Exploration practices and prospect of Upper Paleozoic giant gas fields in the Ordos Basin

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Abstract

Natural gas resources is abundant in the Ordos Basin, where six gas fields with more than 100 billion cubic meters of gas reserves have been successively developed and proved, including Jingbian, Yulin, Zizhou, Wushenqi, Sulige and Shenmu. This study aims to summarize the fruitful results and functional practices achieved in the huge gas province exploration, which will be regarded as guidance and reference for the further exploration and development in this basin. Based on the past five decades' successful exploration practices made by PetroChina Changqing Oilfield Company, we first comb the presentation of geological theories at different historical stages as well as the breakthrough in the course. Then, we analyze a complete set of adaptive techniques obtained from the long-time technological research and conclude historical experiences and effective measures in terms of broadening exploration ideas, such as the fluvial delta reservoir-forming theory, giant tight gas reservoir-forming theory, the idea of sediment source system in the southern basin, etc., and innovating technical and management mechanism, such as all-digit seismic prediction, fine logging evaluation for gas formations, stimulation of tight sand reservoirs, flat project and benchmarking management, and so on.

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1. Discovery of large gas fields

The Ordos Basin is the second largest sedimentary basin in China. Natural gas resources in this basin are up to $15.16 \times 10^{12}$ m$^3$, including $12.61 \times 10^{12}$ m$^3$ in Upper Paleozoic [1]. Currently, PetroChina Changqing Oilfield Company (hereinafter referred to as “Changqing Oilfield”) has discovered nine gas fields (i.e. Sulige, Jingbian, Wushenqi, Yulin, Shenmu, Mizhi, Zizhou, Shenglijing and Liujiazhuang) in this basin; except the Jingbian gas field, the other eight ones are Upper Paleozoic gas fields (Fig. 1). By the end of 2014, the proved gas reserves (including basically proved) in this basin was up to $5.7 \times 10^{12}$ m$^3$, and the annual gas production was $382 \times 10^8$ m$^3$. Discovery of these gas fields presents the successful process of practice — cognition — re-practice, and is the fruitful results achieved by people in the Changqing Oilfield through their continuous searching of new exploration methods, summarizing of exploration experiences and stressing of technical innovations. In practices, the oil and gas exploration activities have been increasingly challenged by higher exploration maturity and higher complexity of exploration targets. Through changing exploration conceptions and dedicating more to exploration studies to make theoretical, technical and management innovations, further new breakthroughs have been made in natural gas exploration in the Ordos Basin. Therefore, Changqing Oilfield has developed to be the largest natural gas production base and the hub of natural gas pipe network in China.
Petroleum industry history of China has demonstrated that the petroleum explorationists should continuously develop new techniques, with a liberated mind, and apply them in practice, rather than drown themselves in predecessors’ experiences and conclusions. During the over 50 years of natural gas exploration history of the Ordos Basin, generations of explorationists always insisted on thought liberation to break the boundaries of knowledge, which thus contributed to more and more breakthroughs in natural gas exploration in this basin. Natural gas exploration in this basin successively underwent several major strategic adjustments “from basin periphery to basin hinterland, from structural traps to lithologic—stratigraphic traps, from low permeability carbonate gas reservoirs in Lower Paleozoic to tight sandstone lithologic gas reservoirs in Upper Paleozoic” [2].

Natural gas exploration in the Ordos Basin started from the 1950s. Early exploration focused on structural gas reservoirs, mainly those in structural traps on the basin periphery; however, only some small gas reservoirs (e.g. Liujiazhuang and Shenglijing) were discovered, without substantial breakthrough. Until the end of 1970s, with the natural gas researches made during the periods of 6th and 7th Five-year Plans of China, researchers recognized that the Upper Paleozoic in the Ordos Basin was a large coal-rich cratonic basin covering a wide area [3]. In this regard, coal-formed gas theory was introduced, and the focus of natural gas exploration in the Ordos Basin changed from the basin periphery to the basin hinterland [4–7]. In 1987, industrial gas flows were obtained in Wells Zhenchuan 1 and Zhenchuan 4 in the eastern basin by gas testing, with the
Mizhi gas field discovered. Breakthroughs were made in Wells Shaan can 1 and Yu 3 drilled in 1989, with the Lower Paleozoic Jingbian giant gas field discovered, which strengthened our determination and confidence in seeking giant gas fields in this basin [8].

During the mid-late 1990s, while expanding exploration in Lower Paleozoic, researchers found that gas shows were generally seen in Upper Paleozoic in the Ordos Basin. Then, more efforts were made on sandstone gas reservoirs in Upper Paleozoic. Researchers recognized that the low permeability in Upper Paleozoic of this basin is a relative expression, as there is relatively higher permeability in low permeability; large sand bodies in fluvial delta facies with high permeability in Upper Paleozoic have fine matching relationship with source rocks in coal-series; large lithologic gas reservoirs may have been developed. Thus, we confirmed the exploration ideas of concurrently exploring Upper Paleozoic and Lower Paleozoic. Hence, the Upper Paleozoic Yulin gas field was discovered in the northeastern part of the Jingbian gas field, which expanded natural gas exploration regions in this basin. Inspired by the discovery of Yulin gas field, we proposed a basic guideline by re-understanding the Ordos Basin, re-understanding low permeability in Changqing Oilfield, and re-understanding ourselves [9]. Based on the success in the Yulin gas field, we reflected and reviewed our previous work. We systematically studied natural gas accumulation regularity in Upper Paleozoic in the whole basin, and pointed out that giant gas fields may have been developed in the western part of the Jingbian gas field. We further confirmed that large gas-bearing sand bodies in the Sulige-miao region are our major exploration target and, as a result, the Sulige gas field was discovered.

Since the 21st century, people in Changqing Oilfield have always worked hard on “three lows” (low permeability, low pressure and low abundance) in gas reservoirs in the Ordos Basin, by way of “three re-understandings” mentioned above. During the exploration practice, they gradually recognized that, in the Ordos Basin, sweet spot areas represented by the Yulin gas field are limitedly distributed, while tight sandstone gas fields represented by the Sulige gas field are widely distributed. By enhancing tight gas resources demonstration, they re-understood natural gas resources potentials in this basin, timely adjusted exploration directions, and insisted on “expanding to wider regions and drilling deeper formations in order to find new regions, new domains and new formations” [10]. In this way, a new picture of tight gas exploration in Upper Paleozoic in this basin was uncovered, and more and more new breakthroughs have been made in Sulige region, and eastern and southern areas of this basin.

2. Progress in geological studies

2.1. Fluvial delta reservoir-forming theory

In the 1980s, with the introduction of coal-formed gas theory and the discovery of Jingbian gas field, researchers recognized that lithologic gas reservoirs in the basin hinterland have huge exploration potentials. By investigating practical explorations, they believed that the central areas of this basin were favorable targets, since they were characterized by stable tectonic development, being close to hydrocarbon generation center, existence of several large fluvial delta sand complexes, fine regional sealing conditions and favorable gas accumulation conditions. In gas exploration in Lower Paleozoic, good gas shows were found in the second member of the Permian Shanxi Fm (Shan 2 Member) in Yulin region. Studies were made on depositional systems and favorable sand belts. Through studies of sedimentary microfacies, palaeontology and organic geochemistry, a new cognition was proposed, namely, the marine delta deposits and reformation in Shan 2 Member were the basis of forming effective reservoir bodies. During the deposition of Shan 2 Member, the northern area of this basin had sufficient deposit source; controlled by episodic marine regression, multi-phase prograded sand bodies were eroded and superimposed to form large-scale coarse quartz sandstone reservoir bodies in delta distributary channels in Yulin and Zizhou regions (Fig. 2). By comprehensive studies on natural gas generation and migration, distribution of sand reservoir beds and cap rocks, and trap features, the conventional hydrocarbon accumulation model (i.e. source rocks in front delta facies generate gas, sand bodies in front facies are reservoir beds, and the formations in plain facies are cap rocks) was revised. It was definitely pointed out that the fine matching relationship between coal beds and dark mudstones in delta plain and paludal facies and sand bodies in distributary channels in the Shanxi Fm in Yulin region is the uppermost factor for forming gas reservoir enrichment. Geological theory for hydrocarbon accumulation in delta facies was proved, which guided the discovery of giant lithological gas fields (e.g. Yulin, Zizhou and Sulige) in Upper Paleozoic with gas resources of over 1000 × 10^8 m^3 [11].

Fig. 2. Mode of marine ingression, marine regression and sand body progradation in the period of Shan 2 Member.

2.2. Giant tight gas reservoir-forming theory

During the evaluation on the early development of the Sulige gas field, it was found that this gas reservoir show
features of low abundance, low permeability, low pressure and stronger heterogeneity in reservoir beds [12,13], which is different from conventional gas reservoirs, so it is typical tight sandstone gas reservoir. Such gas reservoirs are widely distributed in Upper Paleozoic in the Ordos Basin, with extensive gas-bearing potential. The research results provided the following cognitions. Firstly, during late Paleozoic, the sedimentary paleogeography in the Ordos Basin was very gentle (paleo-sediment slope gradient is less than 1°), with shallower lake water, strong river carrying capacity, and long distance of carrying clastic matters, forming large gentle-slope delta sedimentary systems [14]. Secondly, upper Paleozoic coal layers and dark mudstones in this basin are widely distributed, showing a feature of broad hydrocarbon generation [15–17]. The widely distributed reservoir sand bodies are superimposed with effective and broad coal-series source rocks, which laid the foundation for massive gas-bearing in Upper Paleozoic. Thirdly, these gas reservoirs are characterized by “becoming tight first and then accumulated”. Natural gas mainly migrated and accumulated in short distance [18–20], so less gas was lost during reservoir-forming, ultimately accumulation efficiency was increased, and the threshold for forming giant gas field was decreased. The latest petroleum resources evaluation results also indicated that natural gas accumulation coefficient in Upper Paleozoic increased from 0.5% to 1.55%–4.41%, and the threshold of gas generation intensity for gas accumulation decreased from $20 \times 10^8$ m$^3$/km$^2$ to $(10–14) \times 10^8$ m$^3$/km$^2$, which further expanded natural gas exploration domain, and confirmed the features of multiple layer superposition and distribution in the whole basin of tight sandstone gas reservoir in Upper Paleozoic. Guided by the tight gas reservoir-forming theory, the gas-bearing scope in Sulige region was expanded from less than $1 \times 10^8$ km$^2$ to $4 \times 10^8$ km$^2$, and a giant gas region with gas resources of $4 \times 10^{12}$ m$^3$ was discovered.

2.3. New cognition on sediment source system in southern Ordos Basin

There was an old inherent cognition that “oil is mainly in the south and gas is mainly in the north” of the Ordos Basin. This is based on the idea that the south area of this basin is located in deep lake area, without good reservoir beds, which makes the south area less explored and investigated. As tight gas reservoir-forming theory is improved in recent years, natural gas exploration regions have been expanded from the central area to the whole basin. Researchers proposed a new cognition that the Paleozoic sediment source in the southern basin was mainly from the Qinling Group and Kuanping Group in the northern Qinling area — they have closer relationship. The clastic components are obviously different from those in the northern basin, suggesting a different sediment system. Thirdly, proximal delta plain and front deposits were deposited in Upper Paleozoic in the southern basin. Compared with the northern basin, the major sand bodies of He 8 Member and Shan 1 Member in the southern basin extended in a short distance, but on a certain scale, with a width of 10–20 km and a thickness of 10–20 m (Fig. 3). Through enhanced exploration and effective reservoir prediction by seismic data, favorable gas-bearing zones have been found in Longdong and Yichuan-Huanglong areas, making a natural gas exploration breakthrough in the southern basin.

2.4. Re-understanding gas resources to promote the discovery of giant gas fields

Gas resources are the key in gas field development. From coal-formed gas theory to delta reservoir-forming theory, then to tight gas reservoir-forming theory, every important breakthrough and leap of geological theory deepened the overall understanding of the natural gas distribution in the Ordos Basin. Thus, natural gas resources in this basin have been evaluated, and an optimal resource evaluation method has been selected to establish a resource evaluation methodology that is suitable for this basin, which can ensure the cognition on resource potentials more objectively. With the advancement of low permeability gas reservoir exploration and development technologies considered, we comprehensively evaluated the potentials of natural gas resources in this basin, and analyzed the reliability of natural gas resources. Four rounds of petroleum resources evaluation have been conducted on the Ordos Basin. Evaluation results of every round revealed an increase of oil and gas resources. Total natural gas resources in this basin increased by 332% from early $3.51 \times 10^{12}$ m$^3$ to current $15.16 \times 10^{12}$ m$^3$ (Fig. 4). Moreover, the distribution feature of natural gas resources in this basin was confirmed. Natural gas resources in Upper Paleozoic is $12.61 \times 10^{12}$ m$^3$, accounting for 83% of the total natural gas resources in this basin, and they are mainly tight gas with permeability <1.0 mD. The remaining natural gas resources in Upper Paleozoic of this basin is $11 \times 10^{12}$ m$^3$, mainly distributed in Upper Paleozoic of Sulige and eastern area of this basin, accounting for about 65.3% of the total remaining resources. Through deeper and deeper understanding of the overall distribution of natural gas resources in this basin, favorable natural gas exploration targets were confirmed, which allowed the explorationists to be more confident in seeking giant and middle-scale gas fields, and promoted giant gas field discoveries in Upper Paleozoic of this basin.

3. Researches on exploration techniques

During natural gas exploration in the Ordos Basin, Changqing Oilfield always gives the priority to technical
research. While positively learning from abroad advanced techniques, they insist on independent technical innovation. Through years of technical researches, they have gradually developed a complete set of techniques suitable for the geological features of this area.

3.1. All-digital seismic technique

The surface of the Ordos Basin is mainly covered by deserts and loess, with strong attenuation of seismic wave energy, weak reflection signal on target layers, and relative thinner gas formations. The crooked line and straight line seismic surveys in valleys could only be applicable for studying structures and describing sand bodies, but not suitable for predicting gas formations by prestack seismic inversion. By independent researches, a series of all-digital seismic techniques for desert areas and off-line seismic techniques for loess areas (Fig. 4) were developed. The all-digital seismic exploration techniques allow the technical transition from conventional 2D seismic to all-digital seismic, from unicomponent to multi-component seismic, and from poststack seismic to prestack seismic techniques, with high-quality and informative seismic data obtained (Fig. 5). These techniques meet the requirement of gas formation prediction directly by prestack seismic data, and changed reservoir prediction from sand body prediction to gas-bearing sand body prediction (Fig. 6). They also resolved the technical problem in predicting Upper Paleozoic tight sandstone reservoir beds and gas-bearing property (typically in the Sulige gas field). This improved the success ratio of predicting effective reservoir beds in vertical wells from 50% to over 80% [21]. By technical researches, the off-line seismic technique changed from “one shot, two lines” to fascicular survey of “two shots, six lines”, achieving big offset between receiving lines and exciting lines. Some key techniques (such as multi-domain and multiple static correction, well control Q compensation) were developed and applied, improving apparent dominant frequency of seismic data from 30 Hz to 35–40 Hz. These techniques can
help to effectively predict gas-bearing bodies in thin reservoir beds, by addressing the problems of quick attenuation of seismic wave energy and low signal-to-noise ratio in seismic data in very thick loess areas.

3.2. Fine logging evaluation technique for tight gas formations

Well logging responses are slightly different between Upper Paleozoic effective reservoir beds and non-reservoir beds, and between low-saturation gas layers and water layers, and it is hard to evaluate gas layers in the Ordos Basin. Accordingly, on the basis of conventional evaluations by zones and layers, a new idea was proposed that the interpretation units should be subdivided by lithology and diagenetic facies, and a fine logging evaluation method for tight gas formations was established. This method is based on petrophysical researches, taking evaluations on validity and gas-bearing potential of the reservoir beds as the core. As the tight sandstone reservoir beds in Upper Paleozoic of the Ordos Basin have high clay mineral content, forming conductive high irreducible water and low-resistivity in gas formations, for which the classical Archie model is not applicable. Hence, a “three water” conduction model was established that regards the rock conduction as the parallel conduction of free water, micro-pore water and irreducible water in clay (Fig. 7). This model provides a new way for resistivity logging interpretation in sandstone and mudstone. Its application results have better coincidence with core data, with absolute errors of water saturation less than 5%, improving evaluation accuracy of gas-bearing potential. Considering that the Upper Paleozoic low-resistivity gas layers have pore texture with features of high porosity, high micro-porosity and the coexisting of filtrational pores and micropores, a combination of logging series was proposed, including conjunction logging of high-precision numerical control, array induction and lateral resistivity, using additional nuclear magnetic logging and imaging logging in some wells. Besides, six techniques were summarized for identifying low-resistivity gas formations, gas formations and water formations. These techniques include divisional chart method, apparent elastic modulus coefficient method, cross-plot method between density-neutron apparent porosity, P-wave time difference method, gas test comprehensive analysis method, high-resolution integrative induction-lateral log interpretation method. Also on-line interpretation by well logging chart database was realized, with a coincidence rate in well logging interpretation of more than 85%.

3.3. Stimulation techniques for tight sandstone reservoir beds

The Upper Paleozoic sandstone gas reservoirs in the Ordos Basin contain many gas-bearing formations, with features of thin reservoir beds, strong heterogeneity, high debris content in some areas, complex gas–water relationship in local regions, and big technical difficulty for reservoir stimulation. Through continuous researches and experiments, a set of
reservoir stimulation techniques was developed that mainly include low-damage fracturing fluid technique, separated layer fracturing technique in vertical wells, and “water-controlling and gas-increasing” fracturing technique. A kind of new anionic surfactant fracturing fluid was developed that has low surface tension, no remaining slag and complete gel break. Such fracturing fluid can reduce capillary resistance, improve fracturing fluid recovery efficiency, and avoid the damage of cationic surfactant fracturing fluid to reservoir beds. It is mainly suitable for the reservoir beds with a high debris content and small throat radius. Compared with the conventional guar gel fracturing fluid, the core damage rate can be reduced from 27.4% to 18.3%, contributing to a single-well gas production increase of 6100 m³/d in the initial stage of production. Considering “several layers in one well, low production in a single layer” in the eastern basin, two sets of separated layer fracturing techniques (i.e. mechanical packing and casing sliding sleeve) were developed (Fig. 8), and experiments were conducted for separated layer fracturing with individual-layer testing, in order to ensure that reservoir beds are developed more effectively in vertical direction. The separated layer fracturing with individual-layer testing can realize the fracturing of two layers and individual-layer testing in one trip. The mechanical packing and separated layer fracturing technology can realize the continuous fracturing in 11 separated layers, achieving low-cost and quick separated layer fracturing in several layers in vertical wells. The continuous and separated layer fracturing in casing sliding sleeves can realize finite order and separated layer fracturing, with the max of seven layers and discharge rate of 8–10 m³/min. For reservoir beds with complex gas–water relationship, the “water-controlling and gas-increasing” idea is used for reservoir stimulation, forming several reservoir stimulation measures, such as seeking initial production by hydraulic sand blasting perforation, combined controlling fractures by high pressure, chemical curing fracturing, hydrophobic proppant fracturing, etc. On-site experiments indicated that the ratio of wells with high water contents decreased from 52.6% to 26.4%, and gas production increased by about 33%, with an apparent effect of controlling water and increasing gas.

4. Broadening exploration ideas

No oil and gas fields are completely the same in the world. The uniqueness and concealment of targets make their exploration discovery extremely practical, continuous and periodic. Generally, an oil/gas discovery requires several periods like the selection of favorable plays in basin in the early period, preliminary trap exploration in the middle period, and gas reservoir evaluation in the later period. The explorationists must follow correct procedures in exploration, and they are encouraged to work at a faster pace according to the original division of stages. Moreover, they should make every effort to seek exploration ideas suitable for the blanket lithologic gas reservoirs in the Ordos Basin.

4.1. Forming exploration ideas for large lithologic gas reservoirs

Over the past 50 years of oil and gas exploration and development in the Ordos Basin, relevant studies and analysis were carried out for geologic targets and tasks in various periods. Exploration ideas also continuously changed. In the early period, the major task was to obtain discoveries in especially sand belts. In the middle period, the major task was to identify hydrocarbon scale, confirm types, and control facies belts, so as to understand hydrocarbon accumulation regularity. In the later period, the major task was to find hydrocarbon reserves and confirm hydrocarbon-rich areas, and to summarize exploration techniques and experiences to guide the next exploration.

Let’s take the Sulige gas field as an example. In the early exploration period (1998–1999), natural gas enrichment regularity in Upper Paleozoic of this basin was further verified, and at the same time large-scale high-resolution seismic survey in the Sulige region was enhanced. Accordingly, the large-scale fluvial delta sandstone complexes in this region were defined as the favorable targets in Upper Paleozoic. According to the principle that Upper and Lower Paleozoic should be concurrently explored, Well Su 2 was deployed, with an industrial gas flow obtained by gas testing. Together with the drilling results of Wells Tao 2, Tao 3 and Tao 5, He 8 Member and Shan 1 Member in Upper Paleozoic were confirmed to be the favorable gas-bearing zone.

In the middle exploration period (2000), combining fine seismic processing and interpretation, the Tao 5 well field was
selected for implementing the deployment strategy of “regional deployment and breakthrough in a specific site”.

Around Wells Tao 5, Su 5 and Su 6 were deployed. Well Su 6 revealed a high-yield industrial gas flow \((120 \times 10^4 \text{ m}^3/\text{d})\) in well testing, recording important breakthrough in exploration. By systematically summarizing the drilling results of Well Su 6, and combining comprehensive geological study results, we believed that the Sulige gas field is a lithologic gas reservoir with low pressure and low permeability in stratigraphic trap. The distribution of reservoir beds is controlled by sand bodies and physical properties, suggesting it is an expansion type gas reservoir with constant volume. In order to further confirm gas-bearing scope, 16 prospecting wells were deployed to the south and north of Well Su 6, of which 13 wells successively realized industrial gas flows. Then, the outline of a giant gas field was basically confirmed, the distribution form of major gas-bearing sand bodies was generally clear, and gas field scale was primarily controlled.

In the late exploration period (2001–2003), further exploration and evaluation were focused on the Sulige gas field. Along the major sand belt in Su 6 well field, 23 prospecting wells were deployed, of which 16 wells obtained industrial gas flows, with total proven gas in place booked in two estimates of \(5337 \times 10^8 \text{ m}^3\). Moreover, in the west of this gas field, favorable gas layers were encountered in some well fields (e.g. Su 2 and Su 9 etc.), new favorable gas-bearing areas were found, and newly booked probable and possible reserves were \(3156 \times 10^8 \text{ m}^3\), providing the orientation for subsequent exploration. In the exploration process of Sulige gas field, an exploration and deployment idea for large lithologic gas reservoirs was proposed, namely, outstep exploration was made to identify facies belts, major sand bodies were depicted as a whole, and evaluation was made specifically on high permeability regions. This idea provided practical methods and technical guarantee for exploring natural gas in Upper Paleozoic of the Ordos Basin.

### 4.2. Integrated exploration and development for quick increase of natural gas reserves and production

Since the 21st century, Changqing Oilfield has continuously quickened its development. The traditional exploration and development idea, i.e. resources confirmation — evaluation — development, is no longer adaptive to the quickly increased natural gas reserves and production. Driven by quick development and low-cost strategy, considering the blanket lithologic reservoirs in the Ordos Basin, researchers proposed a system of integrated exploration and development. Its core is to make a breakthrough in some key points in exploration, then to conduct evaluation and development as soon as possible, and then to quickly expand oil and gas discovery areas. Meanwhile, unlike the previous idea of seeking single exploration target in major oil and gas layers, this new idea suggests the method of exploring upper and lower formations, seeking both oil and gas in oil and gas overlapping regions, so as to obtain an exploration effect with higher efficiency. The implementation of integrating strategy led to concurrent deployment and running of exploration, evaluation and development, which greatly reduced time for exploring an integrated oil and gas field, and shorten the period from exploration to development.

Changqing Oilfield insists on overall exploration, evaluation and development. Proper measures were taken to timely obtain hydrocarbon discoveries by exploration, then to conduct evaluation positively, and to form a well development pattern at one time. Besides, exploration, evaluation and development were integrated to seek hydrocarbon-rich areas, duplicate construction was reduced, and large-scale production and integrated development were promoted. In this way, exploration and development were accelerated effectively. All these measures helped greatly shorten the exploration and development period of the giant gas fields in the Ordos Basin — for example, 7 years for the Jingbian gas field, 5 years for the Zizhou and Yulin gas fields, and only 2 years for the eastern Sulige gas field.

Integrated exploration and development made oil and gas reserves of Changqing Oilfield increase from a stable level to a quick level. In the past few years, Changqing Oilfield focused on confirming the scale of proven reserves and probable reserves, and seeking gas-rich regions, by fully carrying out the integrated exploration and development strategy. Moreover, the Oilfield continuously carried out the “Peak Growth in Oil and Gas Reserves” Program. Several large-scale reserves regions and strategic replacement regions were quickly confirmed. The overall exploration scale in Sulige area was continuously expanded, forming a giant gas zone of \(4 \times 10^{12} \text{ m}^3\). Exploration in multiple layers in the eastern basin is steadily advanced, contributing to the discovery of Zizhou and Shenmu gas fields, which are endowed with \(1 \times 10^{12} \text{ m}^3\) reserves. Additionally, new discoveries were made in natural gas exploration in Longdong region in the southern basin.

The integrated exploration and development strategy helps to improve the overall exploration and development benefits, since it allows overall planning and deployment, mutual-reference in comprehensive studies, and mutual support and coordination in production, by way of overall deployment, large-scale proving and quick development. Taking the Sulige gas field as an example, many early development evaluations were conducted initially, and 12 development supporting techniques (e.g. well location optimization, borehole throttle, surface optimization, etc.) were integrated and innovated. The comprehensive cost in well construction in development period was significantly reduced. Thus, large-scale and effective development was realized in this gas field, and then secondary overall exploration in the Sulige gas field was promoted, laying reserves foundation for quick production increase in this gas field. Since 2007, exploration breakthroughs have been continuously achieved in the perimeters of the Sulige gas field, triggering the reserves and production in this gas field to increase quickly. Significant breakthroughs have been made in natural gas exploration in east, north and west of this gas field, with new reserves exceeding \(5000 \times 10^8 \text{ m}^3\) in eight consecutive years. Natural gas
production also presented leap-forward growth, with annual gas production increased by $30 \times 10^8$ m$^3$. In 2014, this gas field produced nearly $240 \times 10^8$ m$^3$ natural gas, accounting for over 60% of the total gas production in Changqing Oilfield.

5. Management innovation

Exploration project management is just like a battle. If the battle management fails, strategic targets could not be achieved. Exploration in Changqing Oilfield is designed to realize considerable reserves and production, and is also facing many problems, such as more complex targets, more serious external environments, and less investment. In this circumstance, only by scientific management and innovated management, together with a management system with clear responsibility, right and benefit, can exploration efficiency and benefit be guaranteed.

5.1. Flat project management

Over years of production management practices, Changqing Oilfield formed and gradually improved its flat project management mode. This mode adopts a three-level management organization (i.e. decision, management, execution). Managers and supervisors are the decision-makers in the management organization for exploration projects. Exploration Department and other functional departments jointly form the management of exploration projects. The exploration project management departments are the executive functions in actual implementation. The flat project management mode in Changqing Oilfield, with clear responsibility, right and benefit, has effectively inspired the creativeness of project managers. Managers and supervisors of Changqing Oilfield directly take charge of the decision-making, which can reduce many tedious links (such as intermediate level level reporting, holding meetings in individual departments), achieving quick and efficient production management, and improving work efficiency. Particularly, under the complex surface and underground geological conditions in the Ordos Basin, despite severe interference from the external environment, the flat project management can effectively reduce the events of waiting, stagnation and relying in operation teams, overcome several unfavorable factors (scattered exploration areas, numerous operation teams, poor information feedback), and meet the requirements of large exploration workloads, difficult reserves tasks and quick production rhythm.

5.2. Benchmarking management

Benchmarking management is a good way to seek and learn best management cases and operation modes. Changqing Oilfield carried out positively and effectively benchmarking management in exploration. Benchmarking between the Exploration Department and the Development Department promotes coordination, which is beneficial for smooth implementation of integrated exploration and development. Benchmarking between Changqing Oilfield and other oilfields is useful for finding disparity and making up for deficiencies. Benchmarking between Changqing Oilfield and other industry/enterprise standards helps to meet standards, develop standards and even exceed standards. Benchmarking between Changqing Oilfield and international leading edges reveals its struggle direction. In the past few years, Changqing Oilfield was always a leading entity of PetroChina Company Limited by various benefit indexes like actual ratio of finished exploration workloads, exploration engineering cost, success rate of prospecting wells, success rate of well testing, oil and gas discovery cost, upgrade rate of probable and possible. In recent years, its actual ratio of finished exploration workloads has reached 100%, higher than the average level of PetroChina. Its drilling engineering cost remains at low level. Its oil and gas discovery cost is less than US $1/barrel, far below the average level of PetroChina. The exploitable and producing rate of proved reserves maintains above 90%, and the upgrade rate of probable reserves is up to 100%. Therefore, a virtuous cycle and sustainable development in exploration has been achieved [22].

6. Conclusions

According to the natural gas development plan of Changqing Oilfield, by the end of 2015, its natural gas production will have reached $400 \times 10^8$ m$^3$. In addition, a long-term stable production will be achieved — tight gas production in Upper Paleozoic will have reached $270 \times 10^8$ m$^3$, accounting for more than 65% of the total natural gas production of Changqing Oilfield. Therefore, we will make more efforts in exploring natural gas in Upper Paleozoic in this basin, especially tight gas in the Sulige gas field. By 2020, the new tight gas reserves in the southern Sulige region, east of the Ordos Basin and Longdong region are expected to be over $1 \times 10^{12}$ m$^3$, and the total proved and basically proved natural gas reserves in Upper Paleozoic of this basin will be about $6 \times 10^{12}$ m$^3$, which can ensure the resources necessary for increasing and stabilizing natural gas production.

Fund project

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