Reservoir characteristics and effective development technology in typical low-permeability to ultralow-permeability reservoirs of China National Petroleum Corporation

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Abstract
Low-permeability to ultralow-permeability reservoirs of the China National Petroleum Corporation are crucial to increase the reserve volumes and the production of crude oil in the present and future times. This study aimed to address the two major technical bottlenecks faced by the low-permeability to ultralow-permeability reservoirs by a comprehensive use of technologies and methods such as rate-controlled mercury injection, nuclear magnetic resonance, conventional logging, physical simulation, numerical simulation, and field practices. The reservoir characteristics of low-permeability to ultralow-permeability reservoirs were first analyzed. The water flooding development adjustment mode in the middle and high water-cut stages for the low-permeability to ultralow-permeability reservoirs, where water is injected along the fracture zone and lateral displacement were established. The formation mechanism and
distribution principles of dynamic fractures, residual oil description, and expanding sweep volume were studied. The development mode for Type II ultralow-permeability reservoirs with a combination of horizontal well and volume fracturing was determined; this led to a significant improvement in the initial stages of single-well production. The volume fracturing core theory and optimization design, horizontal well trajectory optimization adjustment, horizontal well injection-production well pattern optimization, and horizontal well staged fracturing suitable for reservoirs with different characteristics were developed. This understanding of the reservoir characteristics and the breakthrough of key technologies for effective development will substantially support the oil-gas valent weight of the Changqing Oilfield to exceed 50 million tons per year, the stable production of the Daqing Oilfield with 40 million tons per year (oil-gas valent weight), and the realization of 20 million tons per year (oil-gas valent weight) in the Xinjiang Oilfield.

**Keywords**
Low-permeability to ultralow-permeability reservoir, reservoir characteristics, development mode, volume fracturing, physical and numerical simulation

**Introduction**

Low-permeability to ultralow-permeability reservoirs have significant development potential. The China National Petroleum Corporation (CNPC) has focused on such reservoirs to increase reserves and facilitate the production of crude oil in the ongoing and coming years (Hu, 2009; Ma et al., 2020; Zou et al., 2010). According to data collected in 2006, the CNPC’s annual proven low-permeability (overburden matrix permeability is less than $50 \times 10^{-3} \mu m^2$) reserves contain 430 million tons of crude oil, accounting for 71.8% of China’s annual proven low-permeability reserves. Of these, the extra-low-permeability (overburden matrix permeability is $1–10 \times 10^{-3} \mu m^2$) and ultralow-permeability (overburden matrix permeability is $0.2–1.0 \times 10^{-3} \mu m^2$) reserves are the main components, accounting for 81.6% of the total low-permeability reserves of CNPC. The annual output of low-permeability crude oil increased by nearly 6%. In 2014, it reached more than 40 million tons. Low-permeability to ultralow-permeability reservoirs of CNPC are relatively diverse in terms of the formation. For example, the Changqing Oilfield is a block reservoir with massive sand bodies; the Daqing Oilfield is a multi-layer reservoir with thin and narrow sand bodies, and the Xinjiang Oilfield is a conglomerate reservoir (Wang et al., 2008a, 2008b; Zeng, 2004; Zeng et al., 2008). These low-permeability to ultralow-permeability reservoirs face two major technical bottlenecks. The first challenge is to improve oil recovery; the fractured water channeling causes a rapid decline in production in combination with the lateral water flooding effect (Wang et al., 2015a, 2015b; Xie et al., 2015; Yan et al., 2011). The second challenge in exploitation of the reserves is that the ultralow-permeability reservoirs have fine pore throats, because of which it is difficult to develop an effective displacement system, and the degree of reserve utilization is low (Du et al., 2014; Gan et al., 2011; Li et al., 2015; 2019; Lin et al., 2020; Shen et al., 2016, 2019; Su and Sun, 1996; Yang et al., 2010; Zeng et al., 2010).

Several studies attempted to address the existing challenges of low-permeability to ultralow-permeability reservoirs. The measures available to counter the difficulties faced
with water injection and water channeling, without flooding the reservoir, restrict the efficient development of fractured low-permeability and ultralow-permeability reservoirs. In the Fuyu fractured low-permeability reservoir, three types of water channeling were introduced, namely water channeling in natural fractures, in artificial fractures, and in high-permeability layers. For enhanced oil recovery (EOR), Zhao et al. (2008) suggested different counter measures for different types of reservoirs. For water channeling of natural fractures with strong directionality and generality, the treatment was conducted by arranging injection well arrays along the fractures in which the fracture direction was previously clarified. For water channeling in artificial fractures and high-permeability layers, deep plugging measures were adopted. Aiming at the water channeling along fractures of the fractured low-permeability reservoir in the Changqing Oilfield, Liu et al. (2009) used the SBED\textsuperscript{TM} Studio, a directional permeability technology model software developed by the Geomodelling Technology Corporation, Canada, to establish the geological model of the study area. They simulated the adjusted development modes using MDS, a molecular dynamics simulation software. Their results indicated that 1) the fracture water injection and area water injection could be combined to develop the fractured reservoir; 2) properly improving the reservoir pressure was favorable for the production of oil and gas in the area under study; and 3) line-water flooding was not the best water flooding mode, but it could be combined with point-water flooding mode. Zhang et al. (2015) analyzed the static geological characteristics of the reservoirs and the development dynamics of water flooding; they then screened 10 static geological indices and seven dynamic development indices as evaluation factors. Using a fuzzy integrated judging method with nine scales, they established an evaluation model for water channeling of fractured ultralow-permeability reservoirs. The results of field verification showed that the identification could provide the right direction for setting the measures of EOR. Shi et al. (2007) discussed the main developmental difficulties in Chang 6 and Chang 8 (Member 8 and 6 of the Upper Triassic Yanchang Formation) ultralow-permeability reservoirs in the Ordos Basin. The discussion covered developmental difficulties including the micropore throat, complex pore structure, high driving pressure, low saturation of moveable fluids, high threshold gradient pressure (TGP), strong stress sensitivity, and evident non-Darcy seepage characteristics. Their study showed that the water flooding of ultralow-permeability reservoirs had a high injection TGP, low injectivity index, unstable formation pressure, and inability to set up an efficient pressure system. Because of the low transmissibility, the injected water concentrates around the holes, thus increasing the pressure and permeability. With regard to the production features, the formation pressure decreases rapidly with the decline of production; moreover, the plastic deformation of the rock framework, which results from the decrease in the reservoir pressure, leads to a drop in the porosity and permeability. In general, these studies have extensively assessed the development of low-permeability and ultralow-permeability reservoirs, but there is a lack of systematic and effective schemes to solve the two major technical bottlenecks mentioned above.

This study analyzed the reservoir characteristics and development potential of low-permeability to ultralow-permeability reservoirs using various methods and techniques, such as rate-controlled mercury injection, nuclear magnetic resonance (NMR), conventional logging, physical simulation, numerical simulation, and field practices. Consequently, an effective development mode was established, and key technologies for providing technical
support for the successful and effective development of low-permeability to ultralow-permeability reservoirs were formulated.

**Analysis of the characteristics of typical low-permeability to ultralow-permeability CNPC reservoirs**

**Comparison of physical properties**

Low-permeability reservoirs have low porosity and permeability, strong heterogeneity, complex pore structure, rapid production decline, and low recovery rate. Therefore, it is important to understand the characteristics of different types of low-permeability reservoirs for effective development. Taking Daqing and Changqing as examples, we compared the differences in the physical properties of their low-permeability (overburden matrix permeability is $10^{-3}$ to $10^{-4}$ m$^2$), extra-low-permeability (overburden matrix permeability is $1$ to $10^{-3}$ m$^2$), and ultralow-permeability (overburden matrix permeability is $0.2$ to $1.0$ m$^2$) reservoirs using rate-controlled mercury injection, NMR, and non-linear seepage physical simulation experiments. The comparison results are shown in Table 1.

The major throat radius is the corresponding throat radius when the cumulative contribution rate of the throat to the permeability reaches 80%, which is measured by high-pressure mercury injection. It is an important parameter that characterizes the microscopic pore structure of the reservoir rock and affects the seepage capacity of the reservoir fluid. From Table 1 that the difference in physical parameters between the low-permeability, extra-low-permeability, and ultralow-permeability reservoirs of Daqing and Changqing are clear. Ultralow permeability reservoirs have a smaller major throat radius, a lower percentage of movable fluid, and a higher pseudo-starting pressure gradient. These results indicate that it is difficult to establish effective pressure-driven systems in ultralow-permeability reservoirs and require large-scale volumetric fracturing prior to industrial utilization. Moreover, the physical properties of the Changqing oilfield are better than those of the Daqing oilfield, regardless of the permeability of the reservoir.

**Reservoir distribution characteristics**

Low-permeability to ultralow-permeability reservoirs of CNPC are relatively diverse. For example, the Changqing block reservoirs are formed with massive sand bodies; the Daqing reservoirs are multi-layered with thin and narrow sand bodies, and those in Xinjiang are conglomerate reservoirs. Figure 1 shows a comparison of the distribution characteristics of the Changqing and Daqing reservoirs. As shown in Figure 1, the Changqing sand body is

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Table 1. Comparison of physical properties of low-permeability, extra-low-permeability, and ultralow-permeability reservoirs in Daqing and Changqing.

| Type of reservoir               | Oil field | Major throat radius (μm) | Percentage of movable fluid (%) | Pseudo-starting pressure gradient (MPa/m) |
|--------------------------------|-----------|--------------------------|---------------------------------|------------------------------------------|
| Low-permeability and extra-low-permeability | Daqing    | >0.80                    | >30                             | <0.08                                    |
|                                 | Changqing | >1.70                    | >45                             | <0.01                                    |
| Ultralow-permeability          | Daqing    | 0.32–0.80                | 10–30                           | 0.08–1.64                                |
|                                 | Changqing | 0.38–1.70                | 15–45                           | 0.01–0.65                                |
large in scale, and the reservoir distribution is uniform, while Daqing is mainly composed of thin interbeds and small sand bodies.

Figure 2 shows the microscopic pore structure diagram of the Xinjiang low-permeability conglomerate reservoir. Large pores appear at locations where the fluid flows into the conglomerate reservoir. These structures lead to an uneven distribution of the residual oil after water flooding.

**Water flooding development adjustment mode and key technologies for low-permeability and extra-low-permeability reservoirs**

Most low-permeability and extra-low-permeability reservoirs are developed by means of high-pressure water injection and advanced water injection. Owing to the multiple effects of the artificial fractures, natural fractures, and dynamic fractures formed by water flooding,
the water seepage is faster along the direction of the fractures, and the water cut is sharp. However, there is a small amount of water in the lateral direction of the fractures, thus resulting in more residual oil that may not be recoverable. Taking the Changqing Wangyao water injection test area as an example, nine inspection wells were deployed along the direction of the fractures and in the lateral direction of the fractures, as shown in Figure 3. The monitoring results show that the inspection wells arranged along the direction of the fractures have a water content of 100%; the inspection wells that are located at approximately 80 m from both sides of the fracture zone have a water content of 30 to 40%, and the inspection wells that are located at more than 100 m from both sides of the fracture zone have a water content of less than 10%; this indicates that the extraction of crude oil in the lateral direction of the fractures is low. Considering these characteristics, a water flooding development adjustment mode of “water injection along fracture zone and lateral displacement” is proposed, which includes the following three key technologies.

Formation mechanism and distribution principle of dynamic fractures

Low-permeability and extra-low-permeability reservoirs have poor physical properties that lead to an increased formation pressure around the injection well. When the formation pressure reaches a certain limit, micro-fractures are generated in the formation, and they continue to extend under specific water injection conditions to form dynamic fractures. A number of tests and dynamic reflections establish the strong influence of the fractures on seepage and water flooding in extra-low-permeability reservoirs, and this influence is a decisive factor in controlling the distribution of the residual oil in the plane. In situ stress and water injection parameters determine the direction and length of the extension of these dynamic fractures. From the test results of the 756 wells in Wangyao District of Ansai Oilfield, it can be observed that the direction of extension of the dynamic fractures is consistent with the direction of the horizontal maximum principal stress. Moreover, a greater water injection intensity corresponds to a longer water injection duration and a larger extension of the dynamic fractures.

The abovementioned observations were also reported by Zhao et al. (2015), who suggested that high dip-angle fractures were predominant in the Chang-6 reservoir in the
Wangyao block in the Ansai oilfield, with the main orientations along ENE–WSW, E–W, S–N, and NW–SE. The opening pressures vary significantly in different reservoir intervals owing to the control of the buried depth, fracture orientation, pore fluid pressure, and current geo-stress. The reasonable injection pressure could be determined according to the maturity of the local natural fractures. In areas with few natural fractures, the water injection pressure could not be larger than the formation fracture pressure to avoid large-scale fracturing that might lead to water breakthrough. In areas with dense fractures, when the fracture opening pressure is less than the formation fracture pressure, the rational injection pressure could be set less than the formation fracture pressure to avoid large-scale opening and connection of natural fractures. Alternately, the injection pressure could be properly set according to the formation fracture pressure to avoid fresh large-scale fracturing.

**Residual oil description**

Physical and numerical simulation were used for studying the residual oil in low-permeability and extra-low-permeability reservoirs. A well group physical simulation was conducted using the self-developed high-pressure large model physical simulation experiment system, which is based on the similarity theory and the equivalent medium theory, and the development and production process of the Wang 16–15 well group was reproduced. The numerical simulation technology mainly considers the influence of the dynamic fractures on the distribution behavior of the residual oil. The simulated results of the residual oil distribution in the Wangyao test area are shown in Figure 4. The results show that the distribution of the residual oil on the plane is controlled by the corresponding relationship between the fractures and the well pattern. Figure 4 presents the strip-shaped characteristics of water flooding. The residual oil was distributed in irregular bands and spindles on both sides of the fractures. After 25 years of water injection, the residual oil was relatively rich.

![Figure 4](image.png)

**Figure 4.** Distribution map of residual oil from numerical simulation considering dynamic fractures.
Expanding sweep volume technology

In the water flooding development process of the low-permeability and extra-low-permeability reservoirs, the artificial fracturing combined with the dynamic fracture generated by the pressurization of water flooding results in the formation of a dynamic fracture zone. Water is injected into the flooded well in the direction of maximum principal stress to control the generation of dynamic fractures and take advantage of the fractures to achieve near-linear lateral displacement; this helps in the application of the sweep volume technology for different types of reservoirs. Using this technology, the Wuerhe Formation in the eighth district of Xinjiang, the Chaoyanggou Mao 9 block in Daqing, and the Wangyao test area in Changqing reported a recovery factor of more than 3%.

Effective utilization development mode and key technologies for ultra-low-permeability reservoirs

Focusing on the problem of ultralow-permeability reservoirs with a small throat and the difficulty to establish an effective displacement, a “horizontal well + volume fracturing” development mode for ultralow-permeability reservoirs was established. This development mode greatly increased the initial single-well output, which prompted large-scale production in ultralow-permeability reservoirs. The mode includes the following four methods and key technologies.

Core theory and optimization design method of volume transformation technology

The core of the theory is to “break” the reservoir matrix to form a network of fractures, maximize the contact area between the fracture wall and the reservoir matrix, minimize the resistance of the matrix fluid to the fracture, greatly improve the overall permeability of the reservoir, and realize the “three-dimensional transformation” of the reservoir. This technology can greatly increase the output of a single well and reduce the lower limit of effective utilization of the reservoir. It is necessary to develop an optimized design method for the integration of geology, development, and engineering; it is also necessary to organically combine geology, oil reservoirs, and engineering (drilling and transformation) to transform geological sweet spots to engineering sweet spots, as shown in Figure 5.

Horizontal well trajectory optimization adjustment technology

Ultra-low permeability reservoirs have characteristics such as low reserve abundance, poor physical properties, fracture development, and strong heterogeneity. To solve the technical difficulties in the selection of reservoir sweet spots, three characteristic technologies were proposed; these were reservoir quantitative classification evaluation, fracture identification and description, and fine reservoir modeling. Well location optimization technology is based on the study of sedimentary and diagenetic facies with a comprehensive evaluation of the reservoir as the core, and a “sweet spot” for horizontal well development is found in ultralow-permeability reservoirs. The core of the trajectory optimization design technology is to determine the main contribution interval in the longitudinal direction. Simultaneously, the three-dimensional geological modeling is introduced to determine the distribution of the main contribution layer in the three-dimensional space, to solve the difficulty of trajectory design in ultralow-permeability reservoirs, and to ensure that the horizontal wells encounter
better oil intervals. Real-time tracking and adjustment technology uses a horizontal well comprehensive management platform to realize the real-time transmission of well site drilling, recording, and logging data, as well as to implement a 24-hour visual monitoring on the horizontal wells, which provides technical support for ensuring the drilling efficiency and rapid drilling of horizontal wells. The Changqing Oilfield increased the drilling meeting efficiency from 80% to over 90% by organically combining the three technologies of well location optimization, horizontal-well trajectory optimization design, and tracking adjustment.

**Optimization technology of injection and production well pattern of horizontal well**

Using the reservoir numerical simulation technology of nonlinear seepage in combination with field practices, the optimized design method of the well pattern was adopted to form the horizontal well injection and production pattern based on the spindle-shaped fracturing and five-point well pattern, as shown in Figure 6. The determination of the row spacing was mainly based on the fluid seepage pattern in ultralow-permeability reservoirs, which does not follow Darcy’s law and has nonlinear seepage characteristics. According to the nonlinear seepage theory, the limit-driving well spacing and effective driving well spacing were determined. The results of the study show that the spindle-shaped five-point well pattern has the advantages of higher single well production and high recovery rate under the same water cut. The injection-production parameters of the optimized spindle-shaped horizontal well injection-production pattern in the Changqing Oilfield are as follows: the length of the horizontal section is 500–600 m; the interval of the large-displacement mixed water volume fracturing process is 80–95 m, and the row spacing is 130–150 m.

**Horizontal well staged fracturing technology**

The Changqing ultralow-permeability reservoirs are block reservoirs with massive sand bodies, and the horizontal well staged multi-cluster fracturing technology with large-scale
development of plane sand has proven to be suitable for this type of reservoirs. In contrast, the Daqing is a multi-layer reservoir with thin and narrow sand bodies and the horizontal well perforation fracturing technology with the development of thin interbeds has proven to be suitable for this type of reservoirs. Details are presented in Figures 7 and 8.

Horizontal well drilling and volume fracturing have proven to be effective stimulation approaches that could increase reservoir contact significantly and have been applied in the development of low-permeability to ultralow-permeability reservoirs (Wang et al., 2017). Hydraulic fracturing generally leads to highly complex hydraulic networks for tight reservoirs. It is important to understand the effect of hydraulic fracture on well performance. Yuan et al. (2018) used a semi-analytical solution for well pressure transient analysis (PTA)
and rate transient analysis (RTA) to determine the inflow performance for different hydraulic fractures. Horizontal well staged multi-cluster fracturing technology based on horizontal well drilling and volume fracturing was proposed according to the geological characteristics of Changqing ultralow-permeability reservoirs. This enabled the transition from the staged fracturing technology, with two wings and regular expansion, to the staged multi-cluster fracturing technology, with multiple fractures forming clusters and expanding the contact volume with the reservoir. The horizontal well penetration fracturing technology was established through further strengthening the integration of geological engineering, dividing the plane into blocks according to the capacity, and considering the vertical penetration concept. The above technologies were applied in Changqing and Daqing, and satisfactory results were obtained. The average single well output in these blocks reached more than three to four times that of the vertical wells. Two horizontal well development demonstration zones with a combined capacity of 1,50,000 tons have also been built at CNPC’s Huaqing Chang 6 and Maling Chang 8, and both locations have achieved good application results.

In addition to these technologies, the imbibition oil recovery technique has also been playing an active role in the development of ultralow-permeability reservoirs and tight reservoirs. Therefore, imbibition has been receiving wide-spread attention, and an in-depth study of the imbibition mechanism is required (Xie et al., 2018; Yang et al., 2019; Zheng et al., 2018).

Conclusions
1. The physical properties and reservoir distribution characteristics of typical low-permeability to ultralow-permeability reservoirs of CNPC were compared, and the factors that affect the yield of the ultralow-permeability reservoirs were unraveled. These findings form a technical basis for the effective development of low-permeability and ultralow-permeability reservoirs.
2. The water flooding development adjustment mode in the middle and high water-cut stages, was established for low-permeability and ultralow-permeability reservoirs,
where water is injected along the fracture zone and along the lateral displacement. The research methods and techniques for the formation mechanism and distribution principle of dynamic fractures, residual oil description, and expanding sweep volume were developed. These technologies have been applied in typical blocks such as Daqing, Changqing, and Xinjiang to increase the recovery factor by more than 3 percentage points, while ensuring the continued stable production of low-permeability to ultralow-permeability reservoirs.

3. The development mode for Type II ultralow-permeability reservoirs with a combination of horizontal well and volume fracturing has been determined, that is, the horizontal well staged multi-cluster fracturing technology was applied to Changqing reservoirs with large-scale development of plane sand, and the horizontal well perforation fracturing technology was applied to Daqing reservoirs with the development of thin interbeds. The volume fracturing core theory and optimization design, horizontal well trajectory optimization adjustment, horizontal well injection-production well pattern optimization, and horizontal well staged fracturing were developed for reservoirs with different characteristics. With the application of these technologies and methods to Daqing and Changqing, the initial single-well output obtained was more than three times that of the adjacent directional wells, which prompted large-scale production in ultralow-permeability reservoirs.

This understanding of the reservoir characteristics and the breakthrough of key technologies for effective development will substantially improve crude oil production, supporting the oil-gas valent weight of the Changqing Oilfield (exceeding 50 million tons per year), the stable production of 40 million tons per year in Daqing Oilfield, and the realization of 20 million tons per year in Xinjiang Oilfield.

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References
Du J, Liu H, Ma D, et al. (2014) Discussion on effective development techniques for continental tight oil in China. *Petroleum Exploration and Development* 41(2): 217–205.
Gan Y, Zhang S, Liu S, et al. (2011) A new method for well pattern optimization and integral fracturing design in low permeability reservoirs. *Acta Petrolei Sinica* 32: 290–294.
Hu W (2009) The present and future of low permeability oil and gas in China. *Strategic Study of CAE* 11: 29–37.
Li X, Lu D, Luo R, et al. (2019) Quantitative criteria for identifying main flow channels in complex porous media. *Petroleum Exploration and Development* 46(5): 998–949.
Li Z, Qu X, Liu W, et al. (2015) Development modes of Triassic Yanchang Formation Chang 7 Member tight oil in ordos basin. *Petroleum Exploration and Development* 42(2): 241–221.

Lin L, Lin W, Xiong S, et al. (2020) Supplementary energy development boundaries of staged fracturing horizontal wells in tight oil reservoirs. *Energy Exploration & Exploitation* 38(6): 2217–2230.

Liu X, Yan J and Wang R (2009) Study on the adjustment of development mode in low-permeability fractured reservoirs. *Journal of Xi’an Shiyou University (Natural Science Edition)* 24(6): 29–32.

Ma X, Li X, Liang F, et al. (2020) Dominating factors on well productivity and development strategies optimization in Weiyuan shale gas play, Sichuan Basin, SW China. *Petroleum Exploration and Development* 47(3): 594–602.

Shen W, Xu Y, Li X, et al. (2016) Numerical simulation of gas and water flow mechanism in hydraulically fractured shale gas reservoirs. *Journal of Natural Gas Science and Engineering* 35: 726–735.

Shen W, Song F, Hu X, et al. (2019) Experimental study on flow characteristics of gas transport in micro- and nanoscale pores. *Scientific Reports* 9: 10196.

Shi C, Wan X, Zhao J, et al. (2007) Development characteristics of super-low permeability oil layers in Ordos Basin, China. *Journal of Chengdu University of Technology (Science & Technology Edition)* 34(5): 538–542.

Su Y and Sun N (1996) Horizontal drilling technology: Present and future. *Oil Drilling & Production Technology* 18(6): 14–20.

Wang R, Chen M and Sun W (2008a) The research of micro-pore structure in super-low permeability sandstone reservoir of the Yanchang Formation in Ordos Basin. *Geological Review* 54: 270–277.

Wang W, Zheng D, Sheng G, et al. (2017) A review of stimulated reservoir volume characterization for multiple fractured horizontal well in unconventional reservoirs. *Advances in Geo-Energy Research* 1(1): 54–63.

Wang X, Yang Z, Liu X, et al. (2008b) Micro pore structure in ultra-low permeability reservoir of Yushulin oilfield. *Journal of Oil and Gas Technology* 30: 508–510.

Wang Y, Song X, Tian C, et al. (2015b) Dynamic fractures: A new development geological attribute in water-flooding development of ultra-low permeability reservoirs. *Petroleum Exploration and Development* 42(2): 247–228.

Xie J, Long G, Tian C, et al. (2015) Genetic mechanism of dynamic fracture and its influence on water flooding development in extra-low permeability sandstone reservoir: a case of Chang6 member in Wangyao area, Ansai oilfield. *Petroleum Geology and Recovery Efficiency* 22: 106–110.

Xie K, Lu X, Pan H, et al. (2018) Analysis of dynamic imbibition effect of surfactant in microcracks of reservoir at high temperature and low permeability. *SPE Production & Operations* 33(3): 596–606.

Yan T, Li W and Bi X (2011) An experimental study of fracture initiation mechanisms during hydraulic fracturing. *Petroleum Science* 8(1): 87–92.

Yang Z, Liu X, Li H, et al. (2019) Analysis on the influencing factors of imbibition and the effect evaluation of imbibition in tight reservoirs. *Petroleum Exploration and Development* 46(4): 779–785.

Yang Z, Yu R, Su Z, et al. (2010) Numerical simulation of the nonlinear flow in ultra-low permeability reservoirs. *Petroleum Exploration and Development* 37: 94–98.

Yuan J, Jiang R and Zhang W (2018) The workflow to analyze hydraulic fracture effect on hydraulic fractured horizontal well production in composite formation system. *Advances in Geo-Energy Research* 2(3): 319–342.

Zeng B, Cheng L, Li C, et al. (2010) Development evaluation of fractured horizontal wells in ultra-low permeability reservoirs. *Acta Petroleum Sinica* 31: 791–796.

Zeng L (2004) Fracture and its seepage characteristics in low permeability sandstone reservoir. *Chinese Journal of Geology* 39: 11–17.
Zeng L, Gao C, Qi J, et al. (2008) The distribution rule and seepage effect of the fractures in the ultra-low permeability sandstone reservoir in east Gansu province. *Ordos Basin. Science China: Earth Sciences* 38(S1): 41–47.

Zhang L, Chen Q, Pu C, et al. (2015) Study and application of identification method of channeling-path in the fractured ultra-low permeability reservoir. *Driling & Production Technology* 38(6): 29–32.

Zhao C, Jiang H, Wang P, et al. (2008) Counter measures for treating water channeling in fractured low permeability reservoirs. *Journal of Oil and Gas Technology* 30(6): 116–118.

Zhao X, Zeng L, Jin B, et al. (2015) Discussion on optimal injection pressure of fractured low-permeability sandstone reservoirs – A case study from Wangyao block in Ansai oilfield, *Ordos Basin. Oil & Gas Geology* 36: 855–861.

Zheng J, Ju Y and Wang M (2018) Pore-scale modeling of spontaneous imbibition behavior in a complex shale porous structure by pseudopotential lattice Boltzmann method. *Journal of Geophysical Research: Solid Earth* 123(11): 9586–9600.

Zou C, Zhang G, Tao S, et al. (2010) Geological features, major discoveries and unconventional petroleum geology in the global petroleum exploration. *Petroleum Exploration and Development* 37: 129–145.