Citation: MA Yongsheng. There is no shortcut to find oil: some thoughts on oil and gas exploration[J], Petroleum Geology & Experiment, 2020 (5): 662-669.

There is no shortcut to find oil: some thoughts on oil and gas exploration

MA Yongsheng

SINOPEC Group, Beijing 100728, China

Abstract: Explorers are the organizers, managers, and practitioners of oil and gas exploration activities. They are also professionals who master petroleum geology and related disciplines, are familiar with exploration techniques, apply exploration methods flexibly, and are proficient in exploration management. So, they are both business and management experts. Successful explorers must first have firm confidence in finding oil and gas, have a scientific spirit that does not blindly follow or agree, and always maintain the sensitivity of thinking. There are no shortcuts to exploration. First, we should solve the basic problems of exploration; second, we should adhere to scientific exploration procedures; third, we should have the awareness of development, efficiency, and dynamic optimization. We should highlight key points, and continue to optimize exploration deployment so as to ensure the completion of the exploration mission. To achieve high-quality exploration, the way of thinking should be changed from the traditional thinking of "heroes based on output" to that of "heroes based on benefits." The top-level design should be done to achieve the integration of investment, benefits, and responsibilities, and further improve and establish the exploration deployment comparison and selection mechanisms and new two-level decision-making management so as to achieve the "five major changes." With the rapid development of geophysical exploration technology and drilling and completion technology, current global oil and gas exploration is undergoing profound changes, and it is constantly developing into more detailed, deeper, broader, more difficult, and more challenging fields. The fault basins in East China, marine carbonate rocks, clastic rocks in Central and West China, and shale gas will be the main areas for increasing oil and gas reserves and production. With advances in theory and technology, coalbed methane, shale oil, and oil shale are also important areas that need to be tackled and cultivated. In the future, with the rapid development of unconventional oil and gas theories, the basic system of oil and gas geology will continue to expand and improve. With the support of a new generation of intelligent technology systems for exploration and development, a conventional-unconventional overall evaluation and multi-layer exploration system of petroliferous basins will be formed, which will bring a new round of growth in oil and gas reserves and production.

Keywords: oil and gas discovery; exploration technology; explorers; China

I am willing to share my reflections here since peer experts and friends from other fields often discuss with me how to find large-scale oil and gas fields better, faster, and more efficiently. As an explorer and geological science & technology worker long engaged in oil exploration, I have experienced and witnessed the amazing discovery of large-scale oil and gas fields and the drastic development of efficient exploration technology over the past thirty years. The discovery of these large-scale oil and gas fields is accompanied by an innovative understanding of geological research. The development of new technologies is always guided by exploration objectives and geological science, and such technologies include geological evaluation technology, laboratory technology, drilling, completion, and testing technology, geophysics, logging and reservoir evaluation technology, and enhancement technology of production capacity. My colleagues and I had the honor to share the brilliant achievements and joy of oil and gas exploration and technology development regardless of the pain of failure. Our work and achievements have gone far beyond what I could have foreseen when I started to engage in geological research and exploration. However, my knowledge and experience convinced me that there is no shortcut to discover oil and gas.

1 On explorers

As explorers, we should first have firm confidence in discovering oil and gas. For geologists, however, it is more important to have the basic distribution layout of oil and gas in mind. "In the final analysis, the first place to discover oil is in people's minds. The undiscovered oil exists only as an idea in the minds of some oil explorers. If no one believes that there is more oil to be found, no more oil will be discovered" [1]. In this paper, I would like to discuss with you the qualities that explorers should possess.

Received: 2020-06-06
Supported by: National Natural Science Foundation of China for Enterprise Innovation and Development (L19B6003)
First author: MA Yongsheng (1961–), male, PhD, academician of the Chinese Academy of Engineering, engaged in the research on geological research of petroleum and natural gas and production practice of exploration. E-mail: mays@sinopec.com

It is often said that oil and gas exploration is characterized by high investment, high risk, and high return from investment, which puts high expectations on explorers. Explorers are the organizers, managers, and practitioners of oil and gas exploration. Most of them start from geologists, but they are by no means equal to geologists. In the past, geologists looking for oil were called explorers for a long time, because oil and gas exploration was mainly completed by geologists. With the development of exploration, the technologies and methods needed for exploration are becoming more and more complex, and the majors and disciplines involved in exploration have far exceeded the knowledge mastered by geologists. Most geologists only engage in geological exploration in a specific field, so geologists can not be called explorers in general terms. According to the requirements of modern exploration, explorers are professionals who master the theories of petroleum geology and related disciplines. Being familiar with exploration technologies, they can apply exploration methods flexibly and are proficient in exploration management. They are both technical and management experts.

The first trait of any successful explorers is that they are truly confident in discovering oil, dare to practice, and are good at practice. The real value of exploration lies in discovery, which is a process of constantly exploring the unknown and pursuing the truth. One example often in my mind is the exploration of Paleozoic marine strata in China. It is hard to achieve today's scene. In 1922, a group of western geologists represented by Blackwell of Stanford University in the United States put forward the theory of "China is short of oil," and they argued that "China's lack of oil can be attributed to three geological conditions: there is no marine deposit in Mesozoic and Cenozoic; most strata in Paleozoic cannot generate oil; except for some regions in West and Northwest China, almost all the rocks in geological times suffer from strong folds and fractures and are invaded by igneous rocks in different degrees." However, a large number of people with lofty ideals dedicated to looking for oil always believe in the possibility of discovering large-scale oil and gas fields in the marine strata in China. They had always sought oil from Qiannan, Sichuan, North China to Tarim through the efforts of several generations. After decades of exploration and prospecting, brilliant achievements have been made in the exploration and exploitation of Paleozoic marine strata in China. Industrial oil and gas flows have been discovered in Tarim, Ordos, and Sichuan basins, and oil and gas production bases have been established. Tarim Basin, the largest Paleozoic marine petroliferous basin, and Sichuan Basin, the largest Paleozoic marine gas-bearing basin, have been identified. These discoveries have realized the dreams of several generations of oil workers, created the glory of China's oil history, and forged the spirit and soul of oil and gas explorers or prospectors.

The second trait of explorers is the agility of thinking. Details determine success or failure. Sensitivity helps grasp and analyze every detail of the exploration process, while indifference and irresponsibility are the enemies of exploration activities, which will lead to the loss of the opportunity of discovery. The discovery of a large-scale oil field by an oil sand is not only a story but true. There are a lot of uncertain factors in the process of oil and gas discovery. The exploration facts have repeatedly told us that some "failures" need to be reflected again. Explorers or prospectors should not deny or give up casually in the process of oil and gas discovery. There are ups and downs in exploration. When taking the initiative in exploration, we should seize the favorable opportunity, actively study the prospective areas, and maintain the stable and sustainable development of exploration. We must have strong faith and an indomitable spirit of struggle, and work more carefully than before when encountering setbacks in exploration.

We should open our minds with innovative thoughts and show our confidence in exploration and development. The present situation and trend of global oil and gas development show that oil and gas exploration has entered a new stage that is dominated mainly by subtle reservoirs. The focus of current exploration lies in both conventional and unconventional exploration no matter in the oil or gas field from a deep or shallow stratum. The complex reservoirs and accumulation, concealed targets and low quality of resources become the common issues for exploration activities. Therefore, we, explorers, should further open our minds to break through the conventional mindsets and existing evaluation conclusions and walk into the forbidden areas of exploration. Guided by innovative theories with an open mindset, we should objectively understand the law of exploration and discovery, change the exploration strategy to find the right exploration direction, and strive to seek new exploration solutions. We should not rush to drill a well when we are not well prepared, because haste makes waste. We should strengthen our confidence, and never give up when facing obstacles. We should learn from failure lessons, prepare well from doing all basic work, do more investigation and keep exploring when there are bottlenecks in our exploration. We are bound to expect new breakthroughs and discoveries.

We should keep calm while exploration is going smoothly, but be confident while there are challenges. It is important to be sensitive in thinking and be meticulous in work. The exploration activities need the integration of firmness in theory and sensitivity in exploration practice. The theoretical firmness is the source of confidence to overcome exploration difficulties and setbacks. Some of us often set up our forbidden areas in the fields where we know little. But numerous achievements are made in those areas, such as the breakthroughs in the TOC lower limit of oil-generating conditions, death line of hydrocarbon generation, accumulation threshold, hydrocarbon generation of carbonate rocks, the lower limit of effective reservoirs, and the buried depth of oil and gas. People always overestimate the knowledge they have mastered (inertial thinking), and some "common sense" still

misleads our understanding and practice to this day. Self-setting forbidden zones in areas where little is known will greatly delay the discovery of oil and gas. Success or failure depends on details. Sensitivity is helpful to grasp and analyze every detail of the exploration process, and method and technology are strategic solutions. The strategic goal cannot be achieved without "bridges" and "roads." Applicability and pertinence of methods and technologies are more important than advancement. An exploration activity is a systematic project, which follows the formula of "multiplication." Any failure in this project will lead to an ultimate loss. High-quality design and construction are needed to ensure the realization of exploration objectives.

The third trait of explorers is the scientific spirit that we do not blindly follow or agree. When many geologists were forced in the political situation to agree that the oil output could be quadrupled in 1982, Academician WENG Wenbo, a famous Chinese scientist, insisted on his prediction under great pressure; i.e., the oil output in 2000 would be 180 million tons instead of 400 million tons, which has been proved completely correct by facts. The true scientific attitude is just as what Mr. ZHU Kezhen said that "Do not blindly follow or agree." Meanwhile, we should have the scientific spirit of exploring truth from facts, rational analysis, openness and cooperation, modesty and tolerance, questioning and innovation. The discovery process of exploration is so exciting just because it is a process of pursuing truth! In a new region or new basin, new discoveries will be made with the old methods; in an old exploration area, there will be no new discoveries without new ideas—this is the dialectical thinking of explorers. This has happened many times in the history of oil exploration. The knowledge about how oil was discovered in the past often blinded our geologists so that oil was not discovered even if it was in front of their eyes.

Exploration is an innovative work of practice, understanding, re-practice, and re-understanding, and mainly depends on perseverance and active exploration and pursuit. As we all know, it is impossible to know anything in one cycle, especially in exploration. Only through a repeated cycle of practice and understanding can our thinking be innovated and our understanding of the underground situation be improved continuously. Hence, it is necessary to follow the principle, work with firm belief on the premise that the basic reservoir-forming conditions are met, and oil and gas exploration can keep advancing and usher in great breakthroughs and discoveries through unremitting exploration. The discovery of a number of super-large gas fields after half a century of exploration in the Sichuan Basin is a good example.

2 On exploration procedure

Oil and gas exploration follows its own development law, so it is particularly important to adhere to scientific exploration procedures, even in a period of rapid development. Through the long-term practice of oil and gas exploration workers in China, the basic principles of "the process cannot be overstepped, the procedures cannot be disrupted, while the progress can be accelerated, and the benefits must be improved" are summarized for scientific exploration procedures. The exploration of a basin, sag, or a block begins with early regional exploration and basin evaluation, with emphasis on selecting sags and setting zones, and clarifying exploration potential and key directions. Then it enters the stage of zone evaluation and trap pre-exploration, with emphasis on clarifying the key zones of oil and gas accumulation and selecting the key breakthrough traps for drilling. After exploration and discovery, it quickly enters the evaluation stage of oil and gas reservoirs to carry out evaluation and exploration, determine oil-bearing area and types & boundaries of oil and gas reservoirs, etc., and then submit proven reserves. The end of the evaluation and exploration stage of oil and gas reservoirs does not mean the end of oil and gas field exploration. The exploration and exploitation from one block to another must be recognized repeatedly and explored many times due to the complexity of oil and gas fields. It is even possible to re-explore shallower or deeper oil and gas reservoirs in the previous block after the current block is put into full exploitation under the inspiration of exploration and exploitation of the later block. The practice has proved that, for complex oil and gas fields, exploration almost runs through the whole process of exploration and exploitation. It must not be simply considered that the exploration work has been completely finished after the evaluation and exploration of oil and gas reservoirs are completed and they are put into exploitation.

It is always a basic requirement to obtain complete and accurate data in exploration. In the process of finding oil, it is necessary to perform a lot of solid fundamental work, strengthen the basic geological study and further the understanding of oil and gas accumulation and enrichment law, so as to provide powerful guidance for exploration practice. Aiming at great basins and oil and gas-rich depressions, we should carry out the evaluation, and strengthen the basin-scale overall research for Tarim, Junggar, Ordos, and Sichuan basins and further the understanding of the basic law of oil and gas distribution. We should reevaluate and recognize the exploration potential based on the whole basin, focus on the key elements such as structure, reservoir, source rock, and reservoir formation, intensify the evaluation of blocks and zones, and optimize the favorable targets. We should deepen the evaluation of resource potential and the study and re-understanding of oil and gas enrichment law in highly mature exploration regions. Guided by new theories, new technologies, and new ideas, we should make sure of "three re-recognitions" in the exploration of old regions by making full use of the existing exploration and exploitation data; i.e., we should re-recognize the exploration process, the resource potential, and the exploration target strata. The aim is to determine the exploration focus, exploration ideas and strive

to achieve new breakthroughs. "Multiple meticulousness" should be achieved in the study of old regions, such as meticulous study on sedimentary facies, prediction of reservoirs, and description of traps.

I always emphasize that the exploration of well location is the result of changing exploration ideas, being solid and rigorous. Reviewing and summarizing the exploration history of many basins, I deeply realize that the change of exploration ideas and the development of exploration technology are the key to discovering oil and gas fields. Sichuan Basin experienced three leaps in exploration thinking, which also brought three great discoveries in exploration. The first leap has identified reserve resources in this basin. Through three times of exploring Longmenshan Mountain, four times of Haitangpu, and three times campaigns in Central Sichuan, the reality of less oil and more gas in the basin is identified and the two main exploration targets of carbonate rock and natural gas are identified. The second leap reveals the understanding of the properties of carbonate rock reservoirs[2–3]. The contribution of fractures in the reservoirs is gradually recognized, and a series of fracture evaluation techniques have been developed accordingly, which has promoted the development of oil exploration. The third leap has demonstrated the understanding of structural-lithologic compound traps, mainly in the understanding of important porous reservoirs such as Huanglong Formation of Carboniferous System, Feixianguan Formation of Triassic System, and Changxing Formation of Permian System, which has brought about great development for the oil and gas exploration.

Key points should be highlighted and exploration deployment should be continuously optimized to ensure the completion of exploration tasks when adhering to the exploration procedures. Optimization should be performed throughout the whole implementation process of exploration. We should reflect "Three Consciousnesses" in the optimization. First of all, we should have a vision of development. We should make strategic plans for sustainable development of oil and gas fields, analyze and consider the comprehensive requirements of short-term and medium/long-term development. We should execute overall plans for earthquake and drilling workload by the coordination of the three levels of deployment, breakthrough, and preparation in an orderly manner. As of the risk exploration stage, we should emphasize the strategic significance, guiding purpose, and resource scale of the exploration objectives. During the trap pre-exploration stage, the significance of new oil and gas discovery and reservoir increase should be focused on. And exploration evaluation should take into account the commercial discovery, increase in scale reservoirs, availability of reserves and combination of exploration and exploitation. The second consciousness is our awareness of benefits. We should effectively unify investment, workload, reserves with the control of discovery cost of reserves and exploration profit and loss rate. After the discovery of oil and gas reservoirs through pre-exploration, it is necessary to strengthen the combination of exploration and exploitation. We should decide very carefully if exploration wells should be drilled on those without a further development plan. And we should not temporarily deploy pre-exploration wells for traps of the same type in adjacent areas. During the implementation of evaluating the exploration project, the deployment plan and project should be revised in a timely manner in case of any serious change of reservoirs when the scale and quality of reserves become significantly worse and are obviously inconsistent with the initial deployment plan for effective exploitation. The third consciousness involves dynamic optimization. There are extremely complex geological objects encountered in oil and gas exploration and many uncertain factors. The deployment plan is developed based on our cognition, experience, and existing technical solutions. New situations and new problems may arise in implementation even if the pre-evaluation study goes deeper. In recent years, great discoveries have been made in Northeast Sichuan and West Sichuan. One of the important reasons is that "three re-recognitions" have laid the philosophical foundation for the continuous development and breakthrough of exploration. The re-recognition of the Sichuan Basin has solved the problems of exploration prospects and main directions, which brings the confidence and determination of great breakthroughs, great discoveries, and great development. Re-recognition of sedimentary facies breaks the bottleneck of geological problems. And the re-recognition of ourselves encourages us to be more positive and proactive. To this end, it is particularly important to strengthen the tracking of deployment implementation. We should keep track of the evaluation progress and be good at the control of the development direction of the exploration. Subtle changes in the implementation can not be ignored. Then we should summarize and analyze all findings to revise the plans timely. The unprecedented challenge from the low oil price requires us to accelerate oil and gas exploration and organizational changes. We should urge ourselves to bear the responsibilities to accelerate exploration breakthroughs. We should be innovative and be careful in our studies. And we must go deeper and perform the target evaluation more precisely. Our implementation strategy must be optimized so that we can finally make great breakthroughs to improve the quality and efficiency of exploration to a new level.

3 On high-quality exploration

Facing the increasingly high exploration cost, especially with the impact of the low oil price, we should always concentrate on economic benefits to perform efficient exploration and exploitation and pay more attention to the acquisition of resources, technology drive, and high-efficiency and high-quality development in order to achieve the sustainable development. We should highlight the substitution rate & conversion rate of reserves and the

discovery cost of barrel oils in the process of exploration and exploitation. We should not only explore more oil and gas reserves but also optimize our process. About how to proceed in efficient exploration, my experience is stated as follows:

First of all, the concept of economic benefits should be kept in the minds of all explorers and engineers. Regardless of their study types, including subsurface, ground engineering study or exploration and deployment, all of them should be aware of the concept of economic benefits. Secondly, from the perspective of exploration, especially the new fields and new regions, the road of high-efficiency development should be followed. New regions should not be explored too early in a concentrated manner. Basic research must be done well and they must be researched ahead of time. Research is the foundation and geophysical prospecting should be carried out in advance. As the exploring regions in West China are basically deep and complicated, without the foundation for geophysical prospecting, and it is hard to explore or prospect oil with drill bits. Thirdly, the management level should be improved. We should accurately calculate and manage the cost of segmentation operations. To reduce cost is not to reduce the fixed expense quota, but to improve the efficiency, which is the best way to reduce costs. For exploration or prospecting, we should push forward the breakthrough in the new regions, reduce the discovery cost, and improve the assessment mechanism and the exploration efficiency. We should base ourselves on great basins, strive for great breakthroughs, and look for large-scale reserves. We should improve the assessment method of reserves and take the reserve replacement ratio listed in the SEC as the main indicators of exploration. For exploitation, we should strive to improve the utilization of reserves, promote the integration of exploration and exploitation, intensify the scale construction and production, so as to match the production capacity and workload with the investment growth, and improve the economies of scale.

The top-level design is very important to achieve high-quality exploration. We should always adhere to efficiency as a guiding principle. In terms of deployment, we should deepen the comprehensive geological research, grasp the law, optimize deployment strategy to improve the success rate. As for the organization and implementation, we should popularize the advanced and practical technologies and pay special attention to every step to drill every well with success. We should strengthen the combination of exploration and development and pay attention to each milestone to obtain the overall benefits. And we should study the reasonable structure of geophysical exploration, pre-exploration, and evaluation of exploration workload and investment, and identify the reasonable structure of oil and gas exploration workload and investment. In addition, we should also investigate the reasonable structure of exploration in new and old areas to ensure the healthy, orderly, and sustainable development of exploration undertakings. We should strengthen the economic evaluation of the whole exploration process, be innovative, optimize pre-exploration targets, and reserve quality and structure. The ultimate goal is to clarify the responsibility and achieve the integration of investment, benefits, and responsibilities. By establishing an exploration center and a project management department, we can manage the workload, investment, reserves, cost, and benefits comprehensively. The exploration center is the main body of taking exploration responsibility and managing the exploration activities. The project management department is an organization led by the exploration center in charge of on-site implementation. The project management department is set up for an individual project and will be dismissed upon the completion of the project. We should make adjustments flexibly and actively based on the real conditions of each case of enterprises.

We should further establish and improve the comparison and selection mechanism for exploration deployment and the new management mechanism for two-level decision-making. We should also improve our evaluation and optimization mechanism. At the level of joint-stock companies, we should improve the unified optimization platform for traps and pre-exploration wells, and for both seismic deployment and exploration evaluation projects. For individual enterprises, we should improve the unified optimization platform for exploration and evaluation wells and newly build a unified optimization platform for exploration evaluation projects. Learning from the evaluation ideas of pre-exploration traps, based on the evaluation parameters such as predicted reserve reliability, reserve grade, reserve upgradability, and reserve value, we should prioritize those early evaluated projects of oil and gas reservoirs. An optimization platform for seismic deployment should be established. The seismic deployment should also highlight the economic benefits. The resource scale, technical feasibility, the number of traps found and implemented in seismic deployment blocks should be regarded as the basic elements for evaluating and optimizing the seismic blocks. The pre-exploration well and geophysical exploration deployment plan should be demonstrated and optimized by the head office. The deployment plan of evaluation wells should be verified by the enterprises and subject to optimal decision-making. The unified demonstration and optimization should be organized in an appropriate and effective sequence. We should make decisions based on the integral study of well location, workload, investment, estimation of reserves, and costs in order to reduce the exploration risk from the very beginning.

Facing the new normal of the oil field sector and the crucial contradictions exposed in low oil prices, we should improve our capability of development, accelerate to change our mindset in development concepts, and resolutely achieve the "Five Major Transformations." Said transformations refer to the transformation from oil and gas discovery to commercial oil and gas discovery, from reserve quantity to reserve quality, from oil field production capacity to profit-making oil production, from technological index innovation to

technology efficiency creation, and from the thinking mode of conventional "output-based success" to "benefit-based success." In practice, the principles of "three no-drilling" should be strictly followed for oil and gas exploration, namely no drilling of risky wells without strategic leading significance, no pre-exploration wells without traps, and no evaluation wells without new commercial development reserves.

4 On four major fields in recent exploration

To achieve the goal of "maintaining the stability of crude oil production and enhancing the production of natural gas" in China, we should mainly concentrate on the study and technical solution of oil and gas exploration problems in the following four major fields.

4.1 Fault basins in East China

The analysis and evaluation of IHS Markit [4] showed that Songliao Basin and Bohai Bay Basin in China are the super oil and gas basins in the world. Many effective source rocks, many superimposed reservoirs, and various types of oil and gas reservoirs are developed in such kinds of basins, and the potential of remaining resources is considerable. Meanwhile, the surface systems of fault basins in East China are well matched, which have the advantage of the rapid transformation of resources after exploration and discovery. They are the top priority to achieve the goal of "maintaining the stability of crude oil production" at low oil prices. At present, the exploration of fault basins in East China has changed from structural traps to subtle oil and gas reservoirs and the discovered scale of reservoirs is getting smaller. In Songliao Basin and Bohai Bay Basin, no integrated oilfields with a proven reserve of more than 50 million tons have been discovered for consecutive seven years since 2013. Seeking "Fine Exploration" has become a consensus. The following four aspects should be emphatically studied: a. the fine study and detailed division of sedimentary microfacies in small series; b. the fine study of tectonics to establish high-precision velocity field and fine structure interpretation mapping of sub-divided series through well-seismic joint fine series; c. the prediction of fine reservoirs and depiction of sand bodies in strata, and d. the fine analysis of the reservoir-forming process, especially the fine analysis of the main reservoir-forming elements that lead to the drilling failure at the early stage.

The study on the differential enrichment mechanism in the process of oil and gas accumulation in the fault basins should be extended while the study on the distribution of remaining oil and gas resources in the fault basins in East China is strengthened. First of all, we should change the thinking for exploration; we can vigorously undertake "three new" exploration (new zones, new stratum series, and new types) by making full use of the massive data collected from old oilfields and re-recognition of the basins with new technologies and methods such as big data. Meanwhile, we should study more of oil and gas resources in the pre-Tertiary System, like Carboniferous-Permian System, and explore the natural gas resources in the middle and deep reservoirs. In terms of engineering technology, the resolution of seismic data and imaging accuracy should be further improved for the seismic exploration technology, which should be economical and applicable so as to meet the needs of fine exploration. In terms of well drilling and completion, for complex fault blocks, thin inter-bedded sand bodies, and other reservoir types, we should find the solutions including the optimized and fast drilling technology with fine trajectory control for extended reach and horizontal wells, the reconstruction technology for low permeability reservoirs and the comprehensive supporting technology for the conservation of oil reservoirs.

Shale oil resources in the fault basins in East China are very important strategic replacement resources. Since the first industrial oil flow well was drilled in the Permian Basin of the United States in 1921, the early conventional oil and gas reserves and productions have run through a cycle of rising, stability, and drop. The transformation from conventional oil and gas to shale oil and gas exploration had been achieved through the innovation of the exploration concept, which "re-rejuvenates" the reserves and production of fault basins. Compared with those in North America, the geological characteristics of continental shale oil in China are quite different. At the early stage, we studied shale oil by learning the experience from North America, and the phenomenon of "failure to fracture, failure to support, low backflow, and difficulty in stable production" generally existed. A recent basic study on movable oil and fracturing property of continental shale has shown that the laminated shale facies of salinized lake basins are the most favorable lithofacies, and the continental favorable areas with medium-high maturity and abnormal high pressure become the main research targets of shale oil in recent years. Based on the features of rapid change of lithofacies, high clay content, and strong plasticity of continental shale, the geophysical prediction methods for shale oil "sweet spots" and the engineering technology series of continental shale oil have been preliminarily formed and the related technical problems have been tackled. Recently, major breakthroughs have been made in continental shale oil in Cangdong Sag of Huanghua Depression in Bohai Bay Basin and Jiyang Depression. In the next step, we should research and develop supporting tools and equipment such as rotary steering and intelligent drilling rigs by learning from the new idea of identifying the shale oil "sweet spot" formed in the low oil price period in North America and using the new methods such as big data optimization technology, so as to improve the production efficiency of drilling and fracturing and continuously reduce the cost of well drilling and completion. We should promote the application of new materials and the research and development of new technologies

including carbon dioxide fracturing and in-situ conversion of shale oil with medium/low maturity to achieve the scale development of shale oil at low oil prices and the fundamental goal to maintain the stability of crude oil in the old oil and gas regions of East China.

4.2 Marine carbonate rocks

Marine carbonate oil and gas fields are characterized by the complete scale and a high abundance of resources and they are generally at the stage of great discovery and development. It is an important field for the discovery of large-scale oil and gas fields in China in recent years. Tarim, Sichuan, and Ordos basins are the main battlefields for the discovery of large-scale marine carbonate oil and gas fields [5–9].

In view of marine carbonate oil and gas exploration in the geological study, we should start with the analysis of the tectonic-sedimentary filling background to further study stratigraphic sedimentation and sequence stratigraphy and clarify the distribution ranges of ancient rifts and uplifts. The study should focus on the development features and distribution ranges of many sets of main source rocks, such as the Cambrian System in Tarim Basin, the Cambrian, Silurian, and Permian Systems in Sichuan Basin, the Pingliang Formation and Cambrian System in Ordovician System in Ordos Basin. In addition to organic reef beach, ancient karst, dolomite, and fractured reservoirs, new types including fault-controlling dissolution [10–11] dominated by strike-slip faults, microbial rocks, silicified carbonate rocks, and marl limestone related to the hydrothermal process have been discovered in recent years according to the study of reservoirs. The said reservoirs are controlled by sedimentary diagenesis environment, tectonic-pressure coupling action, fluid-rock dissolution, and sedimentation in the process of sedimentation, diagenesis, and reservoir formation. However, in different regions and different burial environments, there are great differences in geological controlling factors for the formation of high-quality reservoirs. For this reason, to strengthen the characterization study of new types of reservoirs, we should start with the coupling relationship among sedimentation, diagenesis, structure, and fluid, and carry out the study on the formation, development, and maintenance mechanism of reservoirs or accumulation space, so as to form a development mode of high-quality reservoirs to provide a principle for the reserve estimation. As for the characteristics of marine oil and gas reservoirs undergoing multi-stage structural transformation, we should strengthen the formation process anatomy of typical oil and gas reservoirs and understand the formation law of deep and ultra-deep oil and gas reservoirs [12] based on the perspective of "multi-element and multi-stage hydrocarbon generation" along with the consideration of dynamic formation and adjustment of reservoirs. Attention should also be paid to the evaluation of the marine exploration potential of the Precambrian System in North China, Qiangtang Basin, and South China while considering the evaluation of Ordovician and Cambrian Systems in Tarim Basin, Sinian Whole-Stratum System in Sichuan Basin, and Ordovician and Cambrian Systems in Ordos Basin.

In view of the difficulties in the deep burial of exploration target stratum and strong heterogeneity of reservoirs, we should strengthen the study of 3D seismic acquisition and processing technology of ultra-deep carbonate rocks in complex regions to solve the problems of the low signal-to-noise ratio of ultra-deep seismic data and low imaging accuracy of carbonate rocks [13–14]. Different geological, logging, seismic, and non-seismic methods should be integrated to serve as multiple solutions to the prediction of reservoirs. For the deep and ultra-deep high-temperature and high-pressure environment, we should intensify the study on ultra-deep equipment, and make breakthroughs in the aspects of key ultra-deep drilling equipment, logging tools for high-temperature wells, and completion equipment, so as to provide technical support for exploration breakthroughs.

4.3 Clasolite in basins in Central and West China

Clastic oil and gas reservoirs in the basins in Central and West China are affected by multi-stage tectonic cycles, which are characterized by multiple reservoir-forming stages and complex hydrocarbon migration and accumulation directions. They can be classified into two types according to the structural background of oil and gas reservoirs: intracontinental depressions and piedmont zones. The intracontinental depressions, represented by tight sandstone gas reservoirs in Ordos Basin and Sichuan Basin, are often characterized by a wide distribution area, large reserves, and obvious heterogeneity. It is important to figure out "sweet spots." Firstly, we should strengthen the study on the fine modeling of sand reservoirs and find out the "sweet spots" from sand bodies under the condition of clarifying the distribution range of source rocks. The studies show that there are differences in sand-body accumulation or reservoirs in different sedimentary environments. The porosity and permeability features of a single sand body are different in different positions of the sand body because of different hydrodynamic conditions, so the reservoirs should be subject to a detailed modeling study to find out the distribution law of high porosity and high permeability reservoirs for different types of sand bodies. Secondly, the seismic resolution should be improved and the technical study on the fine description of the sand body and fracture prediction should be strengthened to form an effective "sweet spot" prediction technology. Finally, the relevant experience of shale gas should be learned and the integration of geological engineering should be strengthened. We should intensify the study in aspects of hole trajectory control of horizontal wells with thin sand body and directional wells, multi-layer fracturing of vertical wells, and staged fracturing of low-cost horizontal wells.

In view of the exploration of clasomite in piedmont zones, the key to exploration breakthrough is to solve the key problems in seismic exploration technology. The high-quality

seismic imaging data have been acquired in the piedmont zone where outstanding achievements have been made in exploration. Meanwhile, the technical study on efficient and safe drilling and well completion, deep-stratum high-fracture pressure and reconstruction of complex reservoirs has been carried out to provide technical support for exploration breakthrough against the challenges such as complex stratum attitude, fragmentation, leakage, and high-pressure engineering in the piedmont zone.

4.4 Shale gas

As of 2019, explorers acquired nearly 2 trillion cubic meters of proven reserves in the Longmaxi Formation of Silurian System in the Sichuan Basin, with a shale gas output of 15.3 billion cubic meters. For the exploration of China's marine shale gas at the old stratigraphic age and with multi-staged structural transformation, strategies are as follows: We should determine favorable areas via sedimentology research, determine favorable targets via the study of preservation conditions, study the fracturability to determine horizons and trajectory of horizontal wells, evaluate and optimize engineering design, and finally achieve exploration breakthroughs. At the early stage of exploration, the priority is to clarify the spatial and temporal distribution range of organic-rich shale through the study of sedimentation and organic geochemistry. It includes two aspects: a. The continuous shale section with a high TOC and mineral composition in the formation or stratum should be clarified; b. the planar variation law of shale section with a high TOC should be clarified, including the thickness of shale section with high TOC, TOC value, mineral composition change, etc. Based on these results, the favorable regions for the exploration of shale gas should be identified in combination with the regional structure and project implementation conditions. The preservation conditions and engineering implementation conditions become the main factors to be considered in the optimal selection of the targets as the favorable regions for the exploration of shale gas. As for the preservation conditions, the regional structure of evaluated target regions should be studied, and the structure should be interpreted in detail on the basis of 2D and 3D seismic data interpretation. The study on the structural burial history, fractures, fracture combination, fracture sealing property, etc., should be carried out and the drilling targets should be preferentially selected by giving consideration to the implementation ability of projects. After the drilling targets are determined, it is critical to preferentially select the target window horizon of horizontal wells by obtaining the organic geochemical and petro-physical data of the shale section with a high TOC to evaluate fracturability. The selection of a target window of horizontal wells is the result of a comprehensive evaluation of shale gas-bearing property and fracturability and also the key to obtaining the high output of shale gas wells. When designing the trajectory of horizontal wells, the geologists should closely work with engineering experts to determine the directions and lengths of horizontal wells and determine the trajectory control points of horizontal wells according to current stress direction, detailed structural interpretation, and fracture prediction. The geologists should adjust the trajectory of horizontal wells promptly together with engineering experts according to the target window logging marks identified in the previous studies so as to ensure that horizontal wells run through the predetermined horizon during the drilling process of horizontal wells. After the drilling operation of a horizontal well is completed, the geologists should determine the fracturing operation parameters of fracturing sub-stages and all stages together with the fracturing engineering experts, on the basis of locating the layer through which the horizontal well runs and in combination with the understanding of the fracturability of small strata and the interpretation of fractures obtained via drilling and seismic data. A fine description of shale geological characteristics, detailed interpretation of structural characteristics, geological engineering integration, and precise engineering design play important roles for exploration breakthrough in shale gas [15].

The discovery of shale gas should be actively progressed in new strata including Cambrian, Permian, and Jurassic systems in Sichuan Basin and its periphery, Carboniferous-Permian Systems in North China, Carboniferous-Devonian Systems in Qiannan-Central Guangxi, and new regions including Middle and Lower Reaches of the Yangtze River while continuously expanding the exploration achievements of Wufeng Formation–Longmaxi Formation. For the exploration of shale gas in new marine shale series, we should learn from the successful exploration experience of the Wufeng Formation–Longmaxi Formation [16–17] and start with the sedimentary analysis to clarify the vertical "sweet spots" and planar sedimentary favorable regions of organic-rich shale. Key factors affecting the preservation conditions of shale in Wufeng Formation–Longmaxi Formation should be summarized and the influence of multi-stage tectonics on the enrichment or accumulation of high-quality shale in new strata should be analyzed to determine the favorable exploration targets in combination with the structural characteristics, buried depth and other conditions. The fracturability evaluation should be intensified; the crossing horizon by horizontal wells should be preferentially selected, and the design schemes for horizontal wells and later fracturing should be optimized to ensure the final effect of "going for the goal shot." The continental and marine transitional shale in the Jurassic system, etc. is characterized by complex longitudinal lithological combination and rapid change in planar lithology and high clay content. Thus, we should start with the systematic coring to strengthen the basic research including the sequencing deposition of shale and find out the double "sweet spots" of geology and engineering in combination with the analysis of rock mechanics. Meanwhile, we should extend the study on the geophysical "sweet spot" prediction technology focusing on the description of continental shale change characteristics and the adaptive fracturing

technology for plastic formation characteristics.

5 Development prospect for oil and gas exploration

With the emerging of shale oil and gas and the rapid development of geophysical exploration technology and drilling/completion technology, the current global oil and gas exploration is undergoing profound changes and is developing toward finer, deeper, and more diverse trends. It extends from shallow/middle strata to deep/ultra-deep strata, from shallow water to deep/ultra-deep water, and from conventional oil and gas resources to unconventional oil and gas resources, and the deep-stratum, deep-water and unconventional oil and gas exploration has become a new trend in the world. The results of oil and gas exploration in recent decades show that the oil and gas resources discovered in deep-water and ultra-deep-water fields account for more than half of the newly discovered oil and gas resources in the world, which are mainly distributed at both banks of Central/South Atlantic, East Africa sea area, East Mediterranean, and other basins. The proportion of newly increased unconventional oil and gas reserves in North America to the newly increased global oil and gas reserves has gradually grown, nearly reaching 45% in 2017. It is noteworthy that the continuous new discoveries in new fields, new strata, and new types in the old oil regions with high exploration degrees also re-activate the exploration of old oil regions and become a new highlight in oil and gas exploration to cope with low oil prices. The terrestrial shale oil comes to be a hot spot for exploration. With the staged fracturing technology of long horizontal wells, achievements have been made for the exploration of shale oil with medium/high maturity in Junggar, Bohai Bay, Songliao, Sichuan, and Santanghu basins. New discoveries have been made in the fine exploration of mature basins in East China, and many breakthroughs have been made in the exploration of continental and marine buried hill reservoirs and deep depressions in Bohai Bay Basin, which has become an important field for an effective substitution of oil and gas resources in East China.

As for the basic theory study of petroleum geology, the research on unconventional oil and gas theory is progressing further in the study of conventional oil and gas theory. The study of source rocks extends from the study of the peak period of hydrocarbon generation to the whole process of hydrocarbon generation. In terms of the study of reservoirs, the nano-testing technology expands from shale to conventional sandstone and carbonate reservoirs. The physical properties of reservoirs on multiple scales are described from meter level to nanometer level. And the seepage characteristics of fluids in multiple scales of pore sizes are discussed. In terms of the study of caprocks and preservation conditions, a new understanding of the destruction and sealing mechanism of caprocks is being formed with the continuous in-depth study on shale microstructure and microfracture formation mechanisms. For the study on the hydrocarbon accumulation law, more attention has been paid to the whole process coupling between hydrocarbon generation & expulsion of source rocks and different types of reservoir spaces. It can be expected that the basic theoretical system of oil and gas geology will be expanded using the geology theory of unconventional oil and gas resources and a new discipline connotation will be endowed to the basic theoretical system. In the future, oil and gas exploration technology will be used to evaluate the conventional and unconventional oil and gas basins as a whole. A multi-series three-dimensional exploration strategy will be put forward by analyzing the spatial distribution law of conventional and unconventional oil and gas resources. Moreover, inspired by innovative technologies including nanotechnology, intelligent materials, and artificial intelligence, the oil and gas engineering technology will develop toward the orientation of intelligence, integration, miniaturization, and cost saving. The new generation of intelligent technology systems for exploration and exploitation, including high-efficiency and low-cost drilling and completion technology systems and in-situ modification systems dominated by intelligent and precise guidance, are being developed, which will boost the reserves and production of oil and gas to a new growing climax.

References

[1] PRATT W E. Toward a philosophy of oil-finding [J]. AAPG Bulletin, 1952, 36 (12): 2231–2236.

[2] MA Yongsheng, CAI Xunyu, ZHAO Peirong. The research status and advances in porosity evolution and diagenesis of deep carbonate reservoir [J]. Earth Science Frontiers, 2011, 18 (4): 181–192 (in Chinese).

[3] MA Yongsheng, CAI Xunyu, ZHAO Peirong, et al. Formation mechanism of deep-buried carbonate reservoir and its model of three-element controlling reservoir: a case study from the Puguang Oilfield in Sichuan [J]. Acta Geologica Sinica, 2010, 84 (8): 1087–1094 (in Chinese).

[4] LV Jianzhong, LIU Jia, SUN Naida, et al. The "Super Basin Model": a new idea of increasing reserves and production in mature basins [J]. International Petroleum Economics, 2019, 27 (9): 40–48 (in Chinese).

[5] ZHOU Jingao, LIU Xinshe, SHEN Anjiang, et al. The characteristics of tectonic-lithofacies paleogeography of marine petroliferous basins of China [J]. Marine Origin Petroleum Geology, 2019, 24 (4): 27–37 (in Chinese).

[6] MA Yongsheng, CAI Xunyu, GUO Xusheng, et al. The discovery of Puguang Gas Field [J]. Engineering Science, 2010, 12 (10): 14–23 (in Chinese).

[7] MA Yongsheng, CAI Xunyu, ZHAO Peirong, et al. The gas resources of the "Gas Pipeline from Sichuan to China Eastern Region" project [J]. Engineering Science, 2010, 12 (5): 73–77 (in Chinese).

[8] ZHAO Luzi, WANG Zecheng, YANG Yu, et al. Important discovery in the second member of Dengying Formation in well Pengtan1 and its significance, Sichuan Basin [J]. China Petroleum Exploration, 2020, 25 (3): 1–12 (in Chinese).

[9] MA Yongsheng, HE Dengfa, CAI Xunyu, et al. Distribution and fundamental science questions for petroleum geology of marine carbonate in China [J]. Acta Petrologica Sinica, 2017, 33 (4): 1007–1020 (in Chinese).

[10] QI Lixin. Characteristics and inspiration of ultra-deep fault-karst reservoir in the Shunbei area of the Tarim Basin [J]. China Petroleum Exploration, 2020, 25 (1): 102–111 (in Chinese).

[11] JIAO Fangzheng. Significance and prospect of ultra-deep carbonate fault-karst reservoirs in Shunbei area, Tarim Basin [J]. Oil & Gas Geology, 2018, 39 (2): 207–216 (in Chinese).

[12] HE Dengfa, MA Yongsheng, LIU Bo, et al. Main advances and key issues for deep-seated exploration in petroliferous basins in China [J]. Earth Science Frontiers, 2019, 26 (1): 1–12 (in Chinese).
[13] MA Yongsheng, LI Maowen, CAI Xunyu, et al. Mechanisms and exploitation of deep marine petroleum accumulations in China: advances, technological bottlenecks and basic scientific problems [J]. Oil & Gas Geology, 2020, 41 (4): 655–672, 683 (in Chinese).
[14] MA Yongsheng, ZHANG Jianning, ZHAO Peirong, et al. Requirement analysis and research direction for the geophysical prospecting technology of SINOPEC [J]. Geophysical Prospecting for Petro-leum, 2016, 55 (1): 1–9 (in Chinese).
[15] MA Yongsheng, CAI Xunyu, ZHAO Peirong. The support of petroleum engineering technologies in trends in oil and gas exploration and development: case study on oil and gas exploration in SINOPEC [J]. Petroleum Drilling Techniques, 2016, 44 (2): 1–9 (in Chinese).
[16] MA Yongsheng, CAI Xunyu, ZHAO Peirong. China's shale gas exploration and development: understanding and practice [J]. Petroleum Exploration and Development, 2018, 45 (4): 561–574 (in Chinese).
[17] SUN Huanquan, ZHOU Dehua, CAI Xunyu, et al. Progress and prospect of shale gas development of SINOPEC [J]. China Petroleum Exploration, 2019, 26 (1): 1–12 (in Chinese).

