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# Key Technologies for Oil and Gas Development from Deep Carbonate Fractured-Vuggy Reservoirs

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**ABSTRACT**

China possesses abundant oil resources with a magnitude of 40.66×108 t of geological reserves contained in carbonate fractured-vuggy reservoirs. Fractured-vuggy reservoirs have become one of the most important fields in China's oil and gas exploration and development, with the potential to markedly increase its explorable oil reserves and oil production. However, highly efficient development of this kind of reservoir can present a major challenge due to its large buried depth, i.e., larger than 6500 m, low accuracy in describing the carbonate fractured-vuggy body, and co-existence of diverse flow patterns. To address these issues, numerical models have been utilized to predict oil production and interporosity flow between water injection wells. After an approximately 20-year period of research and practice, key technologies for oilfield development have been proposed, including high-accuracy detection of multi-scale fractured-vuggy bodies, karst geological modeling, precise prediction of water flooding, and sour gas injection. In addition, major advancements have been achieved in numerous aspects, such as implementing a 91.7% production rate in each new well of the Tahe Oilfield, maintaining high production of 5.5 million t per year over a long period of time, and discovery of one billion t of oil in the Shunbe Oilfield with consequent massive and rapid production.

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## Introduction

China is rich in marine carbonate oil and gas resources, in which the area of carbonate sediment is approximately 450×104 km2, with approximately 358×108 t of oil and gas resources. In September 1984, the first major breakthrough was achieved in the Paleozoic marine carbonate reservoir in China, which experienced a prolific hydrocarbon flow in the SC2 well, located in the northern Tarim Basin. This achievement has become an important milestone in the history of Chinese oil and gas exploration history [1]. In 1990, the S23 well assisted to find China's first ancient superdeep marine oversize oilfield in the Tahe Oilfield [2]. To promote the development of the Tahe Oilfield, the world's largest deep carbonate fractured-vuggy reservoir was built in 1997. The annual output of oil and gas of this fractured-vuggy reservoir has reached 900×104 t, demonstrating the great success of Chinese marine carbonate reservoir development in terms of both theory and technology. The formation of carbonate reservoirs has become a major foundation of China's oil and gas exploration and development, potentially dramatically increasing its explorable oil reserves and thus oil production. Compared with carbonate reservoirs abroad, China's carbonate reservoirs feature larger burial depth, longer hydrocarbon accumulation history, and more complex geological conditions [3]. These features bring the following major challenges to reservoir development: (1) difficulties in detecting, identifying, and describing multi-scale fractures, discrete fractures, and vuggies; (2) rapid decline of oil production immediately after water breakthrough; (3) existence of channeling flow of water between injection wells via fissures, which makes the design of well spacing for injection-production wells and efficient displacement markedly difficult; and (4) low recovery efficiency, in which the calibration recovery percentage is only 15.0%.

After nearly a 15-year period of research and practice, key technologies for oilfield development have been established, including detection of multi-scale geophysical fractures, geological modeling of three-dimensional vuggies, numerical simulation of the coupling of free flow and seepage flow within reservoirs, water-flooding modeling, and targeted acidizing technology. Indeed, these achievements have bridged the technical gap between China and other countries. They have also promoted realization of the Tahe Oilfield annual output of oil production to more than 5.5 million tons, with a calibrated recovery efficiency of up to 21%.

## Geological Characteristics and Development Rules of Fractured-Vuggy Carbonate Reservoirs

### Geological Characteristics of Fractured-Vuggy Carbonate Reservoir

Carbonate fractured-vuggy reservoirs are mainly developed in the middle and lower Ordovician Yijianfang Formation dominated by micrite limestone and grain limestone, which are very thick and massive, and the matrix has no storage and permeability. The reservoir space is diverse, the reservoir type is complex, and the heterogeneity is very strong. The karst caves formed along the high-angle weathering fractures and structural fractures are the main reservoir space. The distribution of fracture-cave reservoirs is discontinuous and the scale changes greatly. The development and distribution of reservoirs are not controlled by sedimentary facies, but by faults and karstification. The main reservoir spaces include pores, fractures and large karst caves.

The pores include intercrystalline pores and intercrystalline dissolved pores, intergranular pores and intergranular dissolved pores, moldic pores, intragranular dissolved pores and other types, with diameters ranging from several microns to hundreds of microns, which are the common reservoir space of Ordovician reservoirs in Tahe. Intercrystalline pores and intercrystalline solution pores are mainly developed in the leopard limestone section of dolomitization, and the phenomenon of crude oil seepage can be seen. Fractures mainly refer to structural fractures, pressure-dissolution fractures and dissolution fractures, which are the effective reservoir space for active oil and gas shows in the area. Structural fractures are mainly shear fractures, followed by tensile fractures, and vertical fractures and microfractures are the most developed. Most of the cracks formed in the early stage have been filled or semi-filled with calcite, argillaceous or asphalt, and the cracks with different occurrences in multiple stages in local areas intersect with each other to form network cracks: Most of the pressure-dissolved fractures (stylolites) are parallel to the bedding surface and serrated, and most of the stylolites have been filled or corroded by calcite, argillaceous or asphalt to varying degrees. According to the fluorescent thin section data, part of the stylolites has strong fluorescence display, and there is an effective reservoir space.

Dissolution fractures are mainly caused by dissolution expansion and transformation along the early fracture system, which are very developed in the area. The fracture width is generally greater than Imm, showing irregular dissolution expansion of the fracture surface and growing along the fracture surface wall. The fracture is a secondary reservoir space, and the matrix part has no oil storage capacity. The reservoir permeability is mainly determined by the cavernous reservoir. The largest full-filled cave found on the core is 20 m in height, and the largest full-filled cave identified by logging data is 72 m in apparent height, of which the largest unfilled cave is 30 m in apparent height. The development of fracture-cave body is mainly controlled by fracture and structural deformation, and the fracture-cave body developed along the fracture zone controls the distribution of oil and water, which is distributed in the form of strip and tree in the plane. The drilling along the fracture zone has more venting and leakage, and the single well has high productivity. The oil-bearing karst cave section is mainly distributed in Yijianfang Formation.

### Development Law of Fractured-Vuggy Carbonate Reservoir

The fractured-vuggy reservoirs in Tahe Oilfield are characterized by discrete distribution, coexistence of multiple flow modes, great difference in fluid passing capacity in different flow spaces, complex fluid flow rules, no uniform oil-water contact, normal pressure system and normal geothermal gradient. It is a deep and low saturated oil and gas reservoir formed in multiple periods from light oil to medium oil to super heavy o.

(1) Reservoir development law of fault-controlled reservoir

The formation of fault-controlled reservoirs and the accumulation of oil and gas are mainly controlled by faults. The development of reservoirs, the degree of lateral and vertical connectivity and the degree of oil and gas enrichment are different in different orders of faults. Influenced by the fault development mechanism, the development of fault-controlled reservoir is easier to form polarization, that is, the main fault has a high degree of fragmentation, the reservoir space is more developed, and the oil and gas is easier to charge, while the development degree of the associated secondary fault or lower-order fault reservoir is significantly reduced. Due to the distribution relationship between faults, the development of the main and associated fault reservoirs will be greatly different. This is quite different from the relatively small plane difference caused by the lateral connection adjustment of weathering crust and karst.

The reservoir body of the fault-controlled reservoir body oil reservoir is developed along the fault zone, the trend is segmented and the vertical is separated. The reservoir body on the main fault zone is developed, and the connectivity is good along the direction of the fault zone and vertically. Affected by the transverse segmentation of the fault-controlled reservoir body, the controlled reserves of the reservoir body unit are smaller than those in the weathering crust karst area. Affected by the water energy, the initial capacity of oil wells is 40-200 tons per day. However, the bottom water breakthrough has a great impact on the decline of oil wells; The energy of the secondary fault zone is relatively weak, the reservoir body development scale is small, and the connectivity is poor, the formation energy is insufficient, and the rapid depletion of elastic drive energy leads to the decline of productivity. Water injection to the secondary fault oil wells has slowed down the decline, but due to poor connectivity and relatively limited water injection scale, the impact on the overall decline rate of the fault-controlled reservoir is relatively slow.

### Development Law of Composite Karst Reservoir

The compound karst area has the characteristics of weathering crust karst, develops karst types such as surface layer and ancient channel, and the development degree of reservoir body is stronger than that of karst highland area, and the development scale is larger, but the connectivity of reservoir is relatively poor due to late filling. Therefore, the composite karst area is generally characterized by weak energy and general water activity, so the development characteristics of the karst area are quite different from those of the weathering crust karst area. The development of the reservoir is complex, and the connectivity and energy conditions are quite different, which is between the fault-controlled reservoir and the weathering crust karst.

### Research Status of Development Technology for Fractured-Vuggy Reservoirs at Home and Abroad

In view of the development of fractured-vuggy reservoirs, a lot of research work has been carried out at home and abroad, and the published literature is mainly from the research group. The following mainly investigates the progress of non-research groups, mainly including: In 1997, foreign scholars Dehghani et al. In the simulation of water flooding experiment, in order to simplify the model, fractured-vuggy reservoirs were regarded as macroporous bedrock, and the simulation object of the experiment was carbonate reservoirs In 2004, [4, 5]. Compared the micro-scale of fluid in the macro-scale of porous media to calculate the connectivity of its fractures, which can give a probability value [5]. In the same year, directly pointed out the connectivity pattern of holes in the experimental rock by scanning technique [6]. In 2005, Chen Zhihai, a domestic scholar, put forward the exploitation characteristics of fractured-vuggy reservoirs based on the complex relative relationship among pores, fractures and vugs [7]. According to the production performance curve, the general situation of the reservoir body can be deduced. In 2007, Li Zongyu believed that productivity should be designed according to pipe flow in fractured-vuggy reservoirs [8]. In the same year, Xiunailing also put forward that the flow in fractures of fractured-vuggy reservoirs is seepage, while the flow in karst caves is similar to pipe flow [9].

In the same year, Yang Yu, Kang Yili and others divided the fluid flow units of fractured-vuggy reservoirs according to the pressure change trend, whether there is interference between wells, karst geomorphological characteristics and fluid property differences [10]. In 2009, Wang Diansheng established a mechanism model for numerical simulation, and achieved good simulation results on the basis of a single fracture [11]. In the same year, Zheng Songqing et al. established a flow model that linear and nonlinear flows coexist in fractured-vuggy reservoirs [12]. In 2011, Guo Xiaomei and others studied the seepage mechanism of fracture filling or not through visualization experiments, and the experimental results showed that the water flooding characteristics of conventional sandstone reservoirs were different [13]. In the same year, Wanfang abstracted the three-dimensional data volume from the karst cave model, and through calculation, it was considered that the fracture was the main connecting channel. In 2014, Cao Fei, Zhao Juan and others divided the monadnock into karst and pipeline development type, karst cave and sinkhole development type, supergene planar karst development type and watershed development type according to the differences of structure and karstification [14].

For gas injection development of reservoir, the injection methods of different injection media and different reservoir types are also studied. In 1993, Kantzas et al showed that the density of injected N2 is different from that of oil phase, and the displacement can be achieved regardless of the wettability of the reservoir [15]. In 2000, Zhang Lihui and others concluded that single well gas injection can effectively improve productivity for depletion reservoirs through numerical simulation [16]. In 2006, Wang Qiyao and others carried out a study in Shengli Oilfield in which steam injection was added in addition to N2 injection, and concluded that the best effect would be achieved if the proportion could be grasped [17]. In 2008, Wei Changqing carried out a gas injection experiment on an oil sample in Daqing, and concluded that N2 performed best in gravity flooding [18]. In the same year, foreign researchers Karimaie et al replaced it with CH4 mixed flooding [19]. In 2011, Shadizadeh et al. compared the similarities and differences of N2 and CO2 in the process of carbonate flooding through experiments, and considered that the former was more suitable for immiscible flooding, which coincided with the research conclusions of domestic scholars [20]. Previous studies have enriched the types of gas injection, injection methods, for different reservoirs, as well as the availability of gas sources to give the choice of space, which is conducive to field reference.

It can be seen that the theoretical basis for the study of fractured-vuggy carbonate reservoirs is mostly the theory of multi-porous media seepage. For fractured-vuggy carbonate reservoirs composed of large-scale dissolution pores, caves and fractures, it is necessary to consider the fluid flow mechanism after water and gas injection under the concept of composite media. The discontinuity of medium in fractured-vuggy reservoir is solved by dealing with large-scale fractures and caves.

## Seismic Geophysical Prediction Technology

Complexities of the Tahe Oilfield stem from various types of reservoir burial depth, multi-scale and discrete fractures, vuggies, complicated seismic responses, and multiple solutions of the inverse model, which lead to great challenges in effective reservoir recognition and prediction [21]. Based on diffracted wave separation and high-precision reverse-time depth migration imaging, the internal structure of multi-scale fracture systems can be established through melt-prediction technology [22].

### Diffracted Wave and High-Resolution Image of Reverse-Time Depth Migration

Small scale joints usually lead to weak reflection signals. In this study, we built a diffracted wave separation imaging method based on the earthquake response of the diffraction angle domain to improve the diffraction body in the process of diffraction migration imaging of energy. This approach enables detection of small-scale fracture-vuggy bodies with the reflection phase axis. Based on physical experiments and theoretical analyses, discrepancies between diffracted waves and reflected waves in the direction of propagation may assist to ascertain their different seismic responses within the diffraction angle domain. We establish the method to calculate the diffraction angle in transmission- and diffraction-angle imaging conditions, as well as total diffraction angle deviation. Using the reflection wave diffraction angle range, we also establish a technology for diffracted wave separation and reflected wave fitting through fitting the reflection phase axis of reflected wave elimination. Orthoscopic separation of diffracted wave energy is then achieved. By comparing the two subfigures in Figure 1, it can be seen that the diffraction wave separation method effectively suppresses weathering crust "reflection" energy, and sufficient diffraction energy is maintained to present a small-scale fracture-vuggy with a diffraction body (see the red arrows in Figure. 1).

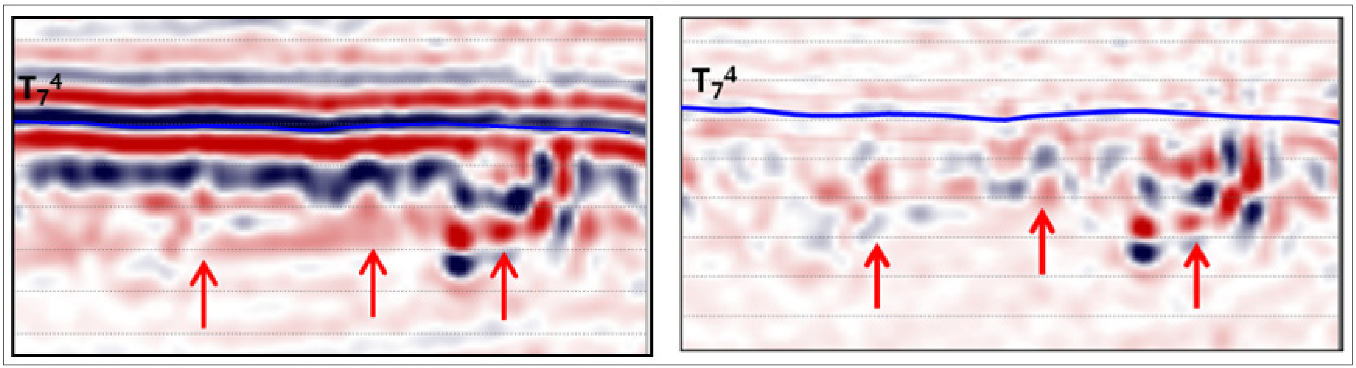

**Figure 1:** Comparison of the effects of (a) RTM full wave field imaging and (b) diffracted wave imaging.

Compared with reflection data, diffraction data reflect more details of geological bodies, and offer a higher resolution in detecting fractured-vuggy bodies. Through comparison of the beaded-reflector amount, diffracted wave data enable us to discern more hidden beaded jewelries than do full wave field data, especially in regions in which the reflection-cover effect is significant. Indeed, it is estimated that the recognition rate of beaded jewelries could increase by approximately 20%. Our research has developed a reverse-time depth migration technique based on the least square method. With the theory of diffraction wave inversion imaging and the 3-D reverse-time migration imaging basis, we proposed a conjugate gradient inversion optimization method and GPU acceleration technology, and developed a 3-D least-square reverse-time depth migration technology. Through multiple iterations, our work could effectively reduce the influence of generalized diffraction factors, such as illumination and absorption, further enhancing the resolution of small-scale reservoirs. Compared with conventional methods, the method of least-squares reverse-time depth migration makes lighting more even, has stronger continuity in the phase axis, and achieves superior convergence performance in beaded reflection. Spectrum analysis reveals that least squares reverse-time depth migration imaging broadens the frequency spectrum to 5 Hz, and therefore augments imaging resolution and improves imaging precision.

### Reconstruction Techniques of Large-Scale Fractured-Vuggy Body

Based on independent research and development, we proposed a novel method to rebuild large-scale fractured-vuggy bodies using prestack cannon-domain frequency division time migration. By integrating the technique of superposition of different frequency energy, we realize a 3-D reconstruction of the internal structure of the fractured-vuggy body. Well log data are used to calibrate the characteristics of collapses and fillings of the fractured-vuggy body. Based on different frequency-bands data collected from prestack CMP preconditioned by the Butterworth filter, we establish different dominant frequency-bands of the prestack data, and finally obtain the prestack time-migration data. In such a way, the quality of prestack data for beaded jewelries can be improved, and post-stack frequency division can be overcome to produce a "signal shock" phenomenon. The low frequency part reflects the cave shape, while the high frequency part reveals the cave's internal details and structural characteristics (Figure. 2). If the high and low frequency energy exhibit good consistency, it can be concluded that each single room water-eroded cave has homogeneous fillings; otherwise, the fractured-vuggy system can be larger, and usually has a complicated internal structure and strong heterogeneity.

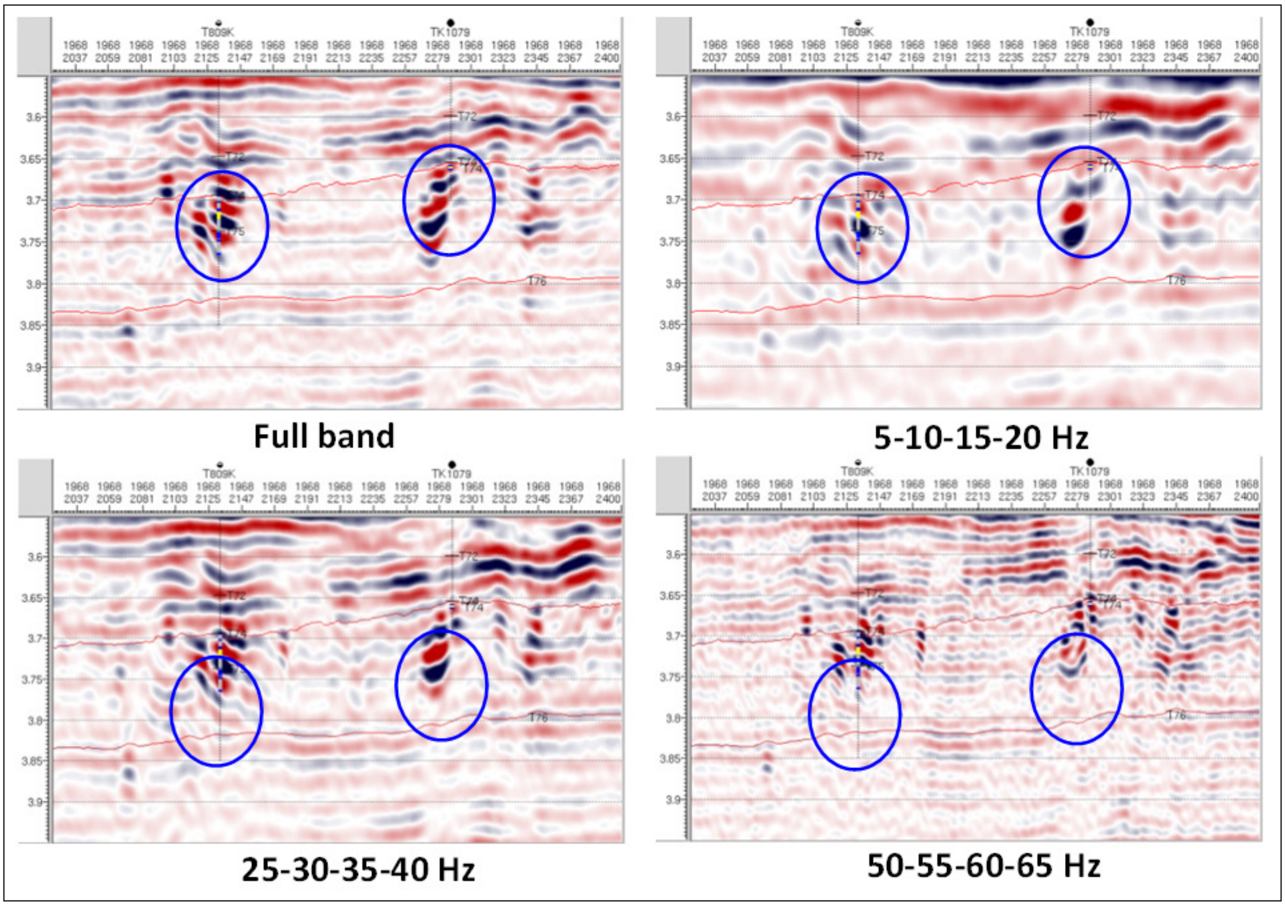

**Figure 2:** Comparison of migration imaging between large-scale fractured-vuggy systems with different frequency.

The reflection coefficient of the odd-even decomposition method is used to increase the ability of the thin bed resolution "contingency" component. The high frequency part of the reflection coefficient inversion component of the reflection coefficient sequence is also utilized. In addition, seismic wavelet convolution data are employed to obtain higher resolution than the original seismic data body. These three efforts cause the seismic data to increase from 25 Hz to 40 Hz, which makes signals of small-scale reservoirs that are suppressed by the weathering crust become more evident. Abnormal responses correspond well to the logging interpretation of fractured-vuggy reservoirs. Indeed, our prediction results show good agreement, i.e., 82.5%, with the log interpretation.

## Prediction Technology for Fault-Controlled Karst Reservoirs

The forward modeling results indicate that the earthquake response of fault karst reservoir distribution width is positively related to the horizontal dimension of the reservoir. The fault-controlled karst reservoir boundary can be identified, but the internal border cannot be identified when the width is less than 100 m. However, the internal border and karst reservoir boundary can be determined when the width is larger than 150 m. By fault karst reservoir and morphological characteristics of stratigraphic-structure enhanced domain prestack processing, gun explanatory processing technology, such as frequency division, and the continuation of spectrum, the fault control reservoir characteristics and formation reflection characteristics of the separation structure are realized, and broken reservoir characteristics are revealed. In addition, through enhancement treatment and structure compression, the inside information becomes richer, the border becomes clearer, and the description effect of the fault karst reservoir increases markedly (Figure. 3).

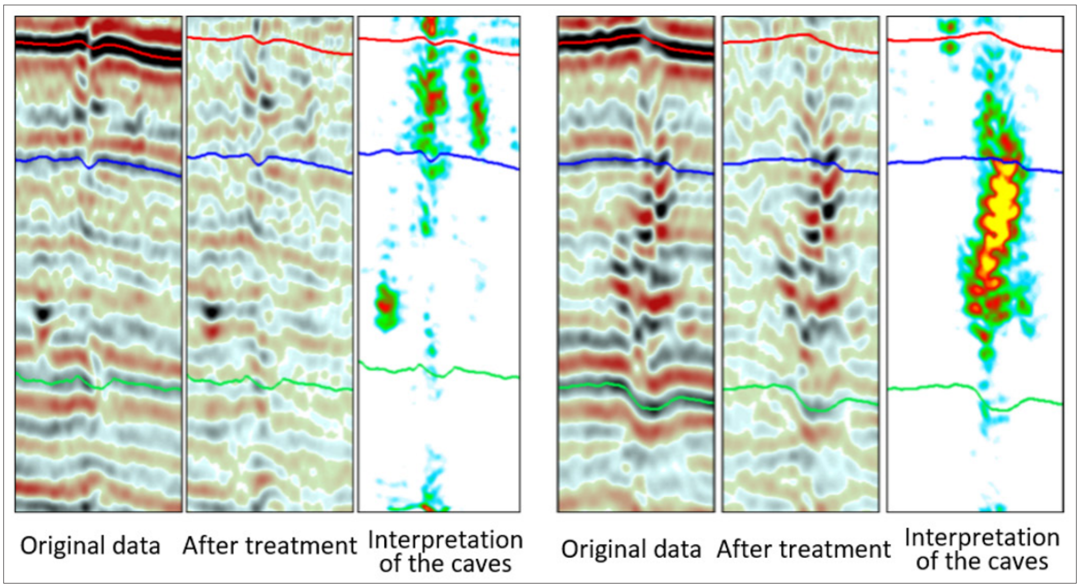

**Figure 3:** Description of fault karst body based on explanatory enhancement processing

Optimization of the structure tensor, waveform decomposition and reconstruction, and certain other processes can effectively depict fault karst reservoir boundary-sensitive attributes. Furthermore, optimization of strong amplitude clustering, impedance class attributes, etc., can describe the broken melt inside of caves as sensitive attributes. It is highly beneficial to select the sensitive properties of the internal structure of the fractured zone. Use of coherence and maximum likelihood will assist to identify trunk fractures. Utilization of the ant traction method could also detect small- and medium-scale secondary fractures. Moreover, use of the medium- and small-scale wave interference detection approach could assist to identify small-scale faults.

## Fractured-Vuggy Oil Reservoir Modeling

Geological modeling of carbonate fractured-vuggy reservoirs can be highly challenging because this kind of reservoir possesses various space types, and presents multi-scale vuggies and fractures with random distributions [23]. We propose a method based on karst facies classification for geological modeling, i.e., multiple constraints to model surface karst reservoirs, multi-point statistical model for ancient rivers' modeling, and targeted carbonate karst reservoir modeling by fault control (Figure. 4). Classification of the reservoir geological model is set up, and then the evolution sequence with a condition assignment method is used to build a comprehensive geological model, effectively improving the accuracy of karst geological modeling [24]. Based on the above techniques, the drilling coincidence rate was improved from 71.1% to 92.7% and the exploitation rate of the reserves increased significantly.

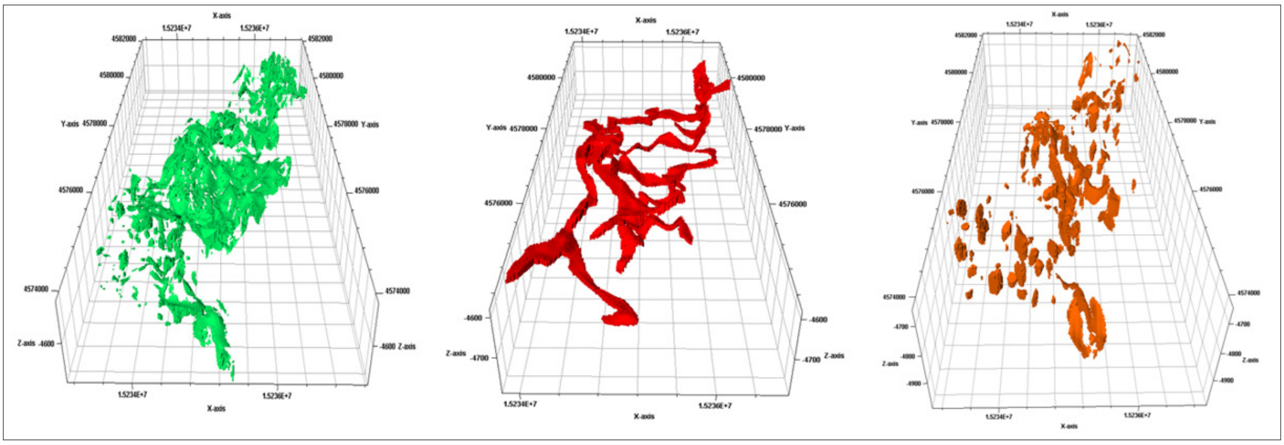

**Figure 4:** Geological models of surface karst aquifers, underground rivers, and fault-controlled reservoirs.

### Geological Modeling of Shallow Carbonate Karst Reservoirs by the Multiple Constraint Method

Surface weathering of carbonate karst reservoirs is mainly located near peak hills, including dissolution karst caves along bedding planes, dissolution cracks within layers, fault-controlled fractured-vuggy systems, and collapsed vuggies. Shallow karst reservoirs are widely distributed, and feature small-scale dissolution holes and cracks with flake and mesh distributions. The sequential indicator simulation method of different seismic attribute constraints is adopted to model small-scale karst caves. In addition, a combination of seismic and well-logging methods is used to stochastically simulate small-scale cracks.

### Modeling Of Ancient Rivers with the Multi-Point Geo-Statistics Method

Ancient rivers possess different structure modes, including hall-type caves with collapsed fillings and sediments, dominant caves with sedimentary fillings, and secondary caves with sedimentary fillings influenced by chemical effects. Controlled by the water table, ancient rivers are commonly located at slope areas with drainage, in which single branch caves are developed upstream and multi-layer caves are developed downstream. Considering complexity, diversity, and filling variability of ancient rivers, we optimize surface outcrop geometric parameters of karst geological knowledge of rivers and combine knowledge of underground rivers' structure using seismic reflection to obtain multiple 3-D training images. The multiple-point geo-statistics method is utilized to simulate underground rivers with multi-layer structures, various spatial patterns, and branched structures. Using well logging and seismic filling as constraints, we build a geo-statistics modeling approach based on complex geological knowledge to simulate ancient rivers.

### Staged and Block-By-Block Geological Modeling Method for Fault-Controlled Karst Reservoirs

Geological faults are characterized as having multiple phases, continuities in time, and hierarchal structures in space. Strike-slip faults are composed of torsion in a compression or tension section, and a smooth section in which there are faults, fractures, dissolution caves, and fractures along discontinuities. Fault karst reservoirs are controlled by faults' properties and structures. Based on the characteristics of fault control karst reservoirs and structures of faults and fractures (e.g., shape, height, distribution, etc.), an external outline of the reservoir can be constructed by using the method of partition with target simulation to obtain training images, and a comprehensive understanding of relevant probabilities can be established [25]. Using impedance characteristics, logging interpretation, drilling vent leakage data, and targeted simulation method, a model can be obtained to describe the spatial distribution of fault-controlled reservoirs.

### Fusion and Dynamic Geological Model of Optimization

Based on the evolution modes of cracks, holes, and caves, we develop a fusion method with the aim to construct large-scale karst caves, large-scale fractures, small-scale holes and small-scale cracks, and establish a different karst phased seam body-piercing distribution model. Based on reservoir connectivity tested by tracers, combined with the spatial distribution of cracks, we achieve an objective function constrained by reservoir connectivity. Moreover, application of the annealing method enables optimization of fracture location between wells, and maintains consistency of the degree of reservoir connectivity and tracer data, which reduces the uncertainty of the geological model.

### Numerical Simulation Technology for Coupled Fractured-Vuggy Reservoirs

Our work builds up a theory for multi-scale coupling numerical simulation, and proposes a modeling framework to incorporate various types of fluid flow with multi-scale characteristics, including Darcy flow through dissolved pore medium (i.e., the hole diameter is less than 2 mm), high-speed pipe flow within the hole medium (500 mm>hole diameter> 2 mm), and non-Darcy flow and free flow in large caves (i.e., the hole diameter is greater than 500 mm) [26]. With the combination of embedded discrete-fracture technology and multi-porosity model, we can accurately simulate complex flow in fractured reservoirs, and achieve a 26% increase in precision [27].

### Numerical Simulation Method for Fractured-Vuggy Reservoirs

We establish a novel mathematical model to consider the coupling of discrete large-scale caves and fractures and multi-porosity continuum media, which can be divided into two categories: the first is based on the Navier-Stokes momentum equation to solve an unfilled cave, in which seepage flow through dissolution caves and fissure networks seepage are treated as source/sink terms; and the second is based on Darcy's law and Navier-Stokes equations to estimate flow in dissolution caves and fractures, and non-filling caves or fractures, respectively [28]. The former offers higher accuracy but lower efficiency, which is suitable for mechanism investigation of different combinations of caves and fractures [17]. The latter has higher computation speed but lower accuracy, which is suitable for production prediction of field-scale reservoirs.

We have developed an advanced software program, KARSTSIM (V2.0), which is tailored for fractured-vuggy reservoirs' simulation. The finite volume method is employed to discretize partial differential equations. Embedded unstructured grid technology is adopted to handle large-scale fractures and caves with the concept of embedded simulation processing and calculation, which greatly improves the computational accuracy of interporosity flow between the fault and the fracture. According to reservoir heterogeneity, a partitioning, multi-porosity simulation technology is established. This approach can effectively divide the target reservoir into a cave zone, fracture zone, dissolved pore area, and their combinations. Based upon this, numerical simulation accuracy increased to 92.2%, and the coincidence rate of oil production, predicted by this software, can be up to 87.6%.

### Simulation Technology Allowing For Ten-Million Grids

The large-scale fine model greatly increases the workload of reservoir simulation and simulation time due to a remarkable increase of grid number [29]. Through the adoption of a hybrid parallel computing simulation scheme, code implementation is performed on an MPI efficient coarse-grained domain-decomposition parallel model, based on a mixture of OpenMP fine-grained multithreaded parallel computing technology. In this way, a large-scale simulation model and a pre- and post-processing module are developed to enable practical applications of ten-million or even hundred-million grids. The computational efficiency of the new version of the KARSTSIM software has been significantly improved. In fact, this simulator can readily run as large as five-million grids on a stand-alone 8-core PC with 128 clusters. We also handle a real field case with strong heterogeneity (see Figure). **Using 26 Million grids, in which the Linear Acceleration Ratio Is up To 1.68**.

An auxiliary space preconditioned algorithm is proposed. Adaptive implicit CPR + AMG fast numerical techniques are employed in our simulator. To address the issue of low efficiency in solving the pressure and saturation of the coupled system, we develop a fast numerical technique based on adaptive discrete CPR + AMG, in which algebra multilayer grid AMG pretreatment is used to control the residual of pressure, leading to a decrease in the number of linear iterations for each time layer. For the issue of the small size of the time step, resultant from heterogeneous and multi-scale characteristics, we propose an optimization technique of time step for multi-scale reservoirs and an automatic adjustment of time step for multiple wells with variable production data. These techniques assist us to effectively enlarge the time step, which substantially improves software running speed.

An auxiliary space preconditioned algorithm is developed. In the mainstream of reservoir simulation software, fully implicit (FIM) or implicit pressure full (IMPES) format, combined with the upstream weighted-space finite-difference discrete method, are usually adopted. Either the FIM or the IMPES linear solver is used, and most of the CPU time is used to solve the FIM Jacobian matrix of the fully implicit equation system or solve IMPES semi-implicit quadratic elliptic equations. In addition, the magnitude of the nonlinear algorithm time step is decided by the convergence and stability of the equation system, and is one of the most important factors therein. Therefore, the performance of convergence speed and stability nonlinear iterative algorithm constitutes a decisive factor of numerical simulation.

We build an auxiliary space preconditioned method (ASP) to design multi-stage pre-conditional operators, and use analytical and physical properties of the reservoir model to develop an auxiliary space solver (or polisher) and preliminary conditions, and combine these with the Krylov subspace method to accelerate calculation speed. It is worth noting that using an easily accessible analysis method and geometry information enables us to make the design of the preconditioned algorithm universal, which can straightforwardly be transplanted to other reservoir simulation models. In order to obtain an efficient, robust, and extensible reservoir simulator, we adopt a sparse matrix storage format that integrates some common solving methods based on storage formats, such as the Gauss-Seidel iterative method, the algebraic multi-layer grid method, and the ILU method. In fact, this new algorithm is more than 10 times faster than that of commonly-used simulators.

### Enhanced Oil Recovery Technology with Improved Water Flooding

Qualitative analysis and quantitative optimization of remaining-oil information and improved water-flooding technology are used for development. A water-flooding strategy for fractured-vuggy oil reservoirs was established in 2006, and the spatial-temporal difference water injection method was proposed [30]. To avoid the problem of channeling water flow in large cracks and realize efficient operations of water injection, we develop a new injection-production strategy, i.e., injection into fractures and production from caves, injection into low formations and production from high formations, injection and production from the same layer from the spatial aspect, and trial-and-error injection at an early period of time. Then, cycle injection is performed at a relatively low rate, followed by injection to depress water breakthrough and reverse oil displacement. With the increase of the amount of injected water into the reservoir, the effect of water-flooding efficiency gradually diminishes and much of the remaining oil becomes unexploitable. Consequently, determination of how to improve water-flooding efficiency constitutes the key problem for different types of remaining oil trapped in reservoirs. Through physical and numerical experiments, it is determined that four types of residual oil after water flooding exist in reservoirs: (1) ceiling loft oil; (2) residual oil bypassed by channeling flow; (3) marginal residual oil; and (4) residual oil trapped in the pores of fillings. We also elucidate some water-flooding mechanisms, such as cyclic water-flooding, water injection pulse water injection, reverse oil displacement (also known as injection-production inversion), surface active agent, and water injection enhancing gas production, yielding a design method for well networks in 3-D space and optimization techniques for injection-production treatments.

### Spatial Structure Pattern Design Technology

For oil and gas development, well pattern deployment is the crucial factor for improving reserve-production ratio, production rate, and oil/gas recovery. Conventional well patterns, such as five-spot, nine-spot, rhombus type, line type, etc., lead to low-production or even zero-production wells, and only a small part of reservoirs can be swept. Therefore, development of new ideas and innovative methods for well-pattern design are urgently needed.

We establish an injection-production well-spacing design method with spatial structures to meet the demand of high-efficiency water-flooding treatments for discrete fractured-vuggy reservoirs. The primary idea is that oil well location is determined by caves, water well location is determined by connections between caves, and the number of injection and production wells is determined by reserves. With this principle, oil production wells should be located at large-scale caves; whereas, water injection wells should be located at the fractured part with holes. Based on the water-cut level of wells to deploy injection and production wells in order, we can achieve means of high-efficiency production, such as injection into fractures and production from caves, injection into low formations and production from high formations, and injection and production from the same layer. In such a way, locations and operating parameters can be readily optimized, and the degree of remaining reserves controlled by water flooding can be improved. Between the karst caves, a pair of production and injection wells are deployed, and injection and production are alternated. In a specific case of design, oil production wells are preferentially deployed in a residual hill within the cave, the fractured-vuggy body controlled by trunk fractures, and the main underground river. According to the connectivity between caves, the location of water injection wells around oil production wells can be determined, and the injection-production relationship can be established. In the process of well-pattern design and determination of well locations, it is critical to consider reserves and economic factors, as well as the number of infill wells and injection-production wells according to the reserves' size of the reservoir unit. The demonstration unit of the Tahe Oilfield utilizes spatial-structure pattern design technology to improve the degree of controlled reserves to 26%.

### Injection-Production Parameter Optimization Techniques

Due to the strong heterogeneity of fractured-vuggy reservoirs, a major difference of remaining oil exists between wells, depending on location. As a consequence, it is necessary to optimize the magnitude of water injection and oil production between and among the injection-production well group, thus improving the efficiency of water flooding. Water flooding constitutes an optimization problem with the goal of maximizing economic benefit. Through an automatic optimizing solution of injection-production parameters of oil and water wells, we can minimize the magnitude of injected water while maintaining the highest oil recovery. It also enables regulation of the production of oil wells, and the development effect is subsequently enhanced. Compared with the design method with manual operations, the automatic optimization approach offers the advantages of high accuracy, high efficiency, fast speed, as well as suitability for fractured-vuggy reservoirs with strong heterogeneity, which is a complicated well-connection relationship.

We here propose three kinds of injection-production parameter optimization methods. The first one optimizes oil production of a well group or a reservoir unit based on geological modeling optimization to establish a geological model for reservoir numerical simulations, so that the magnitude of water injection and oil production of each well can be predicted. This optimization method controls variables on the transformation to the same order of magnitude of the log-domain random-disturbance gradient solution. The second method is a robust optimization method, which is associated with the uncertainty of the geological model. It is based on multiple conditions in accordance with the geological model and dynamic production constraints, and unwanted geological models will be excluded automatically. Combined with the numerical simulation prediction method, all of the design models with different magnitudes of oil production or water injection are tested to select the optimal injection-production scheme with the maximal net present value (NPV).

The third method is based on the optimization method of the well connectivity model, in which the single-well controlled reserves and the degree of well connectivity constitute the basis of the optimization approach. A new numerical model for oil-water flow and production forecasting is established to simulate the development process of fractured-vuggy reservoirs based on injection-production balance and oil-water two-phase frontal advancing theories. Based on these techniques, the optimal injection-production strategy can be selected through building the objective function to optimize the magnitude of injection/production and achieve the desired results. We find that the robust optimization method possesses the strongest anti-risk capability, and the optimization method for well connectivity is the fastest approach.

The amount of accumulated oil would be higher if optimization is performed for the well group and reservoir, and the corresponding accumulated water production and water injection are significantly reduced. This would achieve the optimization goal of less water injection, but higher oil production. The S80 unit experienced the above-described effect after application of the optimization method, in which accumulated oil production increased to 23.1×104 t, water cut decreased by 6.8%, accumulated water production reduced by 4.5×104 m3, and consumption of water decreased by 41.6%.

## Enhanced Oil Recovery Technology for Fractured-Vuggy Reservoirs by Gas Injection

For Tahe fractured-vuggy reservoirs, the injected gas and in-situ oil are non-miscible, and thus the reservoirs always suffer from poor oil displacement, which is unfavorable for gas injection development [31]. For the first time concerning gas injection, in 2009, a numerical simulation experiment for cave reservoir was performed, in which gravitational differentiation could be observed during nitrogen gas injection into the cave. Numerical results showed that oil is driven to the top of the cave, termed the roof-driven mechanism (Figure 6 and 7), which inspires us to propose a nitrogen injection scheme, i.e., “gas-driven at the top of the cave”. This constitutes an effective method for fractured-vuggy reservoirs to enhance oil recovery. Currently, the strategy of nitrogen gas injection development has been widely utilized in the Tahe Oilfield, and has become an essential method to improve recovery efficiency of fractured-vuggy reservoirs.

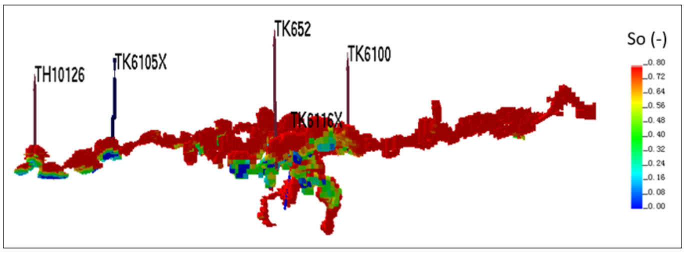

**Figure 5:** Oil saturation distribution of the karst reservoir related to underground rivers

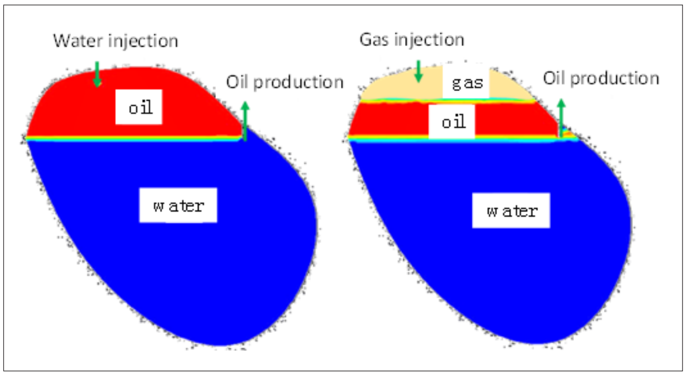

**Figure 6:** High ceiling after oil well water-flooding effect

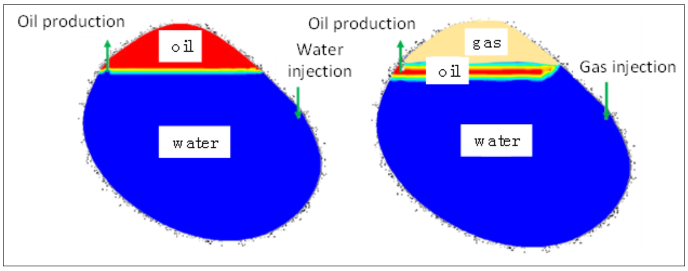

**Figure 7:** Low ceiling after oil well water-flooding effect

## Intelligent Technology of Well Selection for Fractured-Vuggy Reservoirs

We propose a series of novel technologies, including a gas injection effect evaluation and prediction method, assessment and prediction methods for gas channeling flow risks, and the combination of qualitative analysis, quantitative evaluation, and prediction. We regard the weathering crust, ancient underground rivers, and fault-controlled karst formations as research targets of karst reservoirs. We establish the principle and standard for choosing a gas injection wells reservoir, and form a rapid intelligent standardization process of selecting gas injection wells in fractured-vuggy reservoirs. We also develop a software platform for intelligent selection of gas injection wells in fractured-vuggy reservoirs to mitigate certain problems, including long selection cycle for gas injection wells and long response time. This software platform assists to improve the effectiveness of selecting wells from 83% to 90%, and increases additional new cover reserves that are available using gas injection with a magnitude of 125 million t.

### Optimization Techniques for Gas Injection of a Single Well or Well Group

We propose a novel method for oil displacement by gas injection, and develop the application of nitrogen-flooding technology. In addition, we also form an optimization technology of gas injection for a single well or well group, and establish a differential gas injection scheme for a single well or well group. Differential injection-production well-pattern-building technology can be summarized as follows: the application of numerical simulation technology for fractured-vuggy reservoirs to establish a differential injection-production relationship for gas-driven wells, based on a pre-existing spatial structure of the well pattern and the occurrence pattern of remaining oil after water flooding. Because weathering crust reservoirs feature small caves, dissolution pores, small-scale cracks, and good continuity within a layer, the remaining oil is mainly controlled by formation structures between wells or residual hills, such that the strategy of "injection at high elevation and production at low elevation of the cave" can be an effective means to develop remaining oil more effectively.

Reservoirs associated with ancient underground rivers develop along the extending direction of the river, and residual oil mainly resides on both sides of the river channels. Therefore, we should inject water into the branched river and produce from the main river channel. For two-channel rivers, we should use the "high injection low production" scheme with the injection-production well pattern. Fault-controlled reservoirs and dissolution caves are usually distributed around the fault zone and exhibit a zonal shape. The development degree of dissolution caves/cracks gradually weakens from the core to the wing of the fault. The remaining oil mainly distributes within the location of fault wings due to the poor connectivity therein. Consequently, it is appropriate to use the scheme of injection at the wing part, and production from the core part, when designing the injection-production well pattern.

Differential nitrogen-flooding technology, based on the gas-water coordination mechanism, is proposed to develop fractured-vuggy reservoirs, allowing for the co-existence of gas and water. When the bottom water energy is sufficiently strong (e.g., 0.5 > DPr > 0.1), it is recommended to use the alternative scheme of gas-driven and water-flooding methods. For weak energy reservoirs (e.g., DPr > 1.5), it would be better to use the mixed gas and water injection method. We then advance two kinds of differential synergistic modes, i.e., bottom water and gas injection displacement are used for attic lateral displacement oil and water flooding in the lateral direction, respectively. Indeed, the combination of gas and water injection is beneficial for enlarging the sweep volume. The effect of the synergistic mode could be optimal if a balance is determined and achieved between the gas-driven downward and the oil-displacement upward driven by bottom water and water flooding. We here provide a useful optimization method to determine the suitable driven speed of gas injection, and compile and implement the gas-driven scheme for 39 well groups, leading to a significant increase of oil production.

The above-mentioned method has been used for gas-driven scheme design for 262 single well gas injection and 39 well groups, with which oil production increased by 1.761 million t and recoverable reserves increased by 2.484 million t; thus, oil recovery is effectively increased from 14.91% to 17.07%.

### The Technique of Targeted Acid Fracturing Treatments

Traditional acid fracturing usually forms a single bi-wings crack that will limit the sweep region to a small volume. To improve stable oil production, additional complex fractures should be created to connect pre-existing natural fractures and increase the stimulation reservoir volume (SRV). We aim to resolve the issue that only simple fractures are generated and the effective SRV is not large as desired during traditional acid fracturing stimulations for fractured or fracture-cave type reservoirs. To achieve this, we adopt the technique of targeted acid fracturing treatments to change fracturing effectiveness from a single direction to multiple directions, and from a single fracture to fracture networks, effectively increasing the sweep volume of the created fractures. Accordingly, we also markedly improve the hit rate of targeted acid fracturing, as well as its fracturing effectiveness, and enhance the reserves-production ratio of the oilfield.

### The Technique of Complex Acid Fracturing Treatments

Complex acid fracturing should adhere to the following five principles for well/layer selection: (1) natural fractures around the well should be well developed; (2) the size of natural fractures should be larger than 2 m; (3) natural fracture volume density should be up to 6% to 9%; (4) horizontal stress anisotropy should be less than 20 MPa (e.g., ≤ 13 MPa for the zone with closed natural fractures and ≤ 20MPa for the zone with filling natural fractures); and (5) the net pressure of the fracture should be larger than 6 MPa. Prior to fracturing treatments, acid should be injected into the target reservoir, which is beneficial for natural fractures' slippage or opening around wells. Fluid injection is expected to be performed with low viscosity and low injection rate (e.g., ≤10 mPa•s, 0.5-2.0 $m^3$/min) to reactivate natural fractures, but with large injection rate (e.g., ≥ 50 mPa•s or ≥7.0 $m^3$/min) to open natural fractures or generate new fractures.

Temporary plugging in the fracture will dramatically elevate fracture net pressure and increase pressure for fracture reorientation. There are five pump phases: the first phase activates natural fractures near the wellbore through a low viscosity and low injection rate of the acid to connect natural fractures around the well, which is beneficial for the generation of branched main cracks; the second phase propagates many branched main fractures using high viscosity and high injection rate of the acid to deepen the fractures' growth into the formation, in which the viscosity of the fracturing fluid should be higher than 50 mPa•s and the injection rate should be larger than 7.0 m3/min; the third phase further forms branched fractures by alternating injection of high and low rate to connect natural fractures and form secondary fractures; the fourth phase forms temporary plugging in the fractures using multi-level "fiber and fiber particles" to achieve temporary plugging and fracture reorientation, such that the acid fluid can be evenly distributed in the formation, improving fracturing effectiveness along both horizontal and vertical directions.

Indeed, temporary plugging with fiber can readily achieve plugging for high-permeable and fractured zones. The fifth phase enlarges the dissolution volume by gas-driven at the top part of the cave, during which the acid fluid further dissolves fracture surfaces near the wellbore, thus improving the conductivity of the formation near the wellbore. Complex acid fracturing was performed in eight wells without failure. Specifically, we achieved commercial production of the wells with a rate of 100%, and the accumulated oil production increased by 150,400 tons. Compared with the adjacent wells, the reserves, controlled by a single well, increased by more than 20 times.

### Temporary Plugging and Reorientation Acid Fracturing Technology

Large-scale temporary plugging experiments indicate that temporary plugging and reorientation in the fracture are accessible where the crack usually initiates within natural fractures or bedding planes. When natural fractures or bedding planes are absent, however, it becomes highly challenging to achieve fracture initiation and propagation in the intact rock mass. We develop a fracture propagation modeling technique under the condition of temporary plugging in complex fractured-vuggy reservoirs, and establish a mathematical model and numerical model for fracture initiation and propagation under the condition of temporary plugging in complex reservoirs. We elucidate the mechanisms of complex fractures' growth and their controlling factors in naturally fractured reservoirs, as well as fracture propagation behaviors under the condition of temporary plugging.

We have determined the fracture propagation behaviors of multi-staged fracturing in open hole horizontal wells under temporary plugging. Cracks start to initiate in a perpendicular direction to the minimum principal stress where rock strength is also at the minimum. When temporary plugging works in an open fracture, fluid pressure is elevated dramatically, such that the fracture may initiate at a new position. Staged fracturing makes initiation of the perforation at a later time more difficult, and the fluid pressure becomes increasingly high. Temporary plugging acid fracturing technology has been applied in 14 wells, in which accumulated oil production is increased up to 97,500 t, demonstrating a remarkable advantage in improving oil production.

## Conclusions

After continuous exploration and practice, we promoted several key technologies in the field of developing deep carbonate oil and gas reservoirs, including: (1) proposing the technique of diffracted wave separation and high precision of reverse-time depth migration imaging, reconstruction of the fractured-vuggy body in three-dimensions, and prediction of fault-controlled karst reservoirs; (2) forming high-resolution geological modeling technology of dissolutional fractured-vuggy reservoirs, based on geological knowledge and dynamic constraints of the model; (3) establishing a multi-scale coupling numerical simulation theory for reservoir numerical simulation and massive parallel computing to improve reservoir simulation accuracy and speed, which allows for a complex multiple continuum with the co-existence of caves, fractures, and holes; (4) developing water-flooding theory for fractured-vuggy reservoirs, establishing a design method of spatial structure pattern, and implementing several high-efficiency development schemes, such as "injection in fractures and production from caves", "injection at low elevation part and production from the high", and "injection and production in the same layer", which significantly improve accessible reserves for surface-karst reservoirs, underground river karst reservoirs, and fault-controlled karst reservoirs; (5) revealing the roof-driven mechanisms of nitrogen gas injection flooding, forming optimization techniques for nitrogen injection, and optimal selection for the single well and well group; and (6) establishing the technique of targeted acid fracturing treatments, regardless of principal stress, to change fracturing effectiveness from a single direction to multiple directions, and from a single fracture to fracture networks, effectively increasing the hit rate of targeted acid fracturing, as well as fracturing effectiveness.

The application of Tahe demonstration technology has increased economic recoverable reserves of 5.73 million t, and increased the output value of 13.3 billion yuan in RMB. In addition, this technique helped to advance Tarim Basin oil and gas exploration and development, and supported the discovery of a billion-ton oilfield in the Shunbe region and a rapid increase of oil production, and achieving stable oil production in the Tahe Oilfield, the Lungu Gas Field, and the Halahatang Oilfield. During the period of the 13th Five-Year Plan, the Tahe and Shunbe oil and gas fields have built a total of 800 new wells, and the production of accumulative total capacity is 6.5 million t, annual oil production increased by 24% compared with 2015, and the cumulative domestic enterprise supply for the autonomous region is estimated to be 30.32 million tons of crude oil, 8.1 billion tons of natural gas, and 1.15 million tons of liquefied gas light hydrocarbon. These achievements strongly support the economic development of western China [32, 33].

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