



# History, achievements and significance of scientific exploration wells: For the 30<sup>th</sup> anniversary of the Scientific Exploration Well Program



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**Abstract:** Thirty years have past since the “scientific exploration well” program (1986–2000) was initiated in 1986. Review and summary of the exploration history, achievements and management experiences are significant for directing future onshore exploration. The program aimed to address critical and fundamental geological challenges and achieve breakthroughs through scientific exploration in new basins, new strata and new regions, on the basis of new geologic cognitions obtained by PetroChina Research Institute of Petroleum Exploration & Development (RIPED). During 15 years of efforts, 14 wells were drilled, of which Well Taican 1 and Well Shaanacan 1 contributed to the discovery of Tuha Oilfield and Jingbian giant gas field, opening the prelude to large-scale natural gas exploration in the Jurassic System in northwest China and the Ordos Basin. Several wells (e.g. Gaoke 1, Jiucan 1, and Qincan 1) produced low-yield oil and gas flows, laying the foundation for later large discoveries. Moreover, a series of strategic domains and targets have been ascertained. In program management, a scientific and rational exploration procedure has been established: the PetroChina headquarter assumes investment risks, RIPED proposes domains/targets, and oilfields undertake specific tasks under the supervision of RIPED, following the rules of “intensive and thorough explorations”. The significance of the “scientific exploration well” program is manifested in transforming scientific achievements into productivity, guiding and driving oil and gas exploration to achieve strategic breakthroughs, and accumulating valuable experiences for PetroChina to carry out risk exploration.

**Key words:** scientific exploration well; “three new” fields; Tuha Basin; Ordos Basin; Shanshan Oilfield; Jingbian gas field; Well Taican 1; Well Shaanacan 1

## Introduction

As a key scientific research project, the Scientific Exploration Well Program was assigned in 1986 by the CPC Committee of the former Ministry of Petroleum Industry to the Scientific Research Institute of Petroleum Exploration and Development (currently the “PetroChina Research Institute of Petroleum Exploration and Development”, hereinafter referred to as “RIPED”) for implementation. The Program was initialized to expand exploration operations in new areas, new formations and new basins for petroleum industry<sup>[1]</sup>. Ministry of Petroleum Industry allocated over 50 million RMB Yuan to RIPED every year, which shall be fully responsible to select well sites, to implement drilling operations and relevant test operations. To accomplish these goals, RIPED established devoted management team for the Scientific Exploration Well Program to take charge of geologic

assessments, well site selection, team building, drilling and investment management.

From 1986 to 2000, the Scientific Exploration Well Program was in operation for 15 years, researches have been conducted for hydrocarbon potentials, petroleum geologic and engineering problems in Jurassic and Carboniferous-Permian formations in Northwest China, Paleozoic formations in North China, marine formations in South China, buried and Tertiary subsalt deep layers in the Bohai Bay Basin, Paleogene marine formations in the Tarim Basin and some other areas. In addition to opened up two major new areas for exploration in Jurassic formations in Northwest China and Lower Paleozoic formations in North China, the Program directly promoted natural gas exploration in the Turpan-Hami Basin and the Ordos Basin. In addition, the Program directly influenced foundation of the Program

Management Department for exploration of Jurassic formations in Northwest China and marine formations in south China by the former CNPC Exploration Bureau. During implementation of the Program, 14 scientific exploration wells have been drilled. Among these wells, the Well Taican-1 and the Well Shancan-1 are the first two wells drilled. Through these two wells, the Tuha Oilfield and the Jingbian Gasfield were found; with low oil productivity gas flows observed in the Well Jiucan-1, the Well Lengke-1, the Well Wuke-1, the Well Gaoke-1 and the Well Shanke-1, confidences have been gained through this program. Through continuous exploration in these areas in later stages, Jiudong Oilfield, Nanbaxian Gasfield, Niudong Gasfield, Anyue Gasfield and Yubei Oilfield were found; The Well Gaocan-1, the Well Qincan-1, the Well Yingke-1, the Well Haoke-1, the Well Shengke-1 and the Well Qingke-1 encountered oil/gas shows. In addition, two wells have been recommended to different oilfields. Among them, the Well Pushen-8 transferred to the Zhongyuan Oilfield in November 1997 encountered daily oil production 23.93 m<sup>3</sup> in drill stem test (DST). The Well penetrated favorable oil-generating rocks in the Paleogene Sha-3 Member; the Well Wushen-1 recommended to the Dagang Oilfield encountered high-productivity natural gas in Ordovician formations. All in all, significant economic and social benefits have been gained through implementation of the Scientific Exploration Well Program.

Implementation of the Scientific Exploration Well Program covered the transition time from planned economy in dominance to the market economy in dominance with multiple changes in exploration prospects and management system of petroleum industry in China. During implementation of the Program, managing departments changed from Ministry of Petroleum Industry to China National Petroleum Corporation (CNPC), and further to PetroChina Company Limited. In addition, program execution experienced four modes: (1) From 1986 to 1994, CNPC designated RIPED exclusively in the aspects of financing and implementation of the entire Program; (2) From 1995 to 1996, RIPED cooperated with different oilfields for program implementation; (3) From 1997 to 1998, CNPC managed and coordinated uniformly, whereas RIPED was responsible to select optimal well sites and conduct researches while drillings. At the same time, the New Area Exploration Department was responsible to carry out drilling operations; (4) From 1999 to 2000, the RIPED was responsible for entire program implementation under the guidance of PetroChina. Outstanding accomplishments have been achieved in spite of extreme difficulties in geologic, engineering and other conditions. At the 30<sup>th</sup> anniversary of implementation of the Scientific Exploration Well Program, great values can be gained for present exploration operations through reviewing of program history, accomplishments and management experiences.

## 1. Background and processes of initialization of the Scientific Exploration Well Program

### 1.1. Background of Scientific Exploration Well Program initialization

In the 1980s, the newly increased proven reserves and oil production decreased, whereas national economy maintained high-speed development. With rapid increases in demands for oil and gas resources, the imbalance between supply and demand of oil and gas became increasingly outstanding. Under such circumstances, it was extremely important to further identify zones with replacing strategic resources. In other words, new areas with potentials shall be studied and evaluated. In this way, new reserves can be identified through drilling of preliminary exploration wells. With consideration to severe natural environmental conditions and complicated geologic conditions in western China, the former Ministry of Petroleum Industry proposed to further explore these areas, especially the Tarim, Junggar, Ordos, Qaidam, Hexi Corridor and other basins through preliminary researches and explorations on bases of stabilized oil productivity in eastern China.

From March to April 1986, Ministry of Petroleum Industry organized a national forum to review exploration technologies. Aiming to solve the problem about slow rises in reserves and requirements for fast and effective exploration operations, Mr. Zhai Guangming, the director of RIPED at the time, proposed “Deploy 1-2 high-risk exploration well(s) in each oilfield every year in areas with high risks, insufficient data and originally considered low potentials to clarify geologic conditions and to make necessary researches. To achieve these objectives, it is necessary to emancipating the mind and broaden views to perform additional exploration operations other than existing areas. Even with only one exploration well in one oilfield each year, the exploration areas nationwide may be expanded significantly. In this way, bright prospects can be expected in hydrocarbon exploration”. The proposal was adopted by the forum with such exploration wells redefined as scientific exploration wells. It was also proposed that the RIPED should take over this Program. Later, CPC Committee of Ministry of Petroleum Industry officially designated RIPED to take fully responsible for implementation of the Scientific Exploration Well Program. Starting from medium to long-term strategies for on-shore oil/gas development and based on advantages of RIPED in comprehensive researches and expertise, latest research findings can be used to explore hydrocarbon resources in new areas, new formations and new basins. In addition to make breakthrough in exploration operations, the Program was established to provide solutions to key problems related to geologic theories and engineering aspects in petroleum industry. Management and relevant departments of RIPED attached great importance to the Scientific Exploration Well Program. Right after the Forum, the management team for the Scientific Exploration Well Program was established with Mr. Zhai Guangming, the director of

RIPED at the time, as the director of the management team, and with Hu Jianyi and Yu Bingzhong, deputy directors of RIPED, who were responsible for geologic and engineering departments, as deputy directors of the management team. Under the management team, there are three work groups for geology, drilling and routine operations, respectively.

## 1.2. History of the Scientific Exploration Well Program

Generally speaking, the Scientific Exploration Well Program experienced three stages: initialization and breakthrough, reformation and adjustments and development and summarization.

### 1.2.1. Initialization and breakthrough (1986 to 1990)

The period from 1986 to 1990 marked the starting stage of the Scientific Exploration Well Program. As the undertaker of this stage, RIPED tried various innovative research and management modes to explore hydrocarbons in new areas, new formations and new basins actively. Successful completion of the Well Taican-1 and the Well Shancan-1 (See Fig. 1, Table 1) ushered in breakthrough in major discoveries, which established solid foundation for future implementation of the Program.

In fact, the starting time of the Scientific Exploration Well

Program coincided with the initialization of a new round of seismic exploration in the Turpan-Hami Basin commissioned by the former Ministry of Petroleum Industry with the Petroleum Geophysical Prospecting Bureau responsible for acquisition, processing and interpretation of seismic data. At the same time, RIPED was endorsed with responsibilities to identify optimal sites for scientific exploration well. As required by the management team of the Scientific Exploration Well Program, the first scientific exploration well must be proposed on bases of comprehensive petroleum geologic studies with designs in five aspects, geology, drilling, drilling fluids, progress and financial, to be accomplished simultaneously. Later, this work pattern became the blueprint for site identification and drilling of various exploration wells. RIPED cooperated closely with the No. 3 Geologic Survey Department of Petroleum Geophysical Prospecting Bureau to prepare assessment reports for traps and reservoir formations for the Turpan Depression on bases of researches related to hydrocarbon source rocks, sedimentary reservoirs, traps and reservoir formation mechanisms<sup>[2]</sup>. In fact, the Report played vital role in determination of the drill site for the Well Taican-1. With consideration to the Jintai, Kekeya and the Taibei Structural traps recommended by the Petroleum Geophysical Prospecting Bureau and in accordance with assessments for favorable



Fig. 1. Classification of hydrocarbon-bearing basins and distribution of scientific exploration wells in China.

**Table 1. Scientific exploration wells drilled during implementation of the Scientific Exploration Well Program**

| SN | Basin         | Well       | Time of drilling/<br>(yy-mm-dd) | Time of completion/<br>(yy-mm-dd) | Designed well depth/m | Well depth at completion/<br>m | Target formation                 | Pene-<br>trated formation | Major exploration findings and conclusions                                                                                           |
|----|---------------|------------|---------------------------------|-----------------------------------|-----------------------|--------------------------------|----------------------------------|---------------------------|--------------------------------------------------------------------------------------------------------------------------------------|
| 1  | Turpan-Hami   | Taican-1   | 1987-09-22                      | 1988-09-03                        | 4 800                 | 4 466.88                       | J, T, P                          | J <sub>1b</sub>           | Jurassic formation with daily oil production of 24.2t; Discovery of the Tuha Oilfield                                                |
| 2  | Shaan-ganning | Shaancan-1 | 1988-01-24                      | 1989-02-07                        | 4 500                 | 4 068.45                       | O, Pt                            | O <sub>2m</sub>           | Ordovician formation with daily gas production $28.3 \times 10^4 \text{ m}^3$ ; Discovery of the Jingbian Gasfield                   |
| 3  | Bohai Bay     | Gaocan-1   | 1989-01-06                      | 1989-12-16                        | 5 400                 | 5 159.82                       | Es <sub>3</sub> , J, -€          | Pt                        | Penetration of granite with discovery of pay zones in shallow formations                                                             |
| 4  | Chuxiong      | Chucan-1   | 1990-10-15                      | 1992-09-27                        | 4 800                 | 5 286.80                       | T <sub>3</sub>                   | J <sub>1-2</sub>          | Failed to penetrate target formations due to complex structures                                                                      |
| 5  | Qinshui       | Qincan-1   | 1991-04-08                      | 1991-09-24                        | 1 950                 | 1 950.00                       | C, O, -€                         | -€                        | Ordovician formation with freshwater production; Discovery of Carboniferous — Permian coal-bead methane                              |
| 6  | Jiuquan       | Jiucan-1   | 1992-03-10                      | 1993-04-08                        | 5 000                 | 4 700.00                       | K, J                             | J <sub>1-2</sub>          | Cretaceous formations with daily oil production of 4.5 t to confirm potentials for further exploration                               |
| 7  | Tarim         | Yingke-1   | 1994-04-01                      | 1996-03-17                        | 6 500                 | 6 406.00                       | K, E                             | E                         | Paleogene formations with natural gas shows but no reservoir                                                                         |
| 8  | Bohai Bay     | Heke-1     | 1995-04-12                      | 1997-06-07                        | 5 500                 | 5 807.81                       | Es <sub>4</sub> , E <sub>k</sub> | Ek <sub>1</sub>           | Subsalt structures with natural gas shows but no reservoir                                                                           |
| 9  | Qaidam        | Lengke-1   | 1996-05-01                      | 1998-04-16                        | 5 400                 | 5 200.00                       | J, E                             | J <sub>1</sub>            | Jurassic formations with daily oil production of 7.2 t and with discovery of thick source rocks                                      |
| 10 | Subei         | Shengke-1  | 1997-03-10                      | 1998-06-02                        | 4 500                 | 4 250.52                       | O, Pt, -€                        | -€ <sub>3</sub>           | Complex structures were encountered with 2 oil-bearing layers in Jurassic formation                                                  |
| 11 | Sichuan       | Wuke-1     | 1997-11-15                      | 1999-03-02                        | 5 900                 | 6 063.00                       | S, O, -€                         | -€ <sub>2</sub>           | Silurian formation with daily gas production of $1.5 \times 10^4 \text{ m}^3$ , to confirm potentials for further exploration        |
| 12 | Turpan-Hami   | Shanye-1   | 1998-05-10                      | 1999-05-27                        | 5 500                 | 5 500.00                       | J <sub>1</sub> , T               | T                         | Triassic formations with daily oil production of 11.5 t to expand the zones for exploration                                          |
| 13 | Sichuan       | Gaoke-1    | 1998-07-01                      | 1999-07-25                        | 5 400                 | 5 400.00                       | Z                                | Z                         | Sinian formations with daily natural gas production of $0.7 \times 10^4 \text{ m}^3$ . The well was completed with casing fracturing |
| 14 | Jiuquan       | Qingke-1   | 2000-03-28                      | 2000-08-27                        | 5 300                 | 4 525.00                       | J <sub>1</sub> , T               | K                         | Cretaceous formations with oil/gas shows and free flow in initial stages                                                             |

reservoir formation conditions, the Taibei Structure was determined to be the preferential target for the very first scientific exploration well. The Well Taican-1<sup>[3]</sup> was drilled in Taibei depression of the Taibei Structure in Turpan-Hami Basin in September 22, 1987 based on massive previous researches and assessments for the Scientific Exploration Well Program. The Well encountered industrial oil flow of 24.2 t/d on January 5, 1989. Consequently, discovery of the Shanshan Oilfield ushered in the breakthrough in exploration in Jurassic formations<sup>[4]</sup>. With exploration of hydrocarbons in coal-bead formations, new prospects were revealed for exploration of Jurassic formations in Northwestern China.

At the same time with identification of the drill site for the Well Taican-1, RIPED cooperated with the Changqing Oilfield to select drill sites for scientific exploration wells to explore natural gas in Paleozoic formations. After over one year,

the second drill site was selected in Linjiawan Structure in central uplift of the Shaanganning Basin (currently the Ordos Basin) in accordance with research findings for natural gas reserves in Paleozoic formations and with weathered shell in top Ordovician formations as favorable target formations. In 1987, Well Shancan-1 was drilled to determine gas-bearing properties of Paleozoic formations, to highlight geologic conditions for formation of natural gas reservoirs and to expand prospects for natural gas exploration. Drilling of the Well started in January 24, 1988 and the Well encountered industrial gas flow of  $28.3 \times 10^4 \text{ m}^3/\text{d}$  in June 23, 1989. Later, with large-scale natural gas exploration in central parts of the Basin, Jingbian carbonate natural gas field, the largest one in China was discovered, which marked historic breakthrough in natural gas exploration.

Successful completion of the Well Taican-1 and the Well

Shancan-1 expanded natural gas exploration in Jurassic formations in the Northwestern China and Paleozoic formations in the Shaanganning Basin. In addition to promote development of hydrocarbon-generation theories in coal-bed formations, these two wells directly promoted development of these two potential zones<sup>[5-11]</sup>.

### 1.2.2. Reformation and adjustments (1991 to 1996)

With successful completion of the Well Taican-1 and the Well Shancan-1, Scientific Exploration Well Program gained approval of top management of CNPC and supports of oilfields. In later years, one new well was drilled every year to explore new zones. During the period, Scientific Exploration Well Program failed to make breakthrough and big discovery due to insufficient preparations (geologic researches and engineering techniques) and investment. At the same time, Scientific Exploration Well Program also tried various innovative management techniques, such as strengthening cooperation with oilfields to perform joint studies. In addition, workshops for identification of optimal drill site for scientific exploration well were organized annually to accumulate precious experiences and to highlight some favorable zones and targets for future execution of the Scientific Exploration Well Program.

With further development of exploration operations, it was harder to select optimal site for scientific exploration well. Since most of these wells were quite deep, insufficiency in engineering techniques, research investments and various unfavorable conditions became more outstanding. Though favorable oil/gas shows have been observed in several wells, these wells failed to accomplish geologic goals or make any breakthrough. On the other hand, these wells highlighted directions of future exploration operations. For example, the Well Gaocan-1 failed to find weathered shell in deep buried-hill structures, but encountered pay zones in shallow formations; the Well Chucan-1 failed to reach target formation due to repeated geologic structures; the Well Qincan-1 encountered poor preservation conditions with water production in Ordovician formations and CBM in Carboniferous-Permian formations; the Well Jiucan-1 encountered complex geologic conditions with pay zones polluted and free flow in initial stages; the Well Yingke-1 encountered formations with high temperatures and high pressures with inaccurate prediction of pay zone; the Well Haoke-1 encountered poor preservation conditions in deep layers; the Well Lengke-1 penetrated deep formations with complicated conditions and these formations were polluted; the Well Shengke-1 encountered structures with confusing structures and complicated reservoir conditions and with 3 oil-bearing layers identified in Jurassic System.

### 1.2.3. Development and summarization (1997 to 2000)

During the meeting of CNPC for exploration operations in the year 1997, it was determined that the Scientific Exploration Well Program should be taken as a core business to further strengthen scientific management over scientific exploration

wells and to promote management over scientific exploration wells. Major reforms were made in three aspects of program implementation. At the same time, it was clarified that principles and procedures for identification of drill sites for scientific exploration well should remain unchanged.

After the reform and relocation, scientific Exploration Well Program encountered major discoveries in the Turpan-Hami Basin and the Sichuan Basin. On November 15, 1997, RIPED started drilling of the Well Wuke-1 on the southern high of Wubaiti Underlying Structure in Datianchi Structure of the Eastern Sichuan Basin. With low-productivity gas flows encountered in fractured slity mudstone in Xiaoheba Formation of Eastern Sichuan, the Area was verified to have bright prospects for future exploration operations. On May 10, 1998, RIPED designed and started drilling of the Well Shanke-1 on Taibei Shanshan Structure of the Turpan-Hami Basin to explore Lower Jurassic and Triassic formations. With low-productivity oil flows encountered in Triassic formations, Early Jurassic formations in the Taibei depression were confirmed to contain Permian hydrocarbon source rocks with significant potentials for exploration. In addition, new areas for exploration of light oil in Triassic formations have been discovered for the first time. Drilling data show deep formations have favorable prospects for future exploration<sup>[12]</sup>. On July 1, 1998, RIPED started drilling of the Well Gaoke-1 on Gaoshiti Structure of Jialidong Uplift in Central Sichuan Basin. The Well encountered favorable oil/gas shows and low-productivity gas flows. Due to restrictions imposed by borehole conditions and available techniques, no acidization or fracture operation was implemented. Consequently, the opportunity to discover the present Anyue Gasfield was wasted. Anyway, the Well verified significant exploration potential in paleo-uplifts in Central Sichuan Basin<sup>[13-14]</sup>. On March 28, 2000, RIPED started drilling of the Well Qingke-1 on Qingxi-1 Structure in Qingxi Low Uplift of Qingxi Depression in the Jiuquan Basin. The Well encountered favorable oil/gas shows in Lower Cretaceous and Paleogene formations. The Well failed to reach the major target formation due to failure in cementation operations.

The Scientific Exploration Well Program came to an end in 2000. Based on successful experiences of the Program, PetroChina Company Limited initialized risk exploration in the year 2005.

## 2. Experiences in management of scientific exploration wells

After 15 years in operation, the Scientific Exploration Well Program has become a window for discovery of new zones with strategic importance onshore. Scientific exploration wells can be seen as effective ways to discover high-quality and high-efficiency reserves. During implementation of the Program, scientific explorations and breakthroughs have been taken as permanent goals for identification of optimal sites for scientific exploration wells. During review of well sites and selection of exploration targets, principles of “more research

objectives than available well sites, more researched zones than research objectives and more domains than zones” were followed closely to endorse selection and drilling of scientific exploration wells with significance in both sophistication and breakthrough. To identify optimal well sites, lean management was implemented to make sure all design modifications should conform to geologic conditions, surface operations should conform to underground conditions and all measures taken should conform to requirements of discovery. In addition, three major sectors, preliminary site selection, implementation of drilling operations and assessments after drilling, run through the entire processes of management. At the same time, high requirements have been presented for each scientific exploration well. For example, from the very beginning, each well was required to have high-level and high-quality design. In addition, high requirements for quality of operators and excellent management have been proposed.

Successful execution of the Scientific Exploration Well Program can be seen as a result of combination of comprehensive petroleum geologic researches, theoretic breakthrough, progresses in engineering techniques and team spirit. In fact, the Well Taican-1 can be seen as the typical representative for implementation of such successful experiences.

### 2.1. Theoretic breakthroughs in understanding of geologic conditions

Without breakthrough in understanding of geologic conditions, favorable zones for hydrocarbon exploration may not be fully represented and drilling of favorable formations may not be easily implemented. Consequently, it can be seen that breakthroughs in understanding of geologic conditions can be seen as preconditions for implementation of the Scientific Exploration Well Program and to enhance probability of breakthrough in hydrocarbon exploration.

At the very beginning of implementation of the Scientific Exploration Well Program, RIPED organized multi-disciplinary research team to analyze and select Shaanganning, Turpan, Bohai Bay (Jidong, Huabei and Shengli Exploration Area), Jiuquan, Shanxi, Yunnan-Guizhou-Sichuan and some other basins or areas as key zones based on previous research findings and assessments for sedimentary basins nationwide. With addition of Tarim Basin and Sichuan Basin in later stages, 18 targets of hydrocarbon exploration have been identified.

Management Team of the Scientific Exploration Well Program decided to drill the first scientific exploration well in the Taibei Structure of the Turpan-Hami Basin, when great differences exist with regard to structural positions and target formations. Through massive rudimentary works involving survey of field outcrops, reassessments of existing wells, processing and interpretation of breakthroughs in understanding of geologic conditions have been gained in following three aspects: (1) Turpan-Hami Basin was separated from the Junggar Basin to the north by only one mountain, and these

two basins have similar reservoir conditions. After prolonged exploration, the Junggar Basin was determined to be rich in hydrocarbon resources. Accordingly, medium or large-scale oil/gas fields may be discovered in the Turpan-Hami Basin. (2) Junggar Basin contains multiple oil generation and preservation layers in Carboniferous—Permian, Triassic—Jurassic formations and field survey results show these sedimentary layers also developed in the Turpan-Hami Basin (Fig. 2). Consequently, these layers may serve as the key for future explorations. In this way, the Turpan-Hami Basin may contain medium or large-scale oil/gas field. (3) As for the Taibei, Shengjintai and Kekeya structures (Fig. 3), the Well Taibei-1 encountered oil/gas shows in Jurassic formations to prove hydrocarbon accumulation. Accordingly, the Jurassic—Permian formations in the Taibei Structure were taken as the exploration objectives to finalize the position of the Well Taican-1 (Fig. 4).

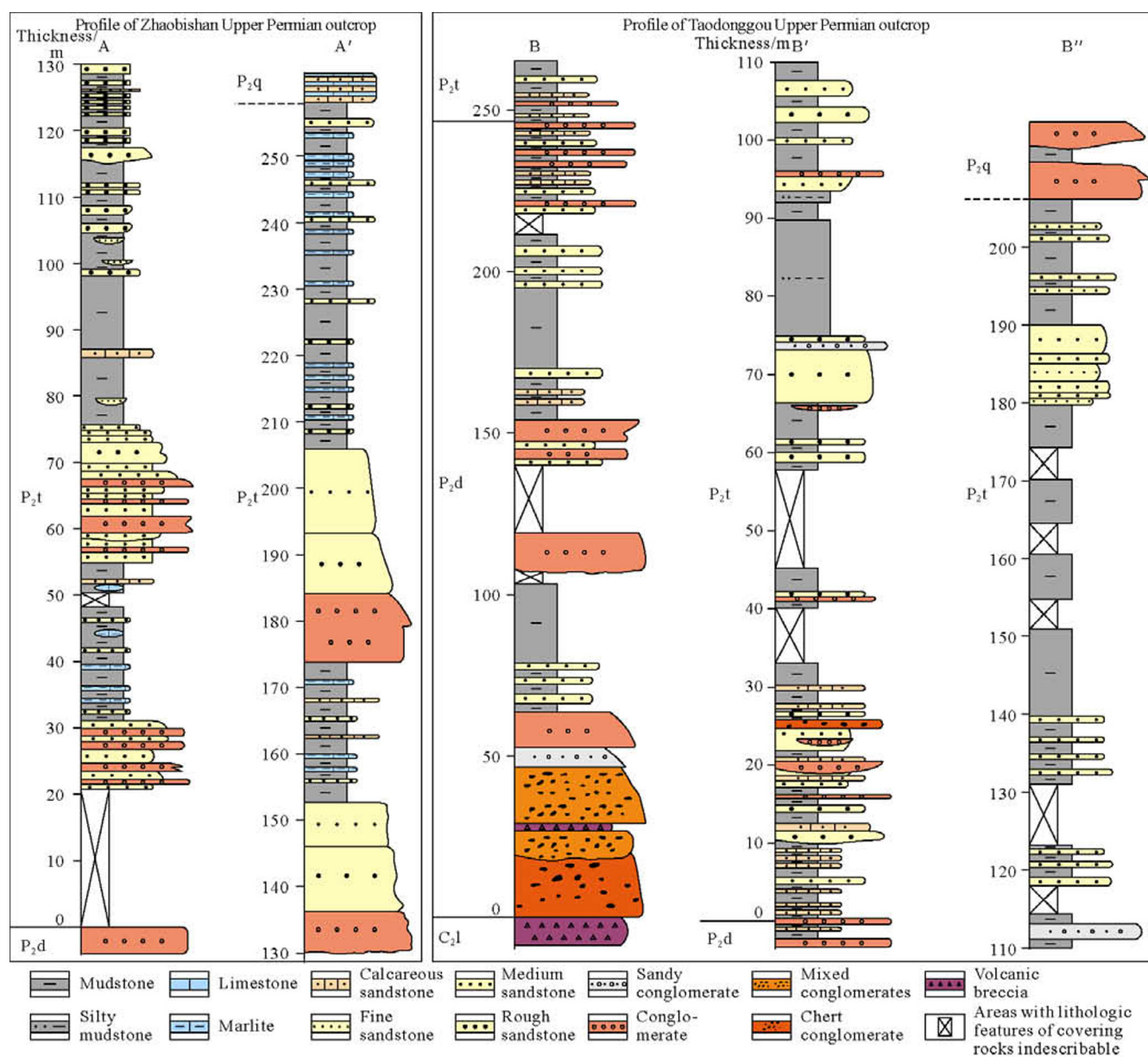
### 2.2. Progresses in engineering techniques

Progresses in techniques for hydrocarbon exploration made the dream of exploration of favorable targets come true. As soon as the position for the Well Taican-1 was finalized, RIPED promptly prepared detailed designs for geology, drilling, engineering, rig reconstruction and cost control individually under guidance of the Management Team. It was proposed to deploy 6 state-of-art techniques at the time: (1) Sophisticated well logging instruments to fully track changes in various parameters during drilling and logging of the well; (2) Assessment techniques for tank-top gases to assess hydrocarbon potentials of reservoir rocks objectively through systematic capturing of gases in the tank; (3) Cation polymer drilling fluid system to ensure proper execution of drilling operations; (4) Near-balance drilling techniques to achieve maximum protection over the pay zone; (5) Sophisticated logging techniques to ensure assessment of the pay zone objectively; (6) Cutting-edge formation testing techniques to ensure proper working processes and breakthrough.

### 2.3. Team spirit

Without close cooperation of geologic and engineering staffs, it would be extremely difficult to achieve breakthrough or major discoveries in new exploration areas with complicated geologic conditions. In fact, implementation of the Scientific Exploration Well Program strictly followed the principles of “management with three key sectors run through the entire management procedure” and “integral lean management” (Fig. 5).

The first key sector refers to the preliminary site selection and risk assessment of the target. It is important to select proper site represented the area. In fact, the Well Taican-1 has the potential  $2 \times 10^8$  t oil reserves and multiple favorable traps in Northwest Jurassic formations and the Turpan-Hami Basin as the exploration objectives (Fig. 6). In practice, principles of “more research objectives than available well



A—Lower section of the Upper Permian Ta'ergang Formation in the Zhaobishan Outcrop; A'—Upper section of the Upper Permian Ta'ergang Formation in the Zhaobishan Outcrop; B—Permian Daheyan Formation in the Taodonggou outcrop; B'—Lower Member of the Permian Ta'ergang Formation in the Taodonggou outcrop; B''—Upper Member of the Permian Ta'ergang Formation in the Taodonggou outcrop; C<sub>2</sub>l—Upper Carboniferous Liushugou Formation; P<sub>2</sub>d—Upper Permian Daheyan Formation; P<sub>2</sub>t—Upper Permian Ta'ergang Formation; P<sub>2</sub>q—Upper Permian Quanzijie Formation.

**Fig. 2. Lithologic profile of Upper Permian outcrop in mountain-front structure of northern Turpan Depression (Generated in accordance with Reference [2], See Fig. 3 for positions of outcrops).**

sites, more researched zones than research objectives and more domains than zones” were followed. Finally, expert team was deployed to navigate hydrocarbon exploration operations. The research team was responsible for implementation of objective geologic assessments, the auditing team was responsible for identification and confirmation of target traps, whereas the approval team was responsible to maintain quality of exploration targets and relevant risks within acceptable extent.

The second key sector involves proper deployment of suitable techniques and measures during exploration. During the period, cares were taken to perform analyses while drilling

rapidly and timely to adjust design properly. Principles of “all design modifications should conform to geologic conditions, surface operations should conform to underground conditions and all measures taken should conform to requirements of discovery” would be abided by to accomplish geologic goals and to meet design requirements. During the period, geologic supervisors, engineering supervisors, mud supervisors and supervisors for test operations designated by the RIPED played vital roles in bidding processes for geologic logging and drilling operations. By selecting the optimal team for exploration operations, close cooperation could be established with the successful bidder for oilfield services.

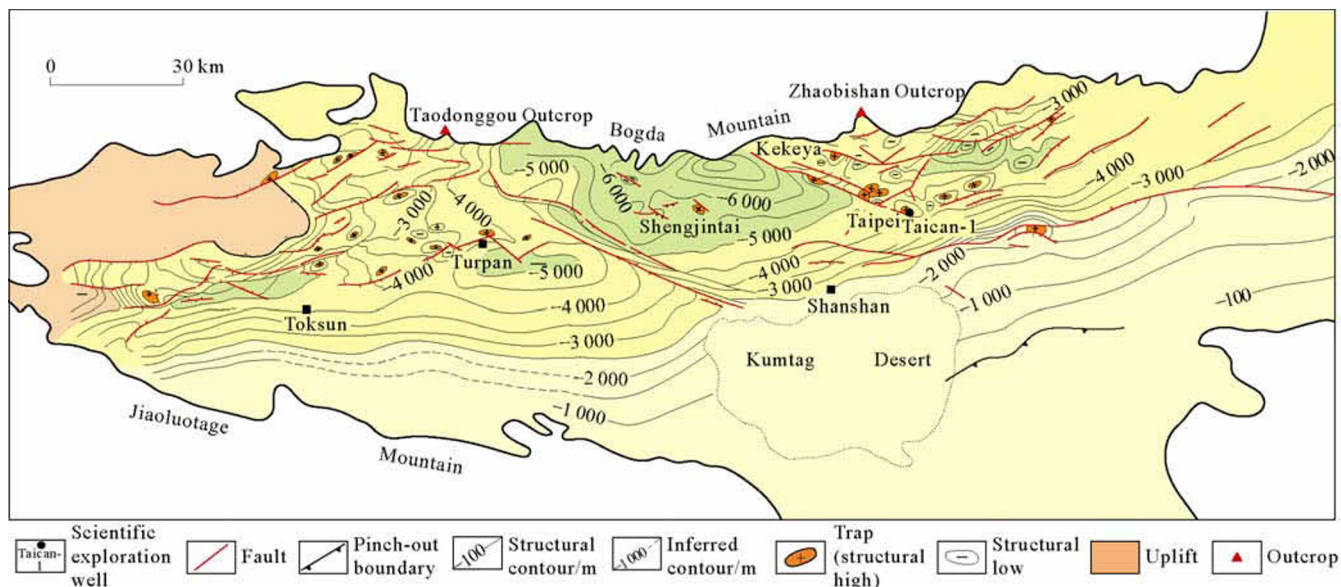


Fig. 3. Structural map of the Tj seismic reflection layer in the Turpan-Hami Basin (Generated in accordance with Reference [2]).

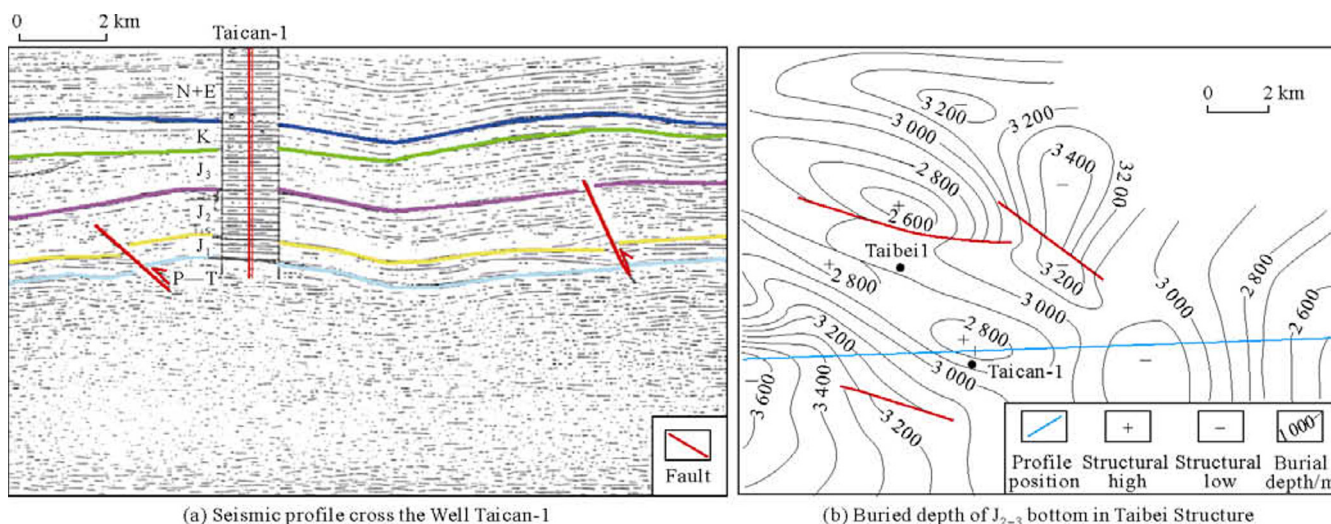


Fig. 4. Seismic profile cross the Well Taican-1 (Generated in accordance with Reference [3]).

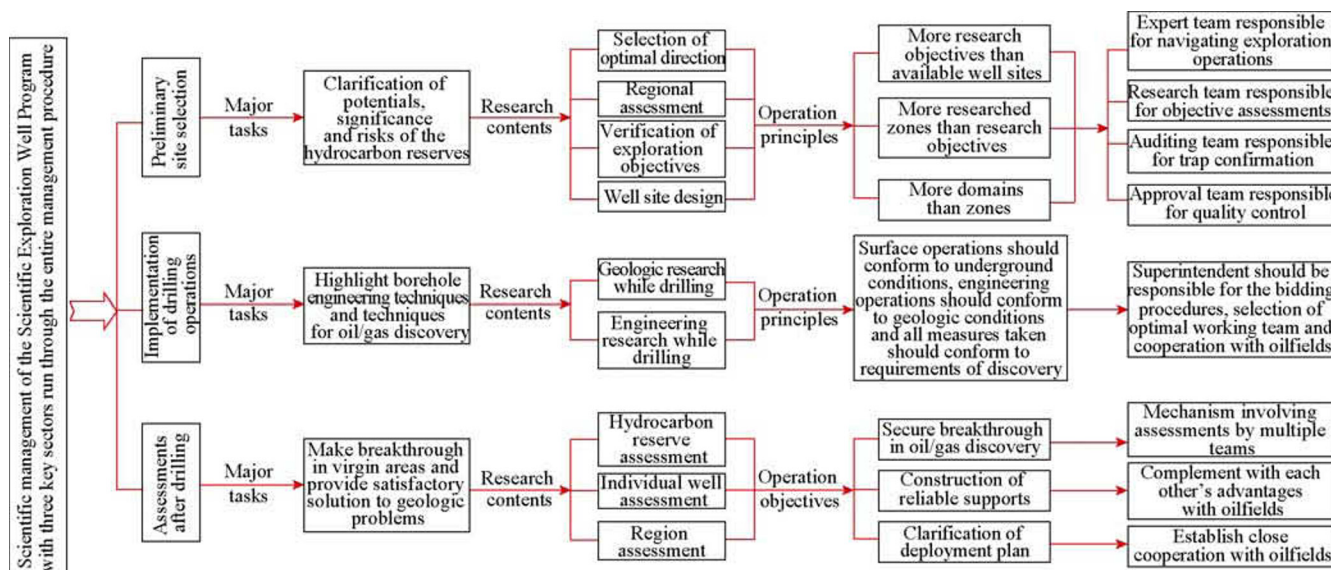


Fig. 5. Workflow for scientific management over the Scientific Exploration Well Program with “Three key sectors run through the entire procedure”.

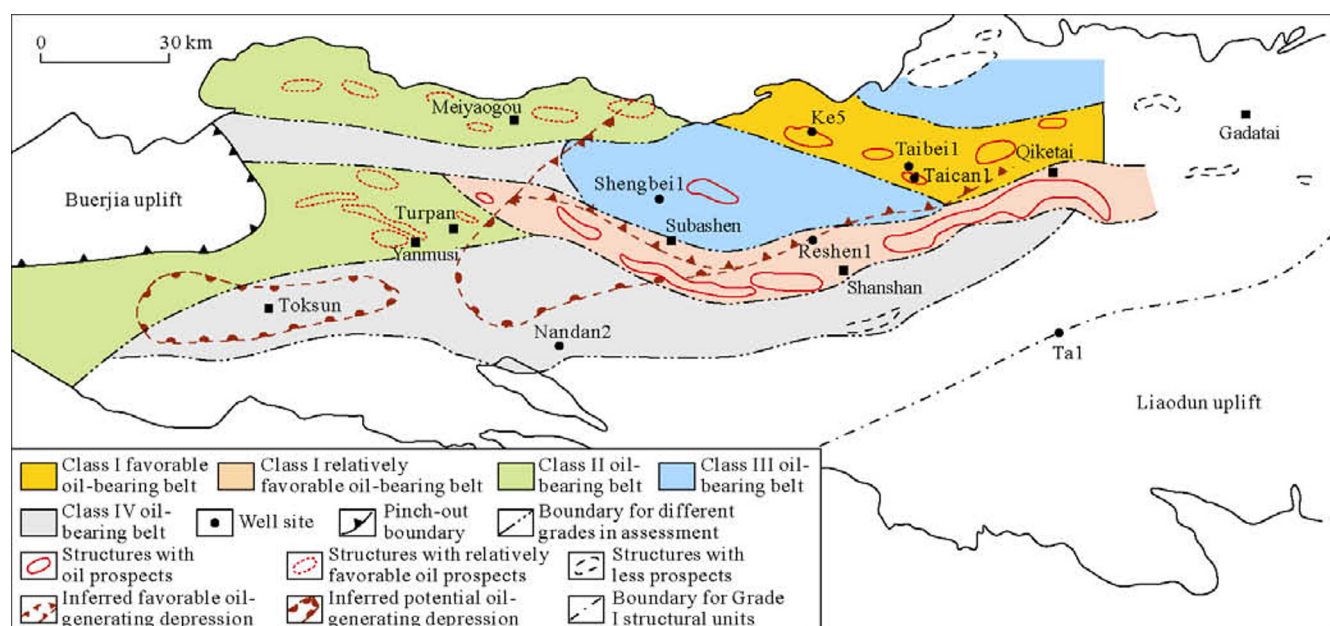


Fig. 6. Favorable oil-bearing zones and traps in the Turpan Depression (Generated in accordance with Reference [2]).

The third key sector involves post-drill assessment and area analyses. With drill sites accurately pinpointed and with suitable borehole techniques deployed, proper assessments and detailed tests in post-drill period are necessary to verify the existence of oil/gas fields penetrated. Major tasks in this stage include breakthroughs in oil/gas exploration in the new areas and solutions to key geologic concerns. Assessments for hydrocarbon reservoirs, stratigraphy and palaeontology, sedimentary, reservoirs, source rocks, hydrocarbon accumulation and other aspects were performed together with regional assessments for concerned areas to provide reliable foundation for future exploration operations. During this stage, the Scientific Exploration Well Program Management Team determined hydrocarbon reservoirs in accordance with different opinions. In addition to assessments for hydrocarbon potentials obtained by logging and well logging data acquired on site, those obtained by the logging companies and by Logging Team of Geology Department of RIPED were also considered. In addition, RIPED invited experts for logging data interpretation to perform relevant assessments as well. For example, in the Well Taican-1, data acquired in the first pay zone logging and the second logging during completion were used to determine hydrocarbon reservoirs. In addition, these data were also used to highlight the OWC. In addition to determine major oil/gas-bearing formations, these data provided reliable foundation for preliminary calculation of hydrocarbon reserves (Fig. 7). Geologic reserve in the trap calculated by using the technique and relevant structural map was  $(2\,385\text{--}5\,049)\times 10^4$  t. With hilly structures in northwestern parts considered, total geologic reserve within the trap can be up to  $10\,155\times 10^4$  t. Eventually, the ultimate productivity achievable was determined to be  $(50\text{--}100)\times 10^4$  t<sup>[15]</sup>. The proven oil reserve in the Shanshan Oilfield was  $4\,187\times 10^4$  t and that of the Qiuling Oilfield was  $5\,405\times 10^4$  t. Total reserve in these two oilfield was  $9\,592\times 10^4$  t. It can be seen that oil reserves were pre-

dicted accurately and reliably with only one exploration well available. In addition to assessments for individual wells, advantages of oilfields were fully taken to establish reliable foundations in formation lithology, paleontology, sedimentation, reservoir and hydrocarbon source rocks. As far as regional assessments were concerned, close cooperation was established with oilfields to clarify exploration objectives for future operations.

Proper coordination of the above three sectors was essential for successful implementation of the Scientific Exploration Well Program. In fact, failure of any of these three sectors may lead to failure of the entire program. Consequently, multi-disciplinary coordination and team spirit could be considered as foundation for the Program. All these 14 wells can verify these practices were absolutely necessary to enhance success rates and to achieve objective of “drill one well to gain understanding to conditions of the entire area”.

## 2.4. Perseverance exploration

Upon completion of drilling operations, the Scientific Exploration Well Program Management Team took advantages of RIPED to organize relevant logging and geologic experts to assess hydrocarbon potentials carefully. Later, trial production operations were performed in identified layers. Furthermore, comprehensive assessments for individual wells and sequential in-depth regional reviews were conducted to further clarify directions and principles for future exploration operations. These practices are essential for successful implementation of the Scientific Exploration Well Program. It was especially true during the period with no breakthrough during execution of the Scientific Exploration Well Program. At that time, different opinions were generated to the Program by different parties. Under such circumstances, staffs engaged in the Scientific Exploration Well Program maintained confidence and meticulous spirits to relevant works because they believe that

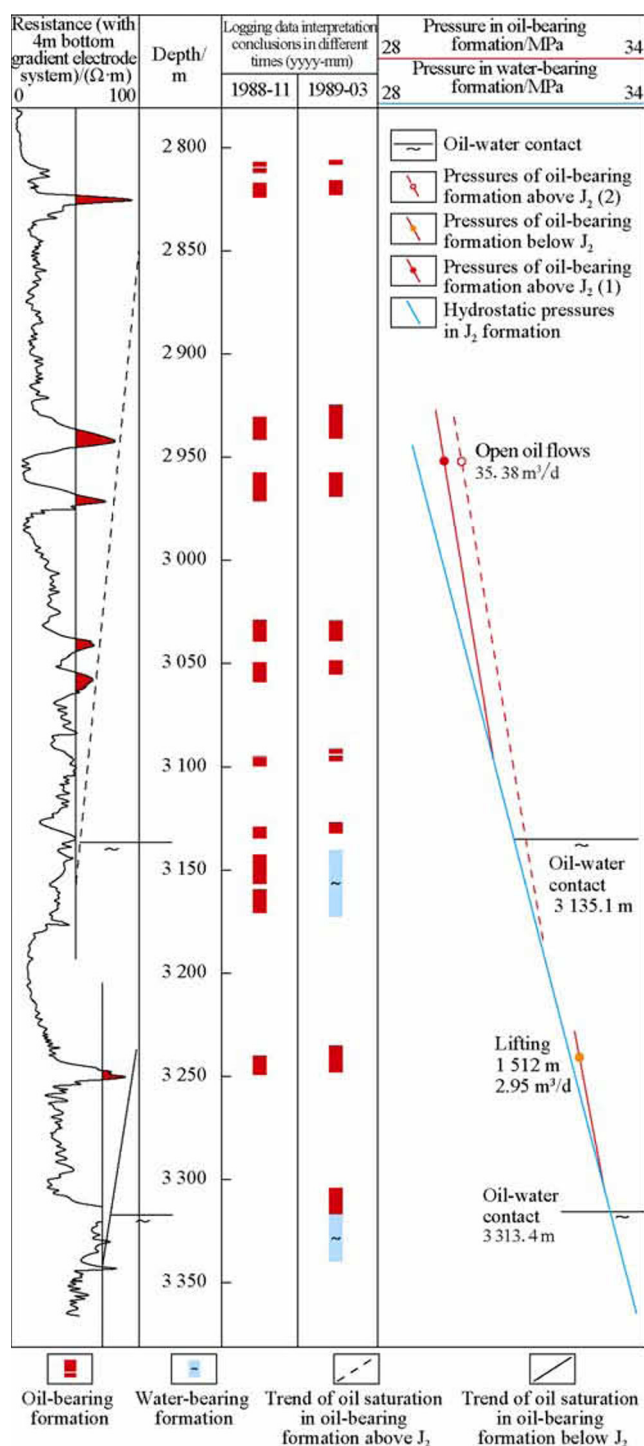


Fig. 7. Predicted oil-water system in Jurassic formation in the Well Taican-1 (Generated in accordance with Reference [15]).

major breakthrough could be achieved only through deployment of scientific techniques, active attitudes, innovation and selfless sacrifices. In fact, the Well Taican-1 was successfully completed under the guidelines of innovative understandings, techniques and management. Through the well, complete data were acquired related to geology, geochemistry, paleontology, seismic data, drilling, logging, DST, trial production and lab tests to establish complete geologic profiles. Through post-drill assessments, hydrocarbon potentials in Mesozoic formations were determined preliminarily. In addition, pay

zones of industrial values, together with their productivity and total reserve in the Taibei Structure have been clarified. All these practices established reliable foundation for deployment of exploration operations in the basin and the Jurassic formations in Northwestern China on the whole. Generally speaking, objectives for drilling of such scientific exploration wells have been achieved successfully.

### 3. Accomplishments and importance of the Scientific Exploration Well Program

Successful implementation of the Scientific Exploration Well Program not only expanded oil/gas exploration in Jurassic formations in Northwestern China and natural gas exploration in Lower Paleozoic carbonate formations in North China, but also promoted confidences in explorations in multiple zones. In addition, the Program may provide reliable theoretical foundation and technical supports for exploration in new zones and for risk exploration.

#### 3.1. Accomplishments of the Scientific Exploration Well Program

After 15 years of delicate organization and hard works, the Scientific Exploration Well Program Team drilled 14 wells to explore Jurassic formations in Northwestern China, natural gas in Paleozoic formations, buried hill and deep structures in the Bohai Bay, marine formations in south China, Mesozoic formations in western China and other major areas for hydrocarbon explorations. In addition to provide satisfactory solutions to geologic concerns, the Program explore a large number of “new areas, new formations and new domains” to establish confidences in exploration of some virgin areas. It is worth noticing that some scientific exploration wells with favorable oil/gas shows and low-productivity oil/gas flows because reliable foundation for consequential breakthroughs in hydrocarbon exploration. Such wells include the Well Gaoke-1, the Well Jiucan-1 and the Well Qincan-1.

##### 3.1.1. Expansion of new zones for hydrocarbon exploration in Jurassic Formation in Northwestern China

The Well Taican-1 and the Well Lengke-1 were drilled to explore Jurassic formations in Northwestern China. The Well Taican-1 encountered industrial oil flows in Jurassic formations for the first time in the Turpan-Hami Basin. At the same time, breakthroughs ushered in by the Well Taican-1 not only lead to discovery of the Tuha Oilfield (with oil reserve of  $26\,651 \times 10^4$  t and natural gas reserve of  $649 \times 10^8$  m<sup>3</sup> in Jurassic formations), but also promoted exploration in Shanji (with proven oil reserve of  $3\,125 \times 10^4$  t and natural gas reserve of  $30 \times 10^8$  m<sup>3</sup> in Jurassic formations), Santanghu (with proven oil reserve of  $4\,842 \times 10^4$  t in Jurassic formations), Kuqa (with Jurassic as the source of natural gas and with proven reserve of  $5\,524 \times 10^8$  m<sup>3</sup> in Cretaceous formations), Qaidam (with Jurassic formations as source of natural gas, and with proven oil reserve of  $775 \times 10^4$  t and natural gas reserve of  $124 \times 10^8$  m<sup>3</sup> in Tertiary formations of the Nanbaxian Structure), Junggar and

other basins with satisfactory exploration efficiency.

The Well Lengke-1 encountered high-quality oil-generating rocks with thickness of 700 m in Jurassic formations<sup>[16–17]</sup>, and accordingly, significantly enhanced hydrocarbon generating potentials of Jurassic formations. In addition, confidences have been gained for exploration in northern edges of the Qaidam Basin. Since these areas contain under-developed reservoir formations, the ideal combination was determined to be generation from below and preservation in upper formations according to relevant assessments. These conclusions effectively promoted discovery of Tertiary condensate gasfield in Nanbaxian and natural gasfields in lithologic formations of Mahai Uplift. Recently, new discoveries have been made in Niudong Area. The Niudongdongping Gasfield and Dongping Gasfield with total natural gas reserve of  $519.14 \times 10^8 \text{ m}^3$  were discovered.

### 3.1.2. Expansion of natural gas exploration to Lower Paleozoic formations in North China

The Well Shancan-1 and the Well Qincan-1 were drilled to explore natural gas in Paleozoic formations in North China. The Well Shancan-1 made major discovery of natural gas reserves in carbonate rocks in the Ordovician Majiagou Formation. In addition to discovery of the Jingbian Gasfield, the Well directly promoted exploration and discoveries in the Shaanganning and nearby areas. After prolonged expansion, large-scale gasfields have been found in upper members of the Majiagou Formation. In addition, natural gas accumulations with significant scales were also discovered in middle and lower members of the Majiagou Formation<sup>[18–20]</sup>. Up to the year 2014, Majiagou Formation was determined to contain proven natural gas reserve of  $6.547 \times 10^8 \text{ m}^3$ . Generally speaking, a major gas-bearing area with reserves of thousands of billion cubic meters has been established.

The Well Qincan-1 encountered Ordovician weathered shells with poor preservation conditions. At the same time, favorable gas shows have been observed in Carboniferous-Permian coalbed formations. With low productivity observed in trial production, significant potentials for Carboniferous-Permian CBM have been identified through assessments. After the Well, the Qinshui Basin experienced continuous exploration and development operations for over 10 years. Currently, the area is one of key zones for exploration and development of CBM.

### 3.1.3. Exploration for natural gas in marine formations of south China

Based on comprehensive researches and consideration of marine formations in southern China, the Well Shengke-1, the Well Wuke-1 and the Well Gaoke-13 were deployed in one batch. All of these three wells encountered favorable oil/gas shows. The Well Gaoke-1 encountered low-productivity oil/gas flows in Sinian formations during DST. No breakthrough has been achieved at the time due to restrictions presented by broken casing and other unfavorable engineering

conditions. But the Well preliminarily highlighted bright prospects in exploration operations in palaeo-uplifts in central parts of the Sichuan Basin. Recently, the large scale Anyue Gasfield with natural gas reserves of trillions of cubic meters has been found through risk exploration<sup>[21–24]</sup>. At present, productivity of  $110 \times 10^8 \text{ m}^3$  has been established with extremely high economic benefits. The Well Wuke-1 encountered low-productivity natural gas flows in Silurian formations. Though these formations have poor physical properties, more confidences have been gained for natural gas exploration in these formations. Recently, Jiaoshiba in Fuling, Weiyuan, Changning and several other large-scale shale gas reserve areas have been discovered in the Silurian Longmaxi Formation of the Sichuan Basin<sup>[25]</sup>.

### 3.1.4. Expansion of Mesozoic new zones in West China

The Well Jiucan-1, the Well Shanke-1, the Well Yingke-1 and the Well Qingke-1 were drilled to explore Mesozoic formations in new zones in Western China. The Well Jiucan-1 encountered low-productivity oil flows in medium and low Cretaceous formations. Consequently, the Jiudong Depression was confirmed to have bright prospects for oil/gas exploration. Though no fracturing operation has been performed due to deformation and breaking of casing induced by improper completion technique, the Well established reliable foundation for hydrocarbon exploration in the area. In the year 2000, the Well Chang-101 drilled southwest of the Well Jiucan-1 encountered high-productivity oil/gas flows. Later, the Jiudong Oilfield was discovered. Up to the year 2015, the Oilfield has accumulated oil production of  $47 \times 10^4 \text{ t}$ .

The Well Shanke-1 encountered light oil with daily production of  $11.48 \text{ m}^3$  in Triassic formations (4 705–4 713 m) for the first time in the Taibei depression. In addition to verify the Permian oil originated from the Taibei depression, the Well indicated that Triassic formations between the Lukeqin heavy oil belt and the Shanshan Structural Belt have bright prospects in exploration<sup>[26]</sup>. The Triassic Kelamay Formation in the area contain proven oil geologic reserve of  $10.991 \times 10^4 \text{ t}$ , producible oil geologic reserve of  $49 \times 10^4 \text{ t}$  and possible geologic reserve of  $2.011 \times 10^4 \text{ t}$ . Up to the end of 2014, total production capacity of  $125.5 \times 10^4 \text{ t}$  and overall oil production of  $285.1 \times 10^4 \text{ t}$  have been achieved.

The Well Yingke-1 encountered formations with properties significantly different from expectation. With complex downhole conditions and poorly developed reservoir formations, no proper trial production has been performed in the Well. In addition, the Well Qingke-1 failed to reach target formations due to complicated engineering conditions. These two wells reflected complications in exploration of Mesozoic formations in Western China. More researches, assessments and exploration operations are required in the future.

### 3.1.5. Clear understanding to difficulties in geologic and engineering techniques in some areas

The Well Gaocan-1 and the Well Haoke-1 were deployed to

explore in buried hill and deep formations in the Bohai Bay Basin, the Well Gaocan-1 encountered new oil/gas layers in Tertiary and Jurassic formations. With no weathered shell observed in pre-Tertiary formations, no trial production has been performed due to insufficient understanding to physical properties of shallow formations. The Well Haoke-1 encountered deep reservoir formations with poor reservoir physical properties. It can be seen that physical properties of deep formations and relevant engineering techniques may present restrictions in exploration of such formations. The Well Chucan-1 deployed for exploration of Jurassic formations in the Chuxiong Basin failed to reach pay zone due to thicker formations encountered than design. Assessment conclusions show more researches are required to determine reservoir formation conditions in the area. The Well Shengke-1 deployed in Jurong Depression of Lower Yangtze Area also failed due to complicated structural and reservoir conditions. It can be seen that fine seismic data processing and geologic interpretations are required for structural zones with complicated conditions in southern China. In the future, cares shall be taken for discovery of primary hydrocarbon reservoirs in areas with relatively stable structures.

### 3.2. Significance and roles of scientific exploration wells

Assessments for new areas through the Scientific Exploration Well Program provided favorable zones, belts and exploration targets for exploration for the “Ninth Five-year Plan Period” in 1997. Beside drilled scientific exploration wells, Scientific Exploration Well Program also involves a large number of favorable belts and exploration targets through researches and assessments over multiple key zones and objectives nationwide through cooperation with relevant institutes (Fig. 8). The Wumaying Buried-hill Structure recommended to relevant oilfields for exploration made major discoveries. Accordingly, natural gas exploration operations in the Dagang Oilfield were hugely promoted. In addition, the Well Pushen-8 encountered industrial oil/gas flows and expanded new zones for exploration in the Zhongyuan Oilfield.

Secondly, the Program provided future preliminary exploration and risk exploration operations with a large number of favorable zones and targets. Up to the year 1999, 14 favorable zones, including the Zhundong and Chepaizi in the Junggar Basin, Tadong and Keping in the Tarim Basin, and the Tiegesumiao in the Ordos Basin, together with 12 potential targets,

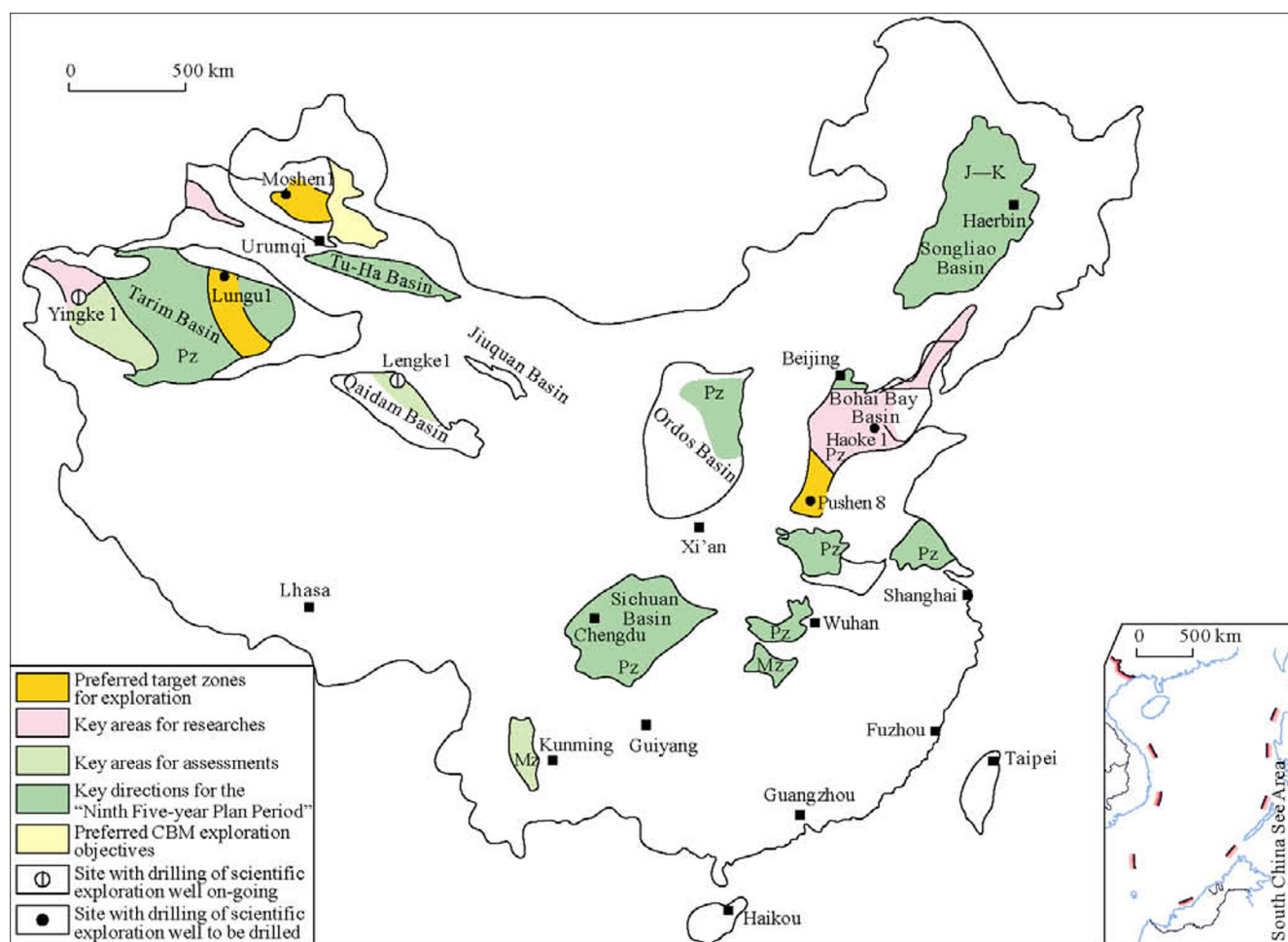


Fig. 8. Distribution of new exploration areas and deployment of exploration targets of the Scientific Exploration Well Program during the “Ninth Five-year Plan Period” (Generated in accordance with Reference [27]).

including Harjin Structure, Gushan Structure, Yubei Structure, Sicundian Buried-hill and Tazhong abnormal Structure have been identified through relevant researches. With termination of the Scientific Exploration Well Program, no more drilling or exploration has been conducted in these favorable zones and targets, but some of them may serve as key zones and potential targets for future exploration and research operations to make breakthroughs and discoveries. Such targets include the volcanic gas zones in Changling Fault in deep layers of the Songliao Basin<sup>[26,28]</sup>, Upper Paleozoic natural gas reservoirs in Sulige Structure of the Ordos Basin<sup>[29]</sup>, natural gas reservoirs in the Junggar Basin<sup>[30]</sup>, Yubei-Yingyer Heavy Oil Reservoir in Huoyanshan Structural Belt of the Turpan-Hami Basin<sup>[31–32]</sup>.

In addition, the Scientific Exploration Well Program clarified exploration domains and key development points for natural gas of various types in China (Fig. 9). In fact, the Program highlighted a large number of favorable zones and targets for medium to long term oil/gas exploration in China and may provide vital supports for rapid development of natural gas for about one whole decade.

#### 4. Core value and significance of the Scientific Exploration Well Program

From the very beginning, the Scientific Exploration Well

Program carried the task of making breakthroughs of strategic importance. Core of the Scientific Exploration Well Program lies in the selection of well sites with great foresight. In fact, the Program is characterized by two major attributes. The first attribute is the scientific nature: before initialization of drilling operations, regional geologic conditions have been studied comprehensively and systematically to clarify target zones and drilling objectives. With consideration to various real-time data acquired during drilling, available data in the area should be analyzed systematically to guide drilling operations. Upon completion of drilling operations, multidisciplinary researches and comprehensive assessments should be conducted to generate guidelines for deployment of wells in the future; The second attribute is initiative: from well site selection, the Program focused on key areas with objectives locked in new areas, new formations and new zones to seek breakthrough in large-scale reserves. The name of the Scientific Exploration Well Program can accurately reflect the scientific and exploration nature of the Program.

Significance of the Scientific Exploration Well Program lies not in drilling of one well, opening up of a new field or acquisition of new data, but in elaboration of exploration potentials of relevant scientists and in construction of a brand new package of management system and standards. In fact may

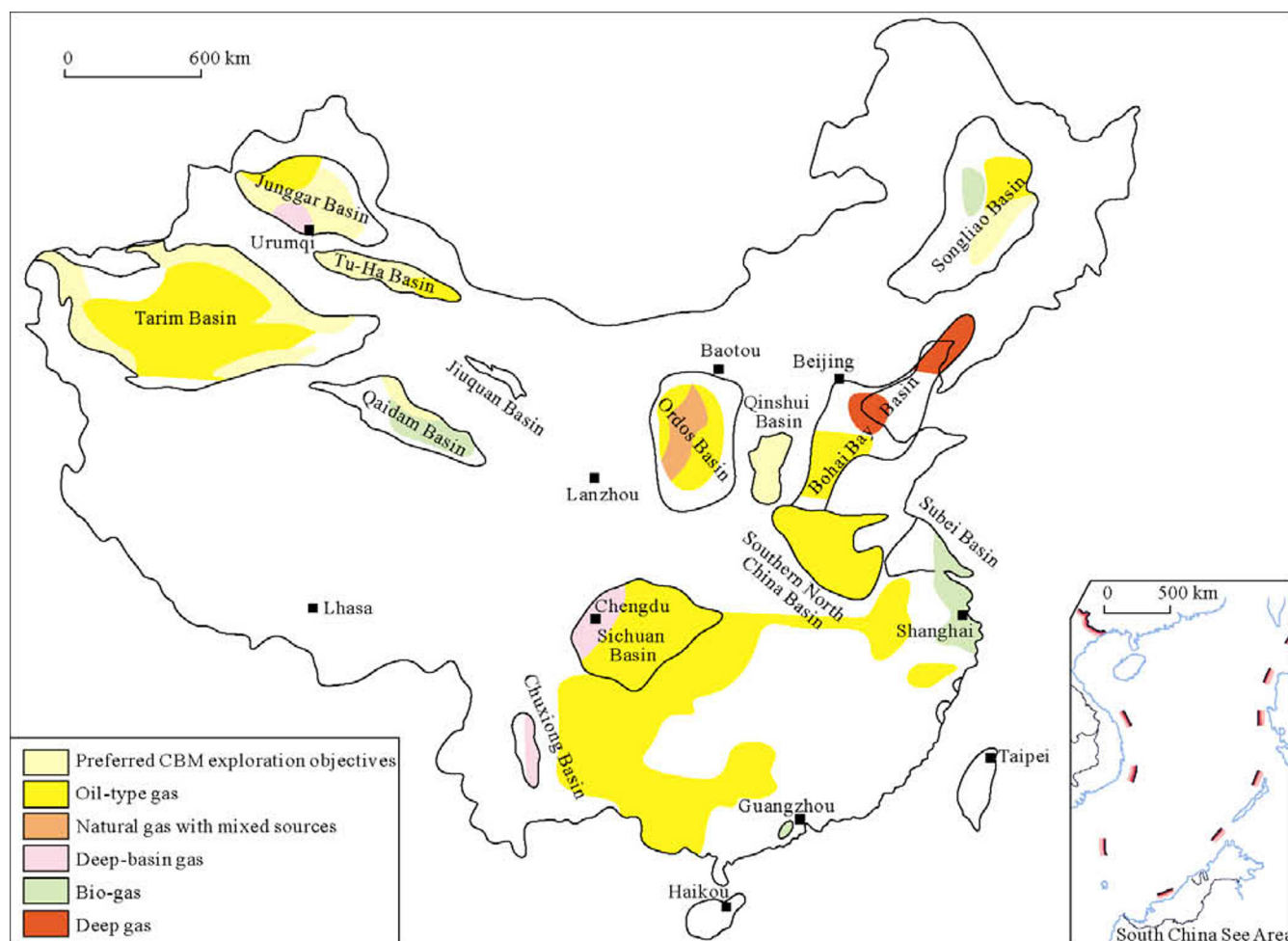


Fig. 9. Distribution of zones for exploration of natural gas of various types onshore China (Generated in accordance with Reference [27]).

oilfields learnt experiences of the Scientific Exploration Well Program to execute them in researches in new domains, selection of well sites, post-drill assessments and management of exploration wells. Five years later, based on the changes of exploration situations, CNPC will adopt successful experiences of the Scientific Exploration Well Program in 2005. The new program made several major discoveries and breakthroughs and contributed significantly to ensure development of oil/gas industry and energy safety of China.

## 5. Conclusions

Through implementation of the Scientific Exploration Well Program, new domains, such as Jurassic formations in Northwestern China, Lower, Paleozoic natural gas in North China, have been explored to promote development of oil industry in China. In addition to drive exploration in virgin areas in late chapters of last century, the Program strengthened confidences in exploration for natural gas in carbonate rocks marine formations in south China, natural gas in deep layers of the Songliao Basin, Jurassic formations and Yingxiongling Complex Structural Zones On the northern edge of the Qaidam Basin, Triassic—Permian, Santanghu Basin Triassic—Permian formations in the Turpan-Hami Basin, Cambrian formations in the Tarim Basin, deep layers and buried-hill structures in the Bohai Bay Basin, together with other key areas.

Through implementation of the Scientific Exploration Well Program, a new mode for hydrocarbon exploration characterized by CNPC headquarters to carry investment risks, RIPED proposed exploration objectives and cooperated with relevant oilfields on conduct drilling operations. Lean management principles have been closely observed throughout the entire process of program implementation. It was determined that scientific selection of well sites and areas with potentials for breakthroughs with great foresight shall be taken as the permanent goal because these selections are vital to secure major discoveries in hydrocarbon exploration. The Program has significant practical and historical significance not only because rich experiences have been gained through implementation of the Program, but also because the Program paved a new path for exploration of virgin areas and prepared a large number of favorable zones and targets to secure strategic reserve of oil and natural gas in China.

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