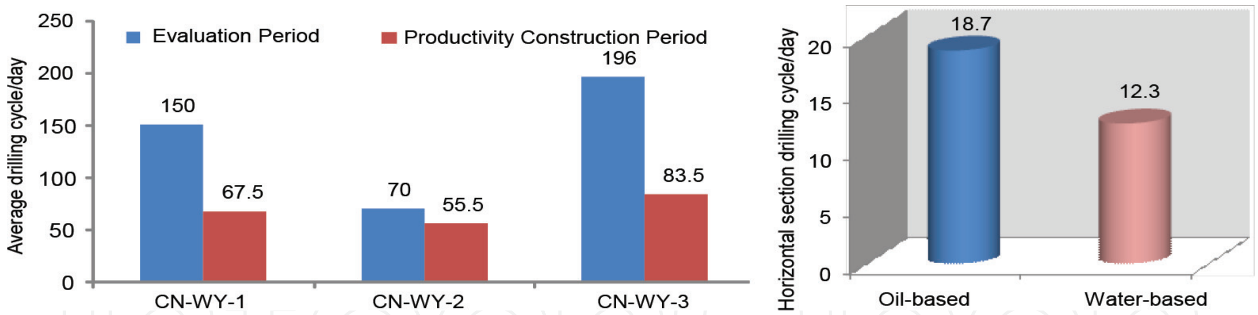

Figure 7. Drilling cycle of different period.

Listed in the following are some of the current typical practices used for drilling horizontal wells:

- Optimum lateral lengths are now preferred over "longer lateral lengths. "Length of horizontal sections varies from play to play, and ranges from 1500 to 2000 m for main shale play.
- High-efficiency water-based drilling fluid was also chosen prior to drilling the curve and lateral to reduce the environmental risks. It is understood that most international horizontal wells will be probably be drilled with water-based drilling fluid.
- Mud weights depend on formation, which range from normal to overpressured.
- Poly-diamond crystalline (PDC) bits were used by oil companies in China.
- Wells are drilled in the direction of minimum horizontal stress.
- The practice of pad drilling (6–8 wells per pad) was quickly adopted by China operators, and currently over 90% shale wells are being drilled from pads.
- The "drilling cost "constitutes 40–50% of the total well cost.

3.3. Multiple fracturing treatments

Fracturing the rock and propping open the induced fractures creates high permeability pathways, which allows the reservoir formation to produce at much higher flow rates than it could naturally [12]. As shown in **Figure 8**, China has built a framework of volume fracturing by integrating zipper-style volume fracturing using high-displacement low-viscosity slick water, low-density moderate-intensity proppant and soluble bridge plug. As a result, the testing production is increasing from 105,000 to 163,000 m^3/d through, and Gas factory reduces the drilling cycle by 30%, and increases the fracturing efficiency by 50%, which reduces the fracturing cycle of half-platform to 30d.

Listed in the following are some of the current typical practices used for hydraulic fracturing:

- high-displacement low-viscosity slick water has the ability of providing sufficient propped flow capacity to develop a gas productivity shale, and overcoming the tendency of the proppants to settle.

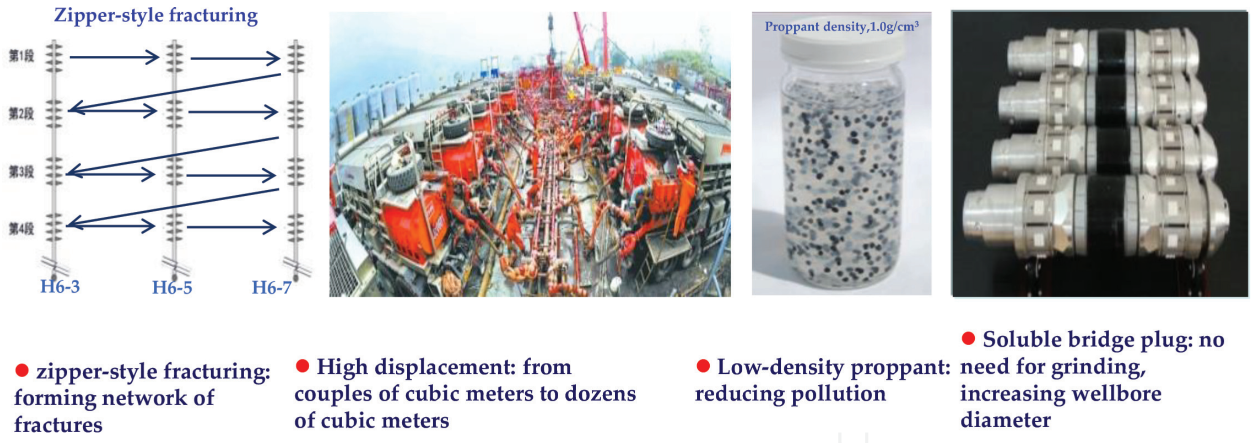

Figure 8. Framework of integrated fracturing techniques.

- Up to three wells could be zipper fractured, although no documentation could be found on more than two zipper fractures at a time. Brittleness of the shale likely has some control on the success of zipper fracturing.

3.4. Productivity evaluation technologies of shale gas

It is critical for investors to investigate the potential benefits and prospective risk in order to determine whether the given shale source should be invested. Performance evaluation is an integrated technique of well testing, production data analysis for quantitatively extracting reservoir (i.e., gas-in-place and reservoirs permeability) and stimulation information (i.e., fracture properties), based on incorporating the statistic data from geoscience research, production log, lab measurement, micro-seismic, well completions and stimulation, and the dynamic data from historical pressure/rate surveillance [13, 14]. This aims at calculating reserves and estimated ultimate recovery (EUR), forecasting future production for prospect analysis, and optimizing the development of shale gas field, and highlighting effectiveness, economy and convenience.

China has present a probabilistic methodology (**Figure 9**), which incorporates the risk and uncertainty with the complexity of flow mechanisms and fracture networks when evaluating shale gas performance.

The method is described for integrated use of newly developed empirical model and modified analytical model incorporating pseudo-variables accounting for changes in fluid properties and reservoirs properties and in operational conditions (variable flow rate and flowing pressure), which is threefold. (1) Establish reliable equations of parameter combinations by dynamic data analysis and linear regression method ($x_f K^{0.5}$ is a constant). (2) Determine the probability distribution model of fundamental parameters such as formation thickness and permeability, etc., by statistical analysis (**Figure 9a**), it is worth noting that the lower limit of permeability is from core testing and the upper limit is determined by the formula of radius probing [12]. (3) Sample randomly from the permeability values based on stochastic simulation to calculate the unknown parameters combined with constraint equations. (4) Rearrange the results from

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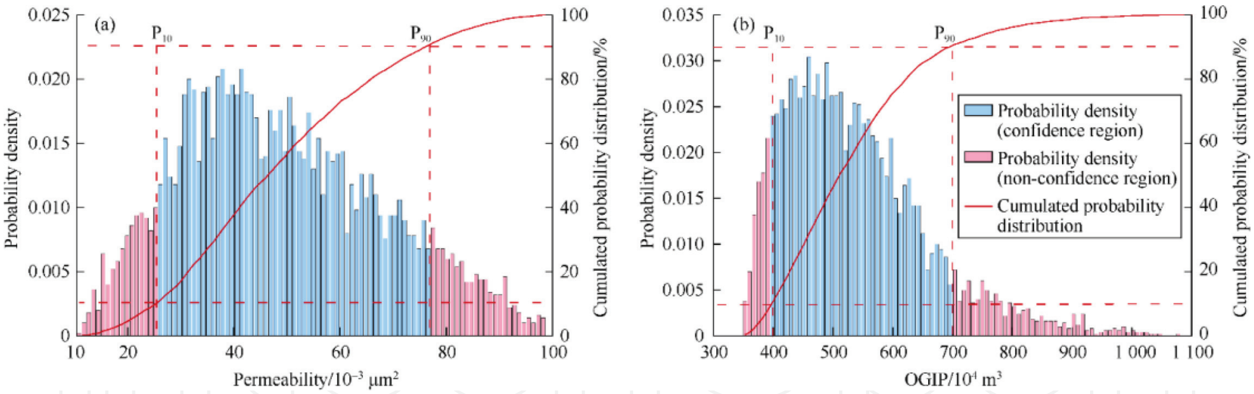

Figure 9. Permeability and OGIP versus confidence region.

small to large, to get the probability distribution and corresponding confidence range of unknown parameters (**Figure 9b**).

The production performance of shale gas wells was predicted with the linear flow model, based on the permeability and controlled reserves of single well at the probability of P10, P50 and P90, furthermore, quantitative risk assessment of production dynamic and cumulative production were performed (**Figure 10**). Average cumulative production of single wells at P50 is $(0.6–1.0)\times10^8$ m^3 according to the production data of 270 stimulated horizontal wells in China (**Figure 11**).

3.5. Parameter optimization technologies for shale gas development

Technology demands of shale gas well development can be basically satisfied by combining geological evaluation, drilling, fracturing and productivity evaluation technologies, but to realize reasonable development of shale gas, the length of horizontal section, fracture placement, production systems and well spacing need to be optimized.

Optimization of horizontal section length and fracture parameters. Optimizing the fracture parameters of horizontal wells requires an integrated optimization of several parameters simultaneously. Gas well productivity is strongly influenced by the horizontal section length

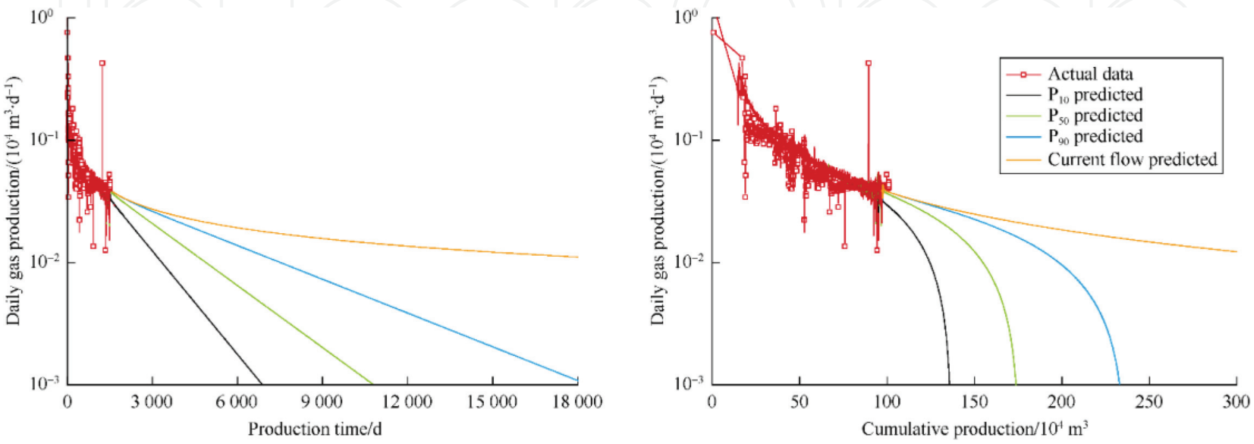

Figure 10. Prediction of production performance at different confidence levels.

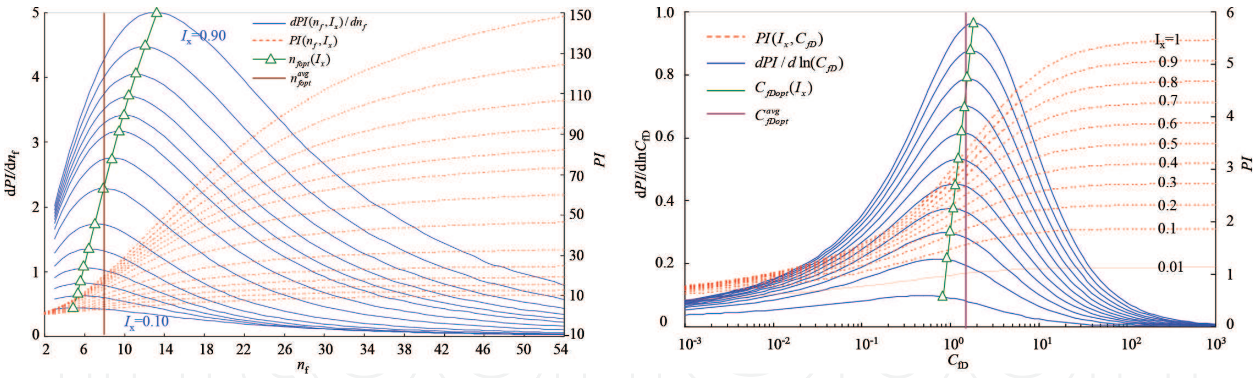

Figure 11. Prediction of productivity performance at different proppant number.

of the fractured well, number of fractures, flow conductivity and fracture length [15]. The optimization idea is: (1) enlarging the contact area between the fracture network system and formation by increasing the fracture number and length; (2) balancing the relationship between inflows and outflows of fracture network through adjusting the limited fracture conductivity; (3) reducing the interference between fractures by regulating the fracture spacing and relative location with the closed boundary. The relationship of multiple fracture parameters is shown in **Figure 12**.

In addition, shale gas development is marginal in benefit now, so the costs of various engineering links are stringent, and parameters of horizontal well and fracturing should be comprehensively demonstrated by combining the theoretical research and actual operation conditions.

Optimization of well spacing. At present, horizontal well deployment from wellpad, factory-like drilling and fracturing, and large-scale continuous operation are widely adopted in drilling shale gas horizontal wells. If the well spacing is too large, some remaining gas reserve will be left behind forever; on the contrary, if the spacing is too small, the cumulative production of single well will decrease, which will lower the development economic benefit. The production

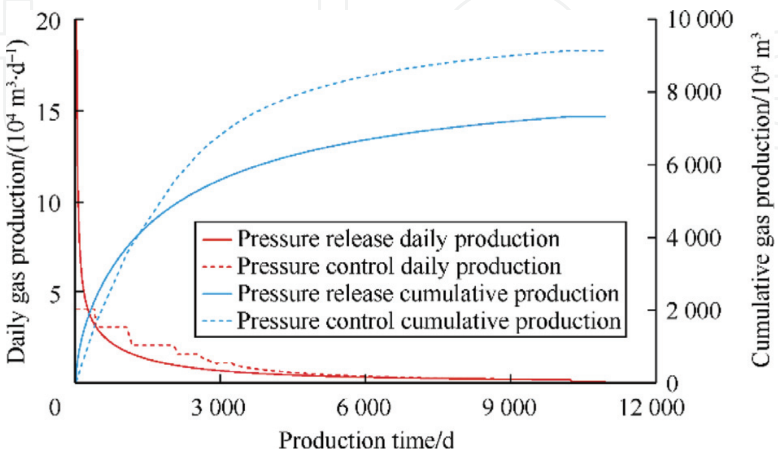

Figure 12. Comparison of predicted production between pressure release and pressure control production system considering stress-sensitivity.

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Area	Horizontal section length (m)	Well controlled area (km^2)	Average well controlled area (km^2)	Average well spacing (m)	Proppant dosage of single stage (t)
Barnett	1219	0.24−0.65	0.45	280	129.7
Haynesville	1402	0.16−2.27	0.50	260	162.3
Marcellus	1128	0.16−0.65	0.42	260	181.2
Eagle Ford	1494	0.32−2.59	0.60	300	112.6
Southern Sichuan Basin	1448	0.36−1.10	0.65	400−500	97.5

Table 1. Comparison of well spacing between typical areas in Southern Sichuan and the United States.

history of China's shale gas is short, and the well spacing is determined mainly based on micro-seismic monitoring results in the early stage of development. But the monitoring of test production performance to date shows that the well spacing determined from micro-seismic monitoring is too large [16]. It can be seen from **Table 1**, compared with the four major shale gas fields in the United States, the average proppant dosage of single stage in shale gas developing areas of south Sichuan Basin is much lower. Besides that, the length of fracture is shorter due to the bedding restriction. Therefore, reasonable well spacing should be smaller [17, 18]. Development well spacing should be optimized through theoretical study, interference well-testing and dynamic data analysis, in combination with field test.

Optimization of production system. Barnett and Marcellus shale gas fields are produced in free pressure release and large pressure difference mode. In contrast, in Haynesville shale field, because of high formation pressure and pressure-sensitivity of the shale formation, the wells are produced at controlled pressure and production [19, 20]. Shale gas plays of CNPC have high pressure in general, so wells in Changning and Weiyuan are producing at big pressure difference, while wells in Zhaotong area are producing at controlled pressure and production. Since the two demonstration areas take different fracturing technologies, they cannot be compared quantitatively. Theoretically, pressure release production will lead fast pressure drop in major fractures, consequently, pressure sensitive effect will cause rapid permeability decline in areas around the major fractures, thus the fast formation of reservoir damage area, which would forbid peripheral gas getting into the major fractures and cause production decrease of well (**Figure 12**). Numerical simulation based on the data of production wells shows that different production systems differ widely in cumulative production (**Figure 7**); and pressure controlling production gets 28% higher cumulative production than pressure release production. Therefore, comparison test between nearby wellpads or wells in the same wellpad could be conducted to select the better production system.

4. Development prospects and technical direction of shale gas

As a new source of energy, shale gas has huge exploration and development potential. According to the latest evaluation of CNPC shale gas project team of nation project on oil & gas, recoverable resources of marine shale gas in southern China are $8.82\times10^{12}m^3$, in which 2.10×10^{12} m^3 are in Fuling, eastern Sichuan Basin, and 4.37×10^{12} m^3 in Changning, Weiyuan, Fushun-Yongchuan, Zhaotong, in southern Sichuan Basin. With the promotion of geologic theories and progress of technologies in China, the marine shale gas production is expected to reach 300×10^{12} m^3 by 2020; the shale gas is likely to become the most productive type of natural gas by 2030. But due to the complex geological conditions in China and the current low prices of oil and gas in the world, large-scale efficient development of China's shale gas is facing lots of problems.

Theories of China's shale gas are still not complete, and comparative studies between sublayers and regions need to be deepened further. Although existent studies have revealed the basic laws and features of shale gas accumulation, in such studies, shale formations are often taken as homogenous reservoirs, differences between different layers and areas have not been examined carefully; therefore, calculation of reserves and selection of production relay block lack effective guidance.

Percolation mechanism and shale gas productivity evaluation methods based on the artificial fracture network and nanometer pores should be further improved. Pores in shale are mostly nanoscale, which lead to gas flow state different from conventional reservoirs, especially in complex fracture network system created by volume fracturing, the combined effect of multiscale flow space and nanoeffect makes the flow space description and seepage pattern characterization very complex, and brings about huge challenge to productivity evaluation.

The key technologies of shale gas development have not finalized. Development policies are essential issues for scientific and efficient development of oil or gas fields. For example, well spacing influences the ultimate recovery of gas reservoir, production system affects the cumulative production of single wells. The determination of these key technology policies only depend on theoretical analysis and simulation so far, because of the deficiency of practical data or big error caused by improper test methods. Therefore, it is of great significance to demonstrate key technologies of shale gas development comprehensively by combining theories with and field data.

From the viewpoint of economic benefits, even if the costs of shale gas drilling and fracturing in China have reduced considerably in recent years, they are still too high. The comprehensive cost of signal well should be less than 50 million to achieve an internal rate of return of 12%, at the current gas price. To transfer resource into production as soon as possible, further improvement and innovation should be encouraged in both technology and management.

5. Summary

By now, China companies have proposed a customized method of developing shale gas resource for our own geologic feature and current level of engineering technology. In summary, the method consists of four aspects, which are summarized as follows:

1. Shale reservoir description is characterized by acquiring, processing and interpreting 3D seismic and logging data from shale in mountainous area; high-quality shale interval in

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vertical distribution and sweet spot in lateral distribution are recognized by integrating comprehensive geological evaluation technology with outcrop, core, geochemical data and sedimentary setting model. These techniques provide a guidance for the target optimization of drilling horizontal well and the mass arrangement of multiwell pad.

2. The geology-engineering workflow is integrated to realize optimum and fast drilling technique by incorporating hole structure optimization, individualized PDC bits, rotary steerable drilling system and implementing the factory drilling model of "double-drilling rigs pattern, mass batched drilling, standardized operation." As a result, single-well drilling cycle is shortened by more than 50%.

3. On the basis of importing, absorbing and innovating foreign technology, China has formed a mature technical system of volume fracturing including high-displacement slick water, low-density proppant, soluble bridge plug, zipper-style fracturing and factory drilling pattern. As a consequence, fracturing efficiency is enhanced by 50%, and associated testing production rate is improved to 20×104 m^3/d.

4. A production performance model is built by incorporating multiscale fracture network and multimechanism flow model to perform production performance analysis of shale gas well. Based on the model, an uncertainty productivity method is proposed to quantify probabilistic production forecasts and the probable range of estimated-parameter outcomes. A systematic optimization of fracturing parameters and well spacing is established by type curve matching, production performance modeling, and analogy with exploited shale field in North America.

In spite of great strides in the development of shale gas in China, there still exists much room for improvement. Based on periodic development regulation of other unconventional resources (such as tight gas), more advanced development techniques are required to be improved with the help of

1. strengthening geological research and technical development for the purpose of realizing cost-effective producing at low gas price;

2. reducing investment costs on single well and increase economic benefits. Draw lessons from tight gas development in China and explore low-cost development for shale gas;

3. reducing investment costs on single well and increase economic benefits;

4. performing sustainable improvements on drilling and completion to reduce low production wells.

6. Conclusion

Compared with the United States, shale gas in China has deeper buried depth, more complicate structures and surface conditions, which add difficulties to the shale gas development. At present, shale gas reservoirs less than 3500 m deep have been put into preliminary scale development. Shale gas exploration is heading toward deeper formations, and shale gas development has wider prospects.

An evaluation criterion of shale gas well classification considering dynamic and static parameters and economic indicators has been basically established, but needs further improvement. Unstable mathematic seepage flow model of horizontal wells and probabilistic evaluation method of productivity based on multiscale space and various flow states are nearly perfect.

Optimization of horizontal section length, fracture placement, production system and well spacing are the keys to ensure the overall proper development of shale gas reservoirs. The theoretical research is basically mature, and field testing is urgently needed.

Establishment of shale gas development theory, optimization of evaluation methods and control of development cost are the core tasks in large-scale shale gas development.

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Conflict of interest

No conflict of interest exists in the submission of this manuscript, and manuscript is approved by all authors for publication.

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