

Investigation of interlayer interference regulation in offshore high-water-cut reservoirs with horizontal-vertical combined well patterns

Kun Qian

qiankun@cczu.edu.cn

Changzhou University

Longzhi Wu

Changzhou University

Yanfeng He

Changzhou University

Xiangji Dou

Changzhou University

Xingbang Meng Meng

Changzhou University

Shenglai Yang

China University of Petroleum, Beijing

Article

Keywords: Offshore oilfield, well pattern optimization, interwell interference, interlayer interference, staggered well pattern

Posted Date: August 11th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10575100/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Scientific Reports on October 1st, 2026.
See the published version at <https://doi.org/10.1038/s41598-026-73845-5>.

Investigation of interlayer interference regulation in offshore high-water-cut reservoirs with horizontal-vertical combined well patterns

Kun Qian^{1*}, Longzhi Wu¹, Yanfeng He¹, Xiangji Dou¹, Xingbang Meng^{1*}, Shenglai Yang²

1 School of Petroleum and Natural Gas Engineering, Changzhou University, Changzhou, 213164, China

2 State Key Lab of Petroleum Resources and Engineering, China University of Petroleum, Beijing, 102249, China

* Correspondence: qiankun@cczu.edu.cn; mengxingbang@cczu.edu.cn

Abstract: Offshore strongly heterogeneous heavy oil reservoirs generally suffer from severe development imbalance during the ultra-high water cut stage, characterized by preferential flow in high-permeability layers, insufficient utilization of medium- and low-permeability layers, and significant remaining oil accumulation between wells. To address these challenges, this study focuses on the progressive adjustment of well patterns based on the existing row well pattern in a typical offshore heavy oil reservoir in the Bohai Sea, rather than evaluating the initial well pattern itself. A combination of three-dimensional physical simulation experiments and numerical simulations with consistent experimental parameters was employed to investigate the effects of different well pattern adjustment schemes. Recovery factor, interlayer interference coefficient, and remaining oil distribution were selected as evaluation criteria to analyze the development performance and interlayer flow characteristics. The results show that introducing horizontal wells into high-permeability thick layers can effectively improve overall oil recovery; however, the increased recovery is mainly contributed by high-permeability layers, while the improvement of medium- and low-permeability layers remains limited due to intensified preferential flow. After shutting down production wells in high-permeability layers, the recovery factor increased by 0.20 and 1.27 percentage points in physical experiments and numerical simulations, respectively,

accompanied by reductions of 0.02 and 0.01 in the overall interlayer interference coefficient. However, the imbalance between different permeability layers was not fundamentally alleviated because the dominant flow behavior in high-permeability layers persisted. Compared with the production shutdown scheme, the staggered well pattern combined with separate-layer injection – production increased the recovery factor by 19.37 and 19.27 percentage points in physical experiments and numerical simulations, respectively, while reducing the interlayer interference coefficient by 0.27 and 0.37, leading to a more uniform remaining oil distribution and improved mobilization of medium- and low-permeability layers. The results indicate that the combination of well pattern adjustment and separate-layer injection – production can effectively regulate interlayer fluid allocation, weaken preferential flow in high-permeability layers, and improve the coordinated development of strongly heterogeneous heavy oil reservoirs during the ultra-high water cut stage.

Keywords: Offshore oilfield; well pattern optimization; interwell interference; interlayer interference; staggered well pattern

1. Introduction

After years of water injection development, most offshore oilfields in the Bohai Sea have entered the ultra-high water cut stage. Due to reservoir heterogeneity, high crude oil viscosity, and long-term water flooding, preferential flow channels have gradually developed in high-permeability layers, resulting in the preferential migration of injected water into these layers, while the water flooding efficiency of medium- and low-permeability layers continuously decreases. Consequently, the development disparity among different permeability layers becomes increasingly significant. Meanwhile, long-term stable injection-production relationships lead to the gradual stabilization of interwell flow paths, causing displacement fluids to preferentially migrate along dominant channels. The swept area gradually decreases, and remaining oil accumulates between wells. During the late development stage, offshore heavy oil reservoirs commonly exhibit severe water breakthrough in high-permeability layers, insufficient utilization of medium- and low-permeability layers, uneven layer development, and interwell remaining oil enrichment. Interlayer interference and interwell interference have therefore become key factors restricting further improvement of oil recovery. Therefore, optimizing well patterns, improving the development performance of different permeability layers, and enhancing remaining oil mobilization are critical issues for reservoir adjustment during the ultra-high water cut stage.

Due to strong vertical heterogeneity and significant permeability contrasts among different layers, interlayer interference has become an important factor affecting the coordinated development of multilayer reservoirs. In multilayer commingled production systems, injected fluids tend to preferentially enter high-permeability layers, forming

dominant flow channels and intensifying interlayer interference, which restricts the improvement of overall reservoir development performance. Therefore, extensive studies have been conducted to clarify the formation mechanisms, evolution characteristics, evaluation methods, and regulation strategies of interlayer interference. Lu et al. [1] experimentally investigated interlayer interference characteristics during commingled production in multilayer tight sandstone gas reservoirs and revealed the influence of reservoir heterogeneity on fluid interaction among different layers. Wang et al. [2] analyzed interlayer interference behavior in multilayer reservoir commingled production wells and demonstrated the impact of layer properties on production responses. Liu et al. [3] quantitatively characterized the dynamic evolution of interlayer interference using numerical simulation and revealed its evolution laws. Zhang et al. [4] further investigated interlayer interference in multilayer tight reservoirs under different water conditions and revealed the influence of movable water on interference development. Liu et al. [5] experimentally evaluated interlayer interference during commingled production under different pressure systems, while Xu et al. [6] investigated the dynamic interference behavior of multilayer commingled production in waterflooded heavy oil reservoirs and analyzed the influence of reservoir properties on interlayer fluid redistribution. Huang et al. [7] and Tao et al. [8] proposed characterization methods and theoretical evaluation approaches for interlayer interference. Furthermore, Liu et al. [9] developed dynamic prediction and optimization methods for profile control in multilayer reservoirs, providing an effective approach for regulating uneven layer development. Liu et al. [10] analyzed the feasibility of multilayer commingled production during the high water cut stage and emphasized the necessity of regulating development differences among individual layers.

These studies have established a systematic understanding of interlayer interference from mechanism analysis, quantitative evaluation, and regulation strategies, providing theoretical support for improving the coordinated development of heterogeneous reservoirs.

In addition to interlayer interference, long-term water flooding development also leads to the stabilization of interwell flow paths and the formation of dominant displacement channels, resulting in limited sweep efficiency and remaining oil accumulation between wells. Therefore, well pattern adjustment, horizontal well deployment, and injection–production optimization have been widely applied to modify interwell flow relationships and improve remaining oil recovery. Zhang et al. [11] investigated water flooding sweep characteristics of horizontal-vertical combined well patterns in offshore heavy oil reservoirs and demonstrated the influence of well pattern configuration on displacement performance. Xu Anzhu et al. [12] proposed new well pattern design and adjustment strategies for multilayer reservoirs, showing that well pattern optimization can modify fluid flow paths and improve reservoir production performance. Hu and Li [13] experimentally investigated remaining oil distribution during water flooding using a two-dimensional visualized physical model and analyzed the influence of reservoir heterogeneity on oil displacement behavior. Deng et al. [14] further optimized horizontal well patterns in offshore reservoirs and proposed approaches for improving horizontal well deployment efficiency. Alzahabi et al. [15] investigated the influence of horizontal well spacing optimization on production performance and recovery, indicating that reasonable well spacing design is essential for maximizing horizontal well performance. Zhao et al. [16] investigated cyclic alternate injection-production strategies in mature multilayer oilfields during the extra-high water cut stage using visual physical simulation experiments and revealed that injection-production

adjustment can effectively alter fluid distribution, expand sweep areas, and improve remaining oil recovery. Zhang et al. [17] optimized reservoir production performance through alternated separate-layer water injection in complex fault reservoirs, demonstrating that injection-production regulation can improve fluid distribution among different reservoir layers. Jincai et al. [18] investigated well pattern adjustment strategies with variable injection-production rates in high water-cut oilfields and confirmed the effectiveness of dynamic well pattern optimization for improving development performance. These studies have demonstrated that well pattern adjustment, horizontal well deployment, and injection–production optimization can effectively improve reservoir development performance.

However, most previous studies have focused on individual adjustment measures and mainly evaluated the development response after implementing a specific adjustment method, while the progressive optimization process based on the response of the previous development stage has received limited attention. Therefore, the evolution of reservoir performance during progressive well pattern adjustment at the ultra-high water cut stage and the effects of different adjustment strategies on interlayer interference and remaining oil redistribution remain insufficiently understood. In this study, a typical ultra-high water cut offshore heavy oil reservoir was selected to investigate the progressive adjustment of an existing well pattern. It should be noted that the target reservoir had already been developed using a row well pattern before entering the ultra-high water cut stage; therefore, this study does not aim to evaluate the original row well pattern but focuses on subsequent adjustment strategies under existing development conditions. To address the considerable remaining oil potential in the high-permeability thick layer and the increasing development disparity among layers with different permeability levels, three-dimensional physical simulation

experiments were conducted to investigate the development responses during different adjustment stages, and numerical simulation was further employed to validate the experimental results and predict the performance of different adjustment schemes. Based on the development response of the original row well pattern, a horizontal well was first introduced into the high-permeability thick layer, followed by production well deployment optimization, injection-production relationship adjustment, and separate-layer injection-production to establish progressive well pattern adjustment schemes. The effects of different adjustment schemes were evaluated using recovery factor, interlayer interference coefficient, and remaining oil distribution. The results reveal the response characteristics of heterogeneous layers under different adjustment strategies and demonstrate that progressive optimization based on the development response of previous stages can improve the coordination of multilayer development and enhance remaining oil mobilization. This study provides experimental evidence and engineering guidance for subsequent well pattern adjustment and development optimization of strongly heterogeneous offshore heavy oil reservoirs during the ultra-high water cut stage.

2 Materials and Methods

2.1 Research Framework

After a strongly heterogeneous offshore reservoir enters the ultra-high water cut stage, the benefits achieved through earlier well pattern adjustments gradually diminish as development continues. Preferential flow through the high-permeability layer becomes increasingly pronounced, remaining oil continues to accumulate in the medium- and low-permeability layers, and the development disparity among layers with different permeability levels further increases. The existing well pattern must therefore be adjusted in response to

the new problems arising during reservoir development. Previous studies have shown that horizontal well infill in high-permeability layers, staggered well patterns, separate-layer injection-production, and adjustment of injection-production relationships can improve development performance to varying degrees. However, most studies have focused on a single well pattern adjustment measure, with comparatively limited attention paid to the reservoir response after each intervention and to the need for subsequent well pattern modification. Such studies therefore do not fully reflect the progressive well pattern adjustment process encountered in field development.

Based on previous research and the development characteristics of the target reservoir, three-dimensional physical simulation experiments were combined with numerical simulation in this study. The problems identified at different development stages were used as the basis for subsequent well pattern adjustment, and the development performance, interlayer interference, and remaining oil distribution under different adjustment schemes were investigated. By evaluating the reservoir response and remaining limitations after each adjustment stage, the applicability and constraints of different measures were determined. The well configuration and operating strategy were then further optimized on the basis of existing adjustment methods to establish subsequent well pattern adjustment schemes. Finally, the schemes were comprehensively evaluated in terms of recovery factor, interlayer interference, and remaining oil distribution, and the most suitable adjustment strategy for the ultra-high water cut stage was identified, providing a reference for the late-stage development of comparable strongly heterogeneous offshore reservoirs.

2.2 Experimental Model

A typical reservoir in the Bohai Sea was selected to investigate well pattern adjustment

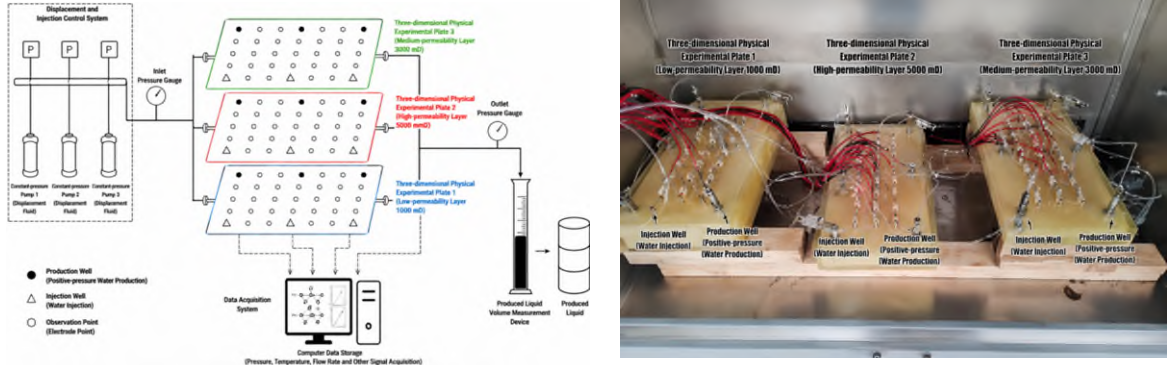
during the ultra-high water cut stage, and a three-dimensional physical model was constructed using the actual geological parameters listed in Table 1. The model configuration and experimental system are shown in Fig. 1(a). The target reservoir is strongly heterogeneous in the vertical direction, with an upper low-permeability layer, a middle high-permeability layer, and a lower medium-permeability layer. Accordingly, the model was divided vertically into three layers with permeabilities of 1000, 5000, and 3000 mD, respectively, consistent with the actual reservoir architecture and the numerical model. The model reproduces the flow characteristics and development disparities among layers with different permeability levels, including preferential flow through the high-permeability layer and limited recovery from the medium- and low-permeability layers during the ultra-high water cut stage, thereby providing an experimental basis for evaluating interlayer interference and development performance under different well pattern adjustment schemes. The layer arrangement and injection-production configuration were also designed to be consistent with those of the target reservoir, ensuring a uniform basis for comparison among the schemes and facilitating analysis of layer-specific development performance and changes in remaining oil distribution during well pattern adjustment.

Table 1 Geological parameters of Block C in the Bohai Sea.

Geological parameter	Value
Average permeability, mD	2815
Depth, m	1560
Crude-oil viscosity, mPa·s	24–452
Initial reservoir temperature, °C	65
Surface crude-oil density, t·m ⁻³	0.971
Reservoir burial depth, m	1175–1605
Initial formation-water salinity, mg·L ⁻¹	4752
Produced-water salinity, mg·L ⁻¹	6500–9800
Ca ²⁺ and Mg ²⁺ concentrations in produced water, mg · L ⁻¹	160–300
Initial reservoir pressure, MPa	14.3
Current reservoir pressure, MPa	13.5
Average porosity	0.32

The three-dimensional physical model is shown in Fig. 1(b). The experimental system consisted of a displacement unit, the three-dimensional physical model, a temperature-control system, a pressure-monitoring system, and a produced-fluid metering system. Before waterflooding, the model was successively saturated with water and oil to establish the initial oil-saturation condition. Water was then injected at a constant rate of 0.5 mL·min⁻¹ at 65 °C, and production proceeded according to the specified well pattern adjustment scheme. At the end of each experiment, the recovery factor and remaining oil distribution were determined. These results were evaluated together with the numerical simulation results to characterize the variations in interlayer interference, development performance, and remaining oil distribution and to support the selection of subsequent well pattern adjustments. To further verify the physical experimental results, a numerical model was established using the same dimensions, well locations, layer thicknesses, permeability distribution, fluid properties, initial conditions, and injection-production controls as the

physical model. The numerical simulations were used to supplement and cross-check the physical experimental results under the different well pattern adjustment schemes.



(a) Schematic of the physical experimental system (b) Three-dimensional physical model
Fig. 1 Experimental setup and three-dimensional physical model.

2.3 Experimental Scheme Design

Table 2 Design of the well pattern adjustment schemes.

Scheme	Scheme design
Reference scheme	Row well pattern with separate-layer injection-production; waterflooding continued until the water cut reached 98%.
Scheme 1	A row well pattern with commingled injection-production was used from 0 to 80% water cut. At 80% water cut, one horizontal production well was added to the high-permeability thick layer, and waterflooding continued until the water cut reached 98%.
Scheme 2	A row well pattern with commingled injection-production was used from 0 to 80% water cut. A horizontal production well was added to the high-permeability thick layer at 80% water cut. At 90% water cut, the central production well in the thick layer was shut in, and waterflooding continued until the water cut reached 98%.
Scheme 3	A row well pattern with commingled injection-production was used from 0 to 80% water cut. A horizontal production well was added to the high-permeability thick layer at 80% water cut. At 90% water cut, selected directional wells were shut in to establish a staggered well pattern, and separate-layer injection-production was implemented until the water cut reached 98%.
Scheme 4	A row well pattern with commingled injection-production was used from 0 to 80% water cut. A horizontal production well was added to the high-permeability thick layer at 80% water cut. At 90% water cut, the injection-production pattern was converted by changing the central production well and the horizontal well into injection wells and converting one original injection well into a production well. Waterflooding then continued until the water cut reached 98%.

A reference scheme and four well pattern adjustment schemes were designed according

to the development conditions of the target reservoir during the ultra-high water cut stage and the sequence of field well pattern modifications, as summarized in Table 2. The reference scheme was established based on the existing row well pattern with separate-layer injection-production to represent the maximum achievable development performance under the current well pattern configuration. In this scheme, each reservoir layer was independently controlled through separate injection-production, thereby minimizing interlayer fluid exchange and providing an idealized development condition for evaluating the potential recovery performance of the existing well pattern. The reference scheme was not considered as an adjustment strategy but was used as a benchmark for calculating the interlayer interference coefficient, evaluating the development potential of the existing well pattern, and comparing the effectiveness of subsequent well pattern adjustment schemes. The four adjustment schemes were not independent alternatives; instead, each subsequent adjustment was developed based on the development response observed during the preceding stage. Scheme 1 introduced a horizontal well into the high-permeability thick layer on the basis of the existing row well pattern to evaluate the additional recovery potential of remaining oil in the high-permeability layer, the development response of the medium- and low-permeability layers, and the associated changes in interlayer interference. Based on the results of Scheme 1, Scheme 2 reduced the development intensity of the high-permeability layer by shutting in its central production well, allowing the effectiveness of a single adjustment measure to be assessed. The results from these stages were then combined with previous findings on staggered well patterns, separate-layer injection-production, and adjustment of injection-production relationships to formulate two further schemes. Scheme 3 established a triangular staggered injection-production configuration and implemented

separate-layer injection-production to improve the coordinated development of layers with different permeability levels. Scheme 4 modified the injection-production relationships to redirect interwell fluid flow and further evaluate the resulting development response. The performance of all schemes was subsequently compared in terms of recovery factor, interlayer interference coefficient, and remaining oil distribution to identify suitable well pattern adjustment strategies for the ultra-high water cut stage.

To quantitatively characterize changes in interlayer interference under the different well pattern adjustment schemes, an interlayer interference coefficient, α , was introduced by adapting an existing evaluation method to the development characteristics of the target reservoir. Interlayer interference is manifested by differences in the development performance of layers with different permeability levels. As preferential flow through the high-permeability layer intensifies, injected water increasingly follows the high-permeability pathway, the development disparity among the layers increases, and interlayer interference becomes more severe. The coefficient therefore provides a consistent basis for comparing changes in interference among the different schemes. A larger coefficient indicates stronger preferential flow through the high-permeability layer, a greater disparity in development among the layers, and more severe interlayer interference, whereas a smaller value indicates more coordinated development and reduced interference. The coefficient is calculated as

$$\alpha = (Q_{\text{ref}} - Q_i) / Q_{\text{ref}} \quad (2-1)$$

where α is the interlayer interference coefficient, Q_{ref} is the total oil production of the reference scheme, and Q_i is the total oil production of the scheme being evaluated. Although the coefficient quantitatively reflects the relative change in interlayer interference, it cannot

fully represent the overall development response after well pattern adjustment. It was therefore evaluated together with recovery factor and remaining oil distribution. Cross-comparison among these indicators was used to clarify the relationship between changes in interlayer interference and reservoir performance and to provide a basis for evaluating and selecting the adjustment schemes.

3 Results and Discussion

3.1 Development Performance of Scheme 1

The well pattern adjustment sequence for Scheme 1 is shown in Fig. 2. A row well pattern with commingled injection-production was used from 0 to 80% water cut. When the water cut reached 80%, one horizontal well was added to the high-permeability layer, and waterflooding continued until the water cut reached 98%. The permeabilities of the upper, middle, and lower layers were 1000, 5000, and 3000 mD, respectively. This scheme was designed to investigate how horizontal well infill used to enhance recovery from the high-permeability layer during the ultra-high water cut stage affects interlayer interference and overall development performance.

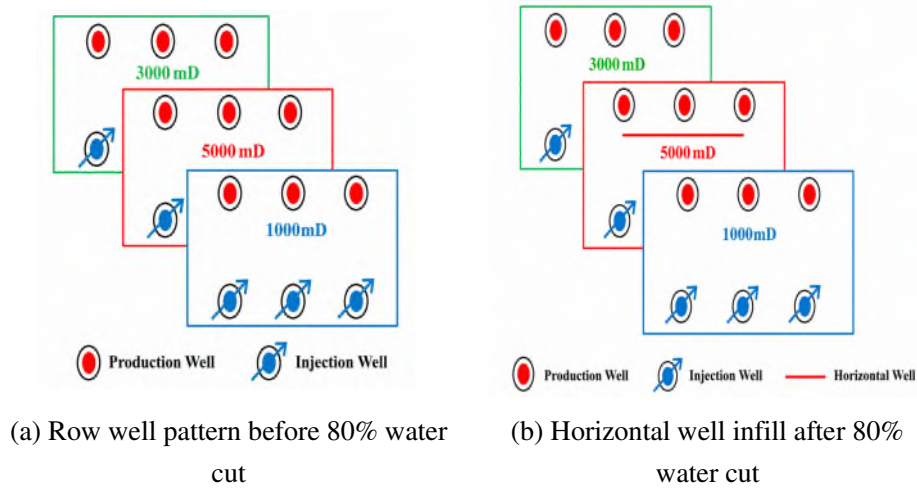


Fig. 2 Well pattern configuration for Scheme 1.

Figure 3 shows the Recovery factor curves obtained from the physical experiment and numerical simulation for Scheme 1. Before the water cut reached 80%, the recovery factor of each layer increased continuously, with the high-permeability layer consistently exhibiting the highest growth rate, while the increases in the medium- and low-permeability layers gradually slowed. After horizontal well infill, the recovery factor of the high-permeability layer continued to increase, whereas those of the medium- and low-

permeability layers tended to stabilize, resulting in only a slight increase in the overall recovery factor. In the physical experiment, the overall recovery factor was 37%, and the recovery factors of the low-, medium-, and high-permeability layers were 21%, 33%, and 45%, respectively. In the numerical simulation, the overall recovery factor was 48.56%, while those of the high-, medium-, and low-permeability layers were 62.35%, 32.96%, and 21.13%, respectively. The increase in the overall recovery factor was mainly contributed by the high-permeability layer, whereas the improvements in the medium- and low-permeability layers were limited. Because the horizontal well was placed in the high-permeability layer, the displacement fluid continued to migrate preferentially through this layer, further mobilizing the remaining oil within it. The medium- and low-permeability layers remained strongly affected by preferential flow, and their development performance improved only marginally.

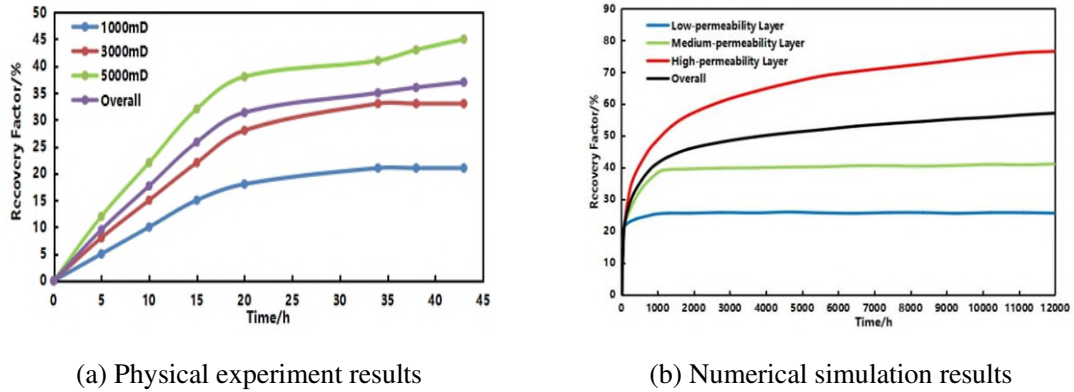
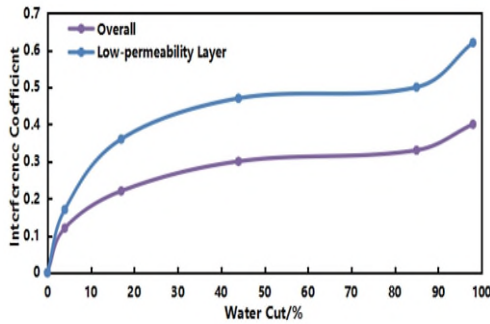


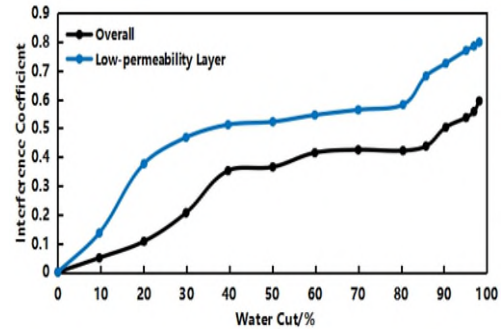
Fig. 3 Recovery factor curves for Scheme 1.

The interlayer interference coefficients were calculated, as shown in Fig. 4. During development under the row well pattern, the interlayer interference coefficient increased continuously with water cut. After horizontal well infill, the overall interference coefficient obtained from the physical experiment increased from 0.33 to 0.40, while the coefficient of the low-permeability layer increased from 0.50 to 0.62. In the numerical simulation, the

overall interference coefficient increased from 0.42 to 0.59, and that of the low-permeability layer increased from 0.53 to 0.76. The physical experimental and numerical simulation results exhibited consistent trends. Placement of the horizontal well in the high-permeability layer further enhanced its flow capacity, and injected water continued to migrate preferentially through this layer. Consequently, most of the incremental recovery was contributed by the high-permeability layer, whereas the medium- and low-permeability layers remained poorly mobilized. Because all three layers were still developed through commingled injection-production, preferential flow through the high-permeability layer continued to intensify, further widening the development disparity among the layers and increasing interlayer interference. These results indicate that horizontal well infill in the high-permeability layer can improve the recovery of remaining oil within that layer but cannot improve coordinated development among layers with different permeability levels; further well pattern adjustment is therefore required.



(a) Physical experimental results



(b) Numerical simulation results

Fig. 4 Variation in the interlayer interference coefficient with water cut for Scheme 1.

Figure 5 shows the remaining oil distribution at 98% water cut under Scheme 1. Remaining oil near the horizontal well in the high-permeability layer was substantially reduced, and the swept area was larger than that achieved under the row well pattern. However, extensive remaining oil accumulations persisted in the medium- and low-

permeability layers, and distinct unswept regions remained between wells. The remaining oil distribution further corroborates the Recovery factor and interlayer interference coefficient results. Although remaining oil near the horizontal well in the high-permeability layer was markedly reduced, extensive remaining oil remained in the medium- and low-permeability layers and in unswept interwell regions, indicating that the additional swept volume was concentrated mainly in the high-permeability layer and that preferential flow was not effectively controlled. horizontal well infill in the high-permeability layer alone was therefore insufficient to coordinate the development of layers with different permeability levels, and further well pattern adjustment was required to improve recovery from the medium- and low-permeability layers.

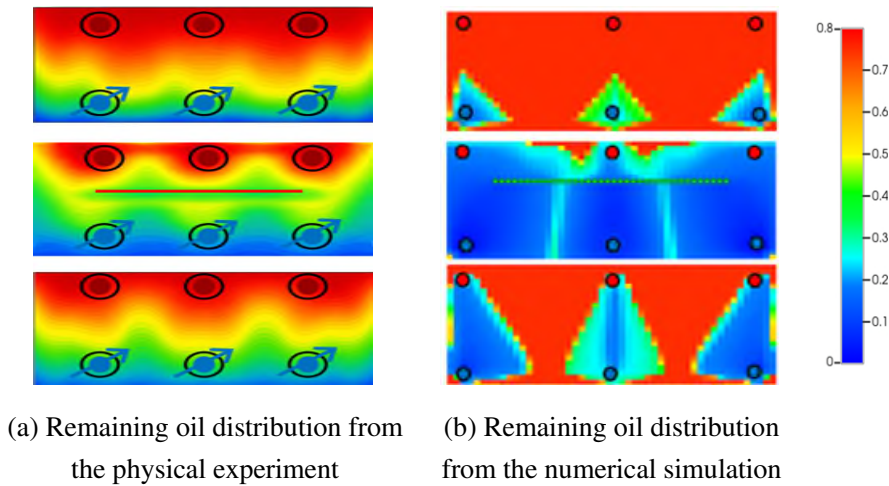


Fig. 5 Remaining oil distribution at 98% water cut for Scheme 1.

3.2 Development Performance of Scheme 2

The well pattern adjustment sequence for Scheme 2 is shown in Fig. 6. A row well pattern with commingled injection-production was used from 0 to 80% water cut. After the water cut reached 80%, a horizontal well was added to the high-permeability layer. When the water cut reached 90%, the central production well in the high-permeability layer was shut in, and waterflooding continued until the water cut reached 98%. This scheme was designed to investigate the effects of well shut-in on interlayer interference and development performance by improving the development balance among layers with

different permeability levels during the ultra-high water cut stage.

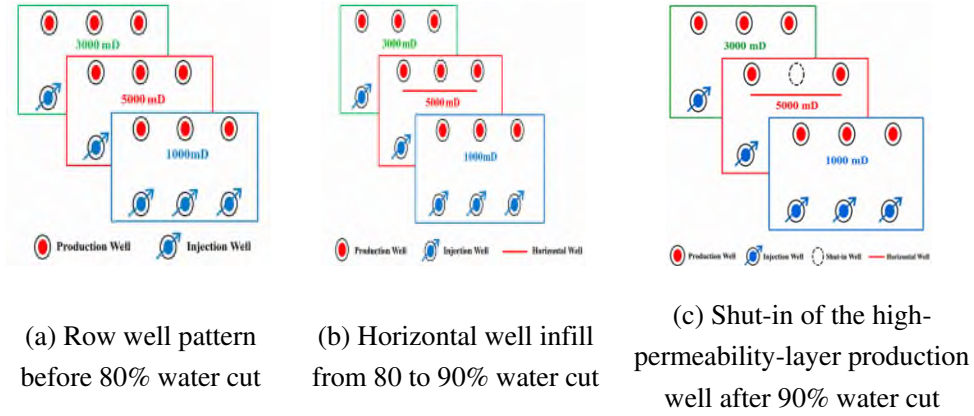


Fig. 6 Schematic of the well pattern configuration for Scheme 2.

Figure 7 shows the Recovery factor curves obtained from the physical experiment and numerical simulation. Before the water cut reached 80%, the recovery trends of the individual layers were essentially the same as those observed in Scheme 1. After the production well in the high-permeability layer was shut in, the recovery factors of the medium- and low-permeability layers continued to increase, whereas that of the high-permeability layer changed only slightly, resulting in a modest increase in the overall recovery factor. In the physical experiment, the overall recovery factor increased from 37.0% in Scheme 1 to 37.2%. In the numerical simulation, the overall recovery factor increased from 48.56% to 49.83%; the recovery factor of the high-permeability layer increased from 62.35% to 62.63%, that of the medium-permeability layer increased from 32.96% to 33.85%, and that of the low-permeability layer increased from 21.13% to 21.96%. Although the improvement in the overall recovery factor was limited, recovery from both the medium- and low-permeability layers increased. This indicates that shutting in the central production well reduced the development intensity of the high-permeability layer and redirected part of the displacement fluid towards the medium- and low-permeability layers, thereby

improving the development balance among the three layers to some extent.

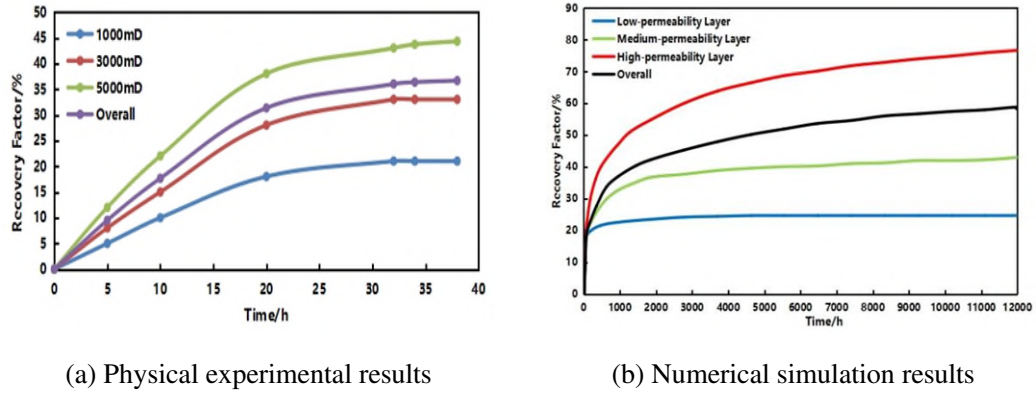


Fig. 7 Recovery factor curves for Scheme 2.

To further clarify the causes of the recovery response, the interlayer interference coefficients were analysed, as shown in Fig. 8. Before the production well in the high-permeability layer was shut in, the interference coefficient followed essentially the same trend as that observed in Scheme 1. After well shut-in, the coefficient continued to increase with development, but its rate of increase declined markedly. In the physical experiment, the final overall interference coefficient and the coefficient of the low-permeability layer were approximately 0.38 and 0.60, respectively, lower than the corresponding values of 0.40 and 0.62 in Scheme 1. In the numerical simulation, the overall interference coefficient decreased from 0.59 in Scheme 1 to 0.58, while that of the low-permeability layer decreased from 0.76 to 0.73. After the central production well in the high-permeability layer was shut in, the development intensity of this layer decreased, and part of the displacement fluid was redirected towards the medium- and low-permeability layers, resulting in some improvement in their recovery factors and a slower increase in interlayer interference. However, because commingled injection-production was still used for all three layers, strong hydraulic communication remained between the high-permeability layer and the medium- and low-permeability layers. Preferential flow through the high-permeability layer

was therefore not eliminated, and interlayer interference continued to intensify during development, although at a slower rate. These results show that shutting in the production well can improve coordinated development among layers with different permeability levels, but this measure alone cannot further suppress preferential flow through the high-permeability layer.

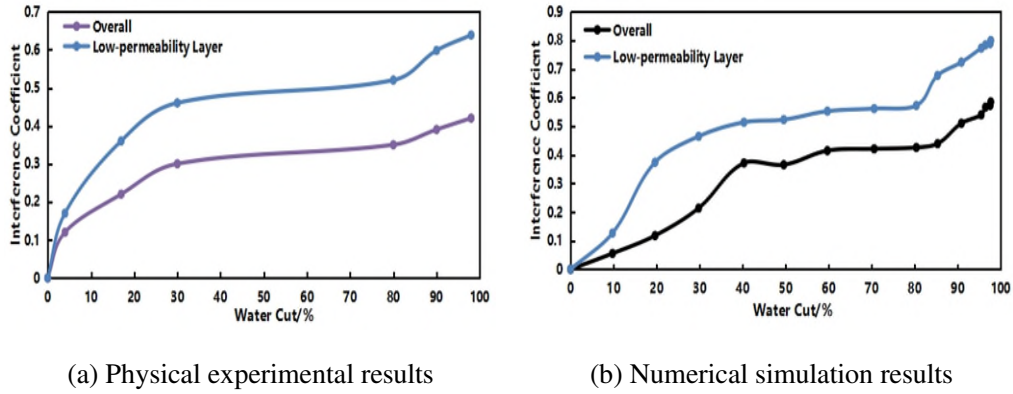


Fig. 8 Variation in the interlayer interference coefficient with water cut for Scheme

2.

Figure 9 shows the remaining oil distribution at 98% water cut under Scheme 2. After the production well in the high-permeability layer was shut in, remaining oil continued to decrease locally within the high-permeability layer, and oil saturation declined in some interwell regions of the medium- and low-permeability layers. However, the overall change in remaining oil distribution was limited, and extensive remaining oil accumulations persisted in the medium- and low-permeability layers and in unswept interwell regions, consistent with the z and interlayer interference coefficient results. Reducing the development intensity of the high-permeability layer allowed part of the displacement fluid to enter the medium- and low-permeability layers and increased their recovery factors to some extent. Nevertheless, because preferential flow through the high-permeability layer remained dominant, the expansion of the swept regions in the medium- and low-permeability layers was limited, and the overall pattern of remaining oil accumulation did

not change substantially. These results indicate that shutting in the production well can improve local development conditions but cannot fundamentally alter the development pattern dominated by preferential flow through the high-permeability layer. Further optimization of both the well pattern configuration and the operating strategy is therefore required. A staggered well pattern can be used to improve interwell flow relationships, while separate-layer injection-production or injection-production conversion can improve development performance among layers with different permeability levels, providing the basis for Schemes 3 and 4.

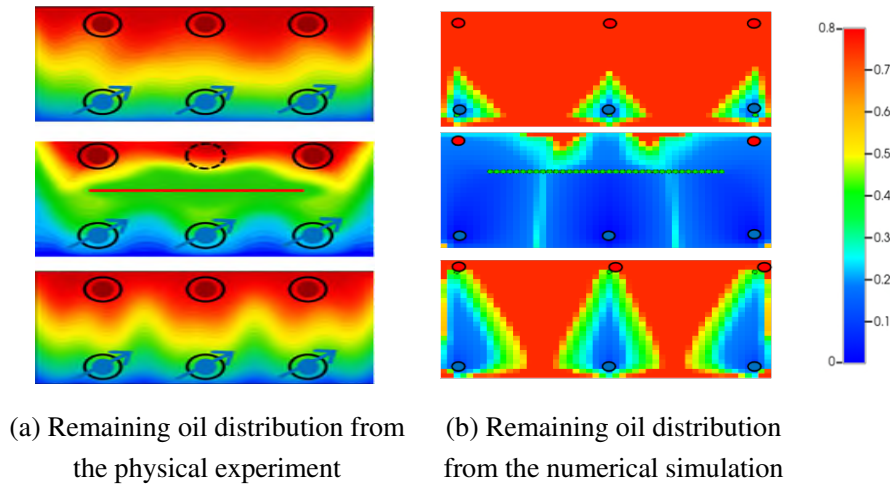


Fig. 9 Remaining oil distribution at 98% water cut for Scheme 2.

3.3 Development Performance of Scheme 3

Based on Scheme 2, and considering that a single control measure could not simultaneously alleviate interwell and interlayer interference, Scheme 3 further optimized the well pattern configuration to address the continued development of interlayer interference and the limited improvement in interwell flow observed in Scheme 2. separate-layer injection-production was introduced to enable independent development of layers with different permeability levels, allowing the combined effects of well pattern optimization and layered development to be evaluated. The well pattern adjustment was intended primarily to improve interwell flow relationships and reduce interwell interference, where as separate-

layer control regulated the injection-production processes of individual layers to mitigate interlayer interference. A staggered well pattern combined with separate-layer injection-production was therefore adopted to investigate its influence on reservoir performance. As shown in Fig. 10, a row well pattern with commingled injection-production was used from 0 to 80% water cut; a horizontal well was added to the high-permeability layer when the water cut reached 80%; and after the water cut reached 90%, selected directional wells were shut in to establish a staggered well pattern, while separate-layer injection-production was implemented until the water cut reached 98%. By combining well pattern adjustment with optimization of the injection-production mode, this scheme was used to investigate the evolution of interlayer interference and its influence on development performance after hydraulic communication among the layers had been weakened.

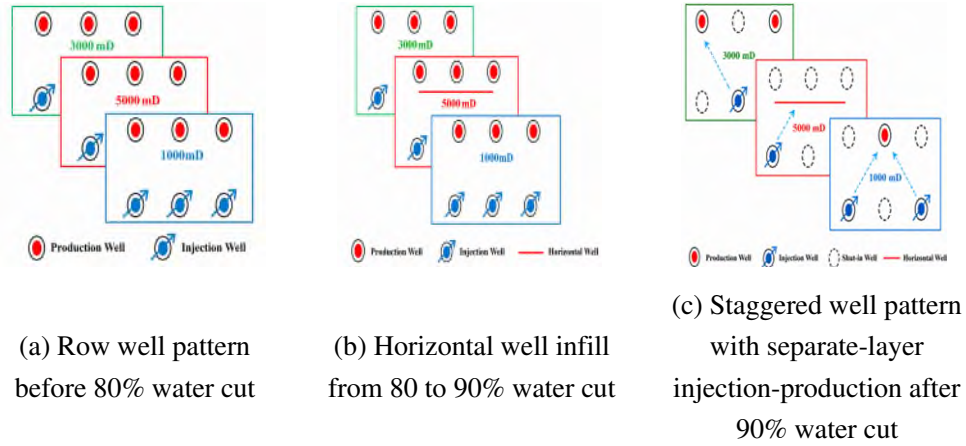
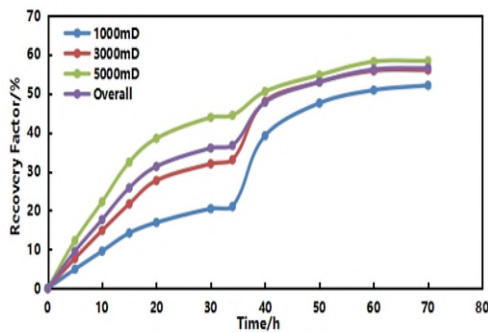


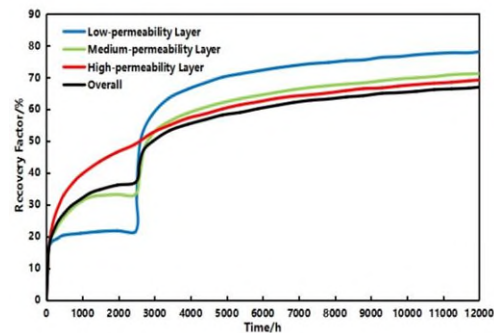
Fig. 10 Schematic of the well pattern configuration for Scheme 3.

Figure 11 presents the recovery factor curves obtained from the physical experiment and numerical simulation. Before the water cut reached 90%, the recovery trends of the individual layers were essentially the same as those observed in Scheme 2. After implementation of the staggered well pattern combined with separate-layer injection-production, the recovery factors of all three layers increased markedly, and the increase in

overall recovery was substantially greater than those achieved in Schemes 1 and 2. In the physical experiment, the final overall recovery factor reached 56.57%, representing an increase of 19.37 percentage points relative to Scheme 2, while the recovery factors of the low-, medium-, and high-permeability layers reached 52.12%, 56.04%, and 58.41%, respectively. In the numerical simulation, the overall recovery factor reached 69.10%, an increase of 19.27 percentage points relative to Scheme 2, and the recovery factors of the low-, medium-, and high-permeability layers reached 77.49%, 68.34%, and 67.62%, respectively. Compared with Scheme 2, not only did the overall recovery factor increase substantially, but the improvements in the medium- and low-permeability layers were also greater than that in the high-permeability layer, resulting in a pronounced reduction in the recovery disparity among the three layers. These results indicate that the staggered well pattern combined with separate-layer injection-production improved both overall reservoir performance and coordinated development among layers with different permeability levels. The staggered well pattern modified the interwell flow relationships, while separate-layer injection-production enhanced fluid intake in the medium- and low-permeability layers, enabling recovery from all three layers to increase simultaneously and substantially improving overall development performance.



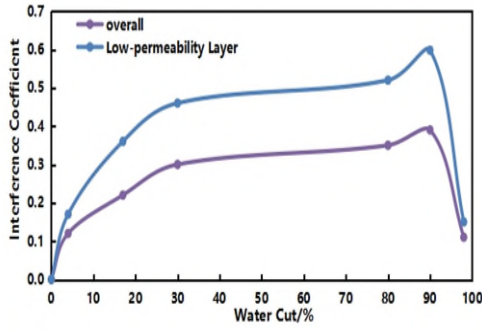
(a) Physical experimental results



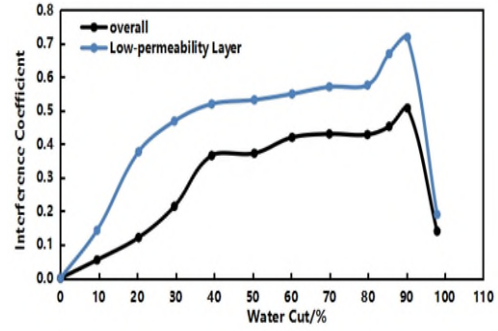
(b) Numerical simulation results

Fig. 11 Recovery factor curves for Scheme 3.

To further clarify the causes of the recovery response, the interlayer interference coefficients were analysed, as shown in Fig. 12. After implementation of the staggered well pattern combined with separate-layer injection-production, the interlayer interference coefficients decreased substantially. In the physical experiment, the overall interference coefficient and that of the low-permeability layer decreased to 0.11 and 0.15, respectively; in the numerical simulation, they decreased to 0.14 and 0.19, respectively. Compared with Scheme 2, the overall interference coefficient decreased from 0.38 to 0.11 and that of the low-permeability layer decreased from 0.60 to 0.15 in the physical experiment, while the corresponding coefficients decreased from 0.58 to 0.14 and from 0.73 to 0.19 in the numerical simulation. Both the physical experimental and numerical simulation results demonstrate that the staggered well pattern combined with separate-layer injection-production markedly reduced interlayer interference and improved coordinated development among layers with different permeability levels. The staggered well pattern altered the original interwell flow relationships and enlarged the displacement sweep, while separate-layer injection-production enabled independent control of the injection energy supplied to each layer. This weakened preferential flow through the high-permeability layer, promoted a more uniform distribution of displacement fluid into the medium- and low-permeability layers, and increased their recovery, thereby achieving coordinated development of the three layers and substantially improving overall reservoir performance.



(a) Physical experimental results



(b) Numerical simulation results

Fig. 12 Variation in the interlayer interference coefficient with water cut for Scheme 3.

Figure 13 shows the remaining oil distribution under Scheme 3. Compared with Scheme 2, the high-permeability layer maintained a high recovery level, while oil saturation in the medium- and low-permeability layers decreased markedly. remaining oil in the original interwell and unswept regions was substantially reduced, the displacement sweep was significantly enlarged, and the remaining oil became more uniformly distributed. The remaining oil distribution further confirms the recovery factor and interlayer interference coefficient results. After implementation of the staggered well pattern combined with separate-layer injection-production, interwell remaining oil in the medium- and low-permeability layers decreased substantially, and the remaining oil distributions among the different layers became more uniform, indicating that the additional swept volume had extended from the high-permeability layer into the medium- and low-permeability layers. Compared with Schemes 1 and 2, Scheme 3 increased the overall recovery factor while also improving coordinated development among the layers, achieving simultaneous improvements in reservoir performance and interlayer development balance and providing an effective approach for further well pattern optimization during the ultra-high water cut stage.

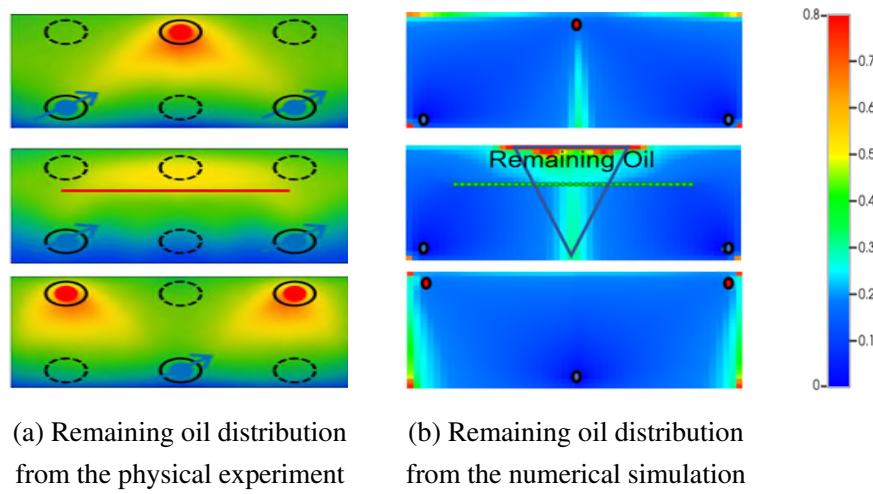
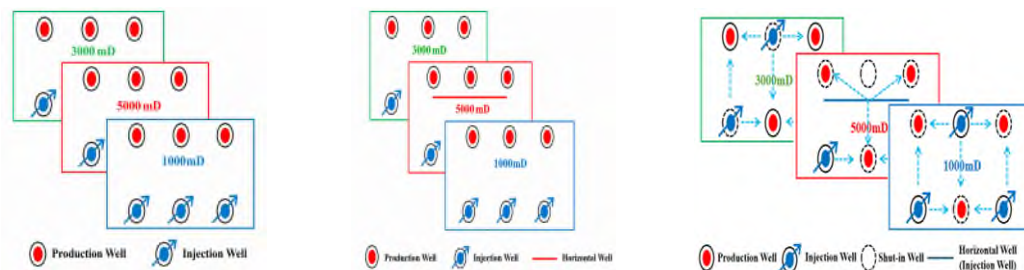


Fig. 13 Remaining oil distribution at 98% water cut for Scheme 3.

3.4 Development Performance of Scheme 4

Scheme 4 was designed to further investigate the effects of different well pattern adjustment methods on development performance. On the basis of Scheme 2, the injection-production roles of selected wells were changed to optimize the existing well pattern, such that some injection wells no longer communicated directly with the high-permeability layer but instead established new injection – production connections with the medium- and low-permeability layers. This scheme was used to examine the development response of layers with different permeability levels after adjustment of the injection-production relationships. As shown in Fig. 14, a row well pattern with commingled injection-production was used from 0 to 80% water cut; a horizontal well was added to the high-permeability layer at 80% water cut; and after the water cut reached 90%, selected injectors and producers were converted to modify the spatial injection-production relationships. Development was then continued until the water cut reached 98%.



(a) Row well pattern before 80% water cut	(b) Horizontal well infill from 80 to 90% water cut	(c) Conversion of the injection- production relationships after 90% water cut
--	--	---

Fig. 14 Schematic of the well pattern configuration for Scheme 4.

Figure 15 presents the recovery factor curves obtained from the physical experiment and numerical simulation. Before the water cut reached 90%, the recovery trends of the individual layers were essentially the same as those observed in Scheme 2. After the well-role conversion, the recovery factors of all three layers increased, and the overall recovery factor continued to rise. In the physical experiment, the final overall recovery factor reached 52.32%, representing an increase of 15.12 percentage points relative to Scheme 2, while the recovery factors of the high-, medium-, and low-permeability layers were 61.23%, 49.49%, and 35.00%, respectively. In the numerical simulation, the overall recovery factor reached 56.38%, an increase of 6.55 percentage points relative to Scheme 2, and the recovery factors of the high-, medium-, and low-permeability layers were 54.62%, 58.39%, and 36.52%, respectively. Compared with Scheme 2, the improvements in the medium- and low-permeability layers were more pronounced, whereas the recovery factor of the high-permeability layer changed only slightly. Adjustment of the injection-production relationships redirected part of the displacement fluid away from the original preferential flow paths towards the medium- and low-permeability layers, thereby enlarging their swept regions and further increasing the overall recovery factor. However, because the basic well pattern configuration remained unchanged, a development disparity among the three layers persisted.

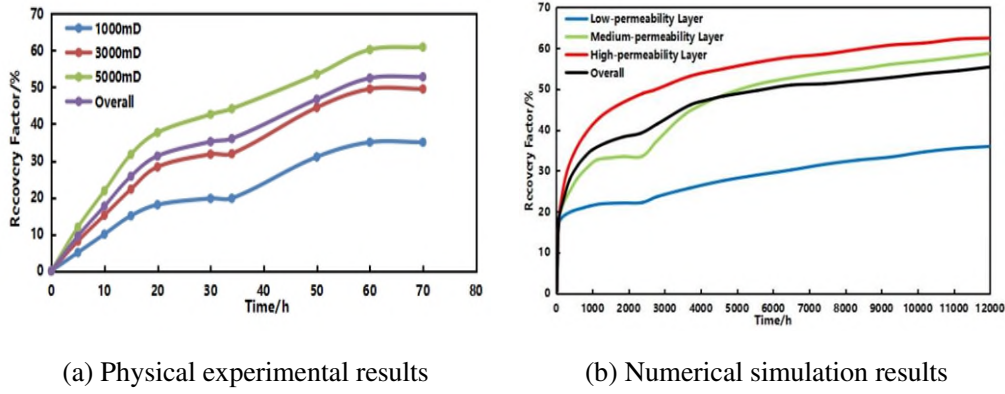


Fig. 15 Recovery factor curves for Scheme 4.

To clarify the causes of the recovery response, the interlayer interference coefficients were analysed, as shown in Fig. 16. After the well-role conversion, the interlayer interference coefficients were lower than those obtained under Scheme 2. In the physical experiment, the overall interference coefficient and that of the low-permeability layer were 0.33 and 0.48, respectively; the corresponding numerical simulation values were 0.44 and 0.60. Relative to Scheme 2, the overall and low-permeability-layer interference coefficients decreased by 0.05 and 0.12 in the physical experiment and by 0.14 and 0.13 in the numerical simulation, respectively. Adjustment of the injection-production relationships established new connections between some injection wells and the medium- and low-permeability layers, redirecting part of the displacement fluid away from the high-permeability layer and improving local flow directions. Interlayer interference and interwell interference. Nevertheless, the original well pattern configuration was retained, strong hydraulic communication persisted among the layers, and preferential flow through the high-permeability layer was not completely eliminated. Although interlayer interference was further alleviated, development disparities among the layers remained, and the overall interference coefficient was therefore still higher than that obtained under Scheme 3.

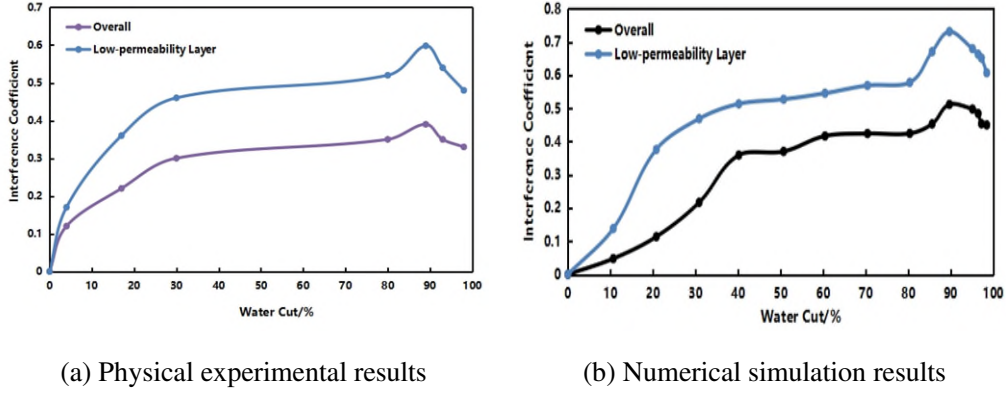


Fig. 16 Variation in the interlayer interference coefficient with water cut for Scheme

4.

Figure 17 shows the remaining oil distribution at 98% water cut under Scheme 4. After the well-role conversion, oil saturation decreased locally in the medium- and low-permeability layers compared with Scheme 2, part of the interwell remaining oil was mobilized, the high-permeability layer retained a high recovery level, and the overall swept area increased. The remaining oil distribution was consistent with the recovery factor and interlayer interference coefficient results, indicating that adjustment of the injection-production relationships improved development performance in some regions by redirecting local flow. However, extensive remaining oil remained concentrated in unswept interwell regions of the medium- and low-permeability layers, and preferential flow through the high-permeability layer persisted. Compared with Scheme 3, Scheme 4 relied primarily on adjustment of the injection-production relationships to improve local flow conditions and did not incorporate separate-layer control. It could therefore alleviate part of the interlayer and interwell interference but could not achieve coordinated development among layers with different permeability levels, and its overall development performance remained inferior to that of Scheme 3. Scheme 4 demonstrates that adjustment of the injection-production relationships can improve local flow conditions and provide additional displacement opportunities for the medium- and low-permeability layers; however, because

a complete separate-layer development system was not established, the resulting improvement was concentrated mainly in local regions.

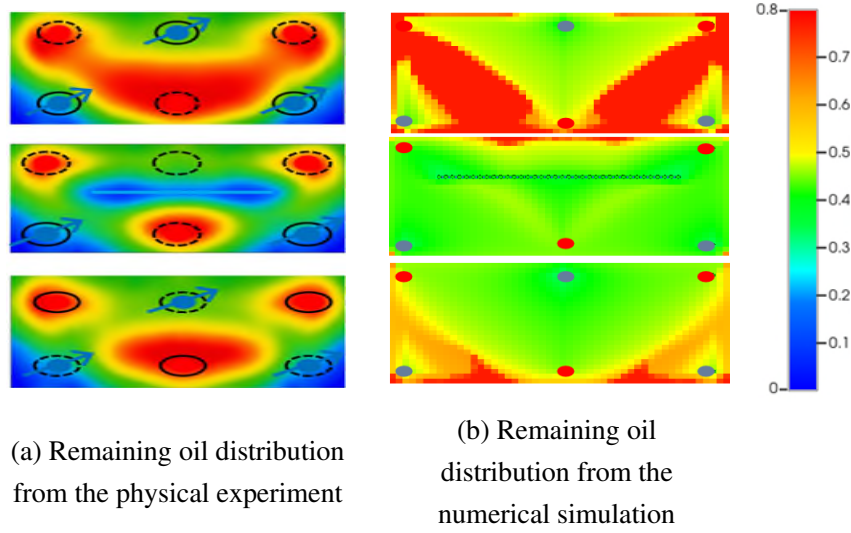


Fig. 17 Remaining oil distribution for Scheme 4.

3.5 Comprehensive Evaluation of the well pattern Adjustment Schemes

In order to evaluate the development performance of the different well pattern adjustment schemes, the final recovery factors of all schemes were compared, as shown in Fig. 18(a). In the physical experiments, the final recovery factors of Schemes 1, 2, 3, and 4 were 37.0%, 37.2%, 56.57%, and 52.32%, respectively, while the corresponding values obtained from the numerical simulations were 48.56%, 49.83%, 69.10%, and 56.38%. Schemes 1 and 2 produced only minor improvements in the overall recovery factor. After further well pattern optimization on the basis of Scheme 2, the recovery factors of Schemes 3 and 4 increased markedly, with Scheme 3 exhibiting the largest improvement. These results indicate that horizontal well infill in the high-permeability layer and shut-in of the high-permeability-layer production well can improve local development performance, but further optimization of the well pattern configuration or development mode is required to substantially increase the overall recovery factor. Figure 18(b) shows the variation in the overall interference coefficient at different water-cut stages. At water cuts of 30% and 80%,

the overall interference coefficients were essentially identical among the schemes, with physical experimental values of 0.22 and 0.33 and numerical simulation values of 0.21 and 0.42, respectively. During these stages, all schemes employed the same well pattern and development mode, and neither the interwell flow relationships nor the development conditions of the individual layers had changed; therefore, the interference coefficients remained consistent. After entering the high-water-cut stage, different well pattern adjustment measures were implemented, and differences in the overall interference coefficients gradually emerged. Under Scheme 1, horizontal well infill in the high-permeability layer further intensified preferential flow through this layer. Under Scheme 2, shutting in the high-permeability-layer production well reduced the development intensity of the high-permeability layer and slowed the increase in the interference coefficient; however, because commingled injection-production was retained, interlayer interference continued to develop. Under Scheme 4, adjustment of the injection-production relationships further reduced the overall interference coefficient, but the well pattern configuration remained unchanged and strong hydraulic communication persisted among layers with different permeability levels. Under Scheme 3, the staggered well pattern combined with separate-layer injection-production produced the lowest overall interference coefficients, with final values of 0.11 and 0.14 in the physical experiment and numerical simulation, respectively, indicating that the combined effects of well pattern optimization and separate-layer development promoted more coordinated development among the different permeability layers. Schemes 3 and 4 were both developed as further optimization measures on the basis of Scheme 2, but followed different adjustment approaches. Scheme 4 retained the original well pattern configuration and improved development performance by adjusting

the injection-production relationships, whereas Scheme 3 further optimized the well pattern configuration and implemented separate-layer injection-production to enable independent development of layers with different permeability levels. The former focused primarily on improving interwell flow relationships, while the latter simultaneously incorporated well pattern optimization and separate-layer development, thereby achieving a higher overall recovery factor and a lower degree of interlayer interference.

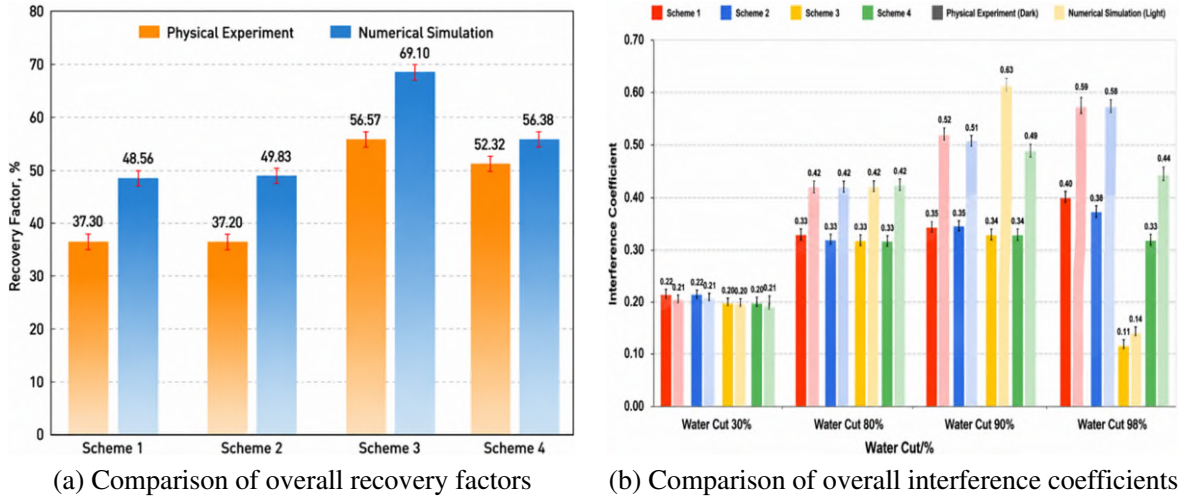


Fig. 18 Overall comparison of the different well pattern adjustment schemes.

The results demonstrate that, during the ultra-high water cut stage, a single well pattern adjustment measure cannot simultaneously improve development performance and coordination among the different layers. As reservoir development proceeds, well pattern optimization should be implemented progressively according to the observed development response. When preferential flow through the high-permeability layer continues to restrict recovery from the medium- and low-permeability layers, adjustment of the injection-production relationships alone cannot provide further substantial improvement. In contrast, a staggered well pattern combined with separate-layer injection-production can simultaneously optimize the well pattern configuration and development mode, increase

recovery from the medium- and low-permeability layers, and reduce interlayer interference. This approach is therefore more suitable for further well pattern adjustment in the target reservoir during the ultra-high water cut stage and may also provide a reference for the late-stage development of comparable strongly heterogeneous offshore heavy-oil reservoirs.

4 Conclusions

(1) Individual adjustment measures are insufficient to resolve the development imbalance during the ultra-high water cut stage. Horizontal well infill and high-permeability-layer well shut-in improved local development performance but could not fundamentally eliminate interlayer development disparities.

(2) The combination of a staggered well pattern and separate-layer injection-production achieved better development performance. This strategy reduced interlayer interference, improved layer coordination, and enhanced remaining oil recovery from medium- and low-permeability layers.

(3) A progressive well pattern adjustment strategy based on development response was established. The proposed strategy provides guidance for late-stage optimization of strongly heterogeneous offshore reservoirs during the ultra-high water cut stage.

Data availability: To access the measured experimental data, one can contact Dr. Kun Qian by contacting email of qiankun@cczu.edu.cn.

Acknowledgments: This publication is based upon work supported by CNPC-CZU Innovation Alliance and National Natural Science Foundation of China. The authors would like to acknowledge the support received under the Research Program 2021DQ06 and National Natural Science Foundation of China (52404018).

Funding: This study received funding from CNPC-CZU Innovation

Alliance(2021DQ06) and National Natural Science Foundation of China (52404018).

References

- [1] Lu, Y.; He, W.; Wang, J.; Liu, J.; Shi, H.; Yang, D. Experimental Study on Interlayer Interference Characteristics During Commingled Production in a Multilayer Tight Sandstone Gas Reservoir. *Appl. Sci.* 2024, 14, 10534. <https://doi.org/10.3390/app142210534>.
- [2] Wang, K.; Zheng, W.; He, Y.; Tang, C.; Pan, Y.; Li, J.; Jiang, J.; Cai, S.; Li, J. Analysis of Inter-Layer Interference in Multi-Layer Reservoir Commingled Production Wells. *Processes* 2024, 12, 1644. <https://doi.org/10.3390/pr12081644>.
- [3] Liu, D. , Zhang, F. , Zhu, Q. , Wang, X. and Fan, J. (2019) Quantitative Characterization and Dynamic Law of Interlayer Interference for Multilayer Commingled Production in Heavy Oil Reservoirs by Numerical Simulation. *World Journal of Engineering and Technology*, 7, 379-395. doi: [10.4236/wjet.2019.73028](https://doi.org/10.4236/wjet.2019.73028).
- [4] Zhang T, Wang BR, Zhao YL, et al. Inter-layer interference for multi-layered tight gas reservoir in the absence and presence of movable water. *Petroleum Science*, 2024, 21(3):1751-1764. DOI:10.1016/j.petsci.2024.01.009.
- [5] Liu G, Meng Z, Luo D, Wang J, Gu D, Yang D. Experimental evaluation of interlayer interference during commingled production in a tight sandstone gas reservoir with multi-pressure systems. *Fuel*, 2020, 262:116557. <https://doi.org/10.1016/j.fuel.2019.116557>.
- [6] Xu J, Hu X, Ning B. Dynamic Interference Behaviors of Arbitrary Multilayer Commingling Production in Heavy Oil Reservoirs with Water Flooding. *ACS Omega*, 2021, 6(15):10005–10012. <https://doi.org/10.1021/acsomega.0c06154>.
- [7] Huang S, Kang B, Cheng L, Zhou W, Chang S. Quantitative characterization of interlayer interference and productivity prediction of directional wells in the multilayer commingled production of ordinary offshore heavy oil reservoirs. *Petroleum Exploration and Development*, 2015, 42(4):533-540. DOI:10.1016/S1876-3804(15)30046-X.
- [8] Tao X, Okere CJ, Su G, Zheng L. Experimental and theoretical evaluation of interlayer interference in multi-layer commingled gas production of tight gas reservoirs. *Journal of Petroleum Science and Engineering*, 2022, 208:109731. DOI:10.1016/j.petrol.2021.109731.
- [9] Liu, Wei, Zhao, Hui, Zhong, Xun, Sheng, Guanglong, Fu, Meilong, Ma, Kuiqian, A Novel Data-Driven Model for Dynamic Prediction and Optimization of Profile Control in Multilayer Reservoirs, *Geofluids*, 2021, 3272860, 15 pages, 2021. <https://doi.org/10.1155/2021/3272860>.
- [10] Liu, X., Qi, H., Liu, J. *et al.* Feasibility analysis of commingle production of multi-layer reservoirs in the high water cut stage of oilfield development. *J Petrol Explor Prod Technol* **14**, 2219–2228 (2024). <https://doi.org/10.1007/s13202-024-01773-z>.
- [11] Zhang, Z., Liu, Z., Wang, F. et al. Study on water flooding sweep characteristics of horizontal-vertical combined well pattern in offshore heavy oil reservoirs. *Sci Rep* 16, 17632 (2026). <https://doi.org/10.1038/s41598-026-48163-5>.
- [12] Anzhu, Xu, Longxin, Mu , Lun, Zhao , Zlfei, Fan , Xuanyu, Yang , Ling, He , and Xue Xia. "A New Strategy of Well Pattern Design and Adjustment to Enhance Production of Oil Fields with Vertical Multiple Series of Reservoirs.." Paper presented at the SPE Kuwait International Petroleum Conference and Exhibition, Kuwait City, Kuwait, December 2012. doi: <https://doi.org/10.2118/163297-MS>.
- [13] Hu J, Li A. Experimental Investigation of Factors Influencing Remaining Oil Distribution under Water Flooding in a 2-D Visualized Cross-Section Model. *ACS Omega*, 2021, 6(24):15572-15579. <https://doi.org/10.1021/acsomega.0c05534>.
- [14] Deng C-H (2023) Vector well pattern optimization of horizontal well in offshore edge water reservoirs. *Front. Energy Res.* 11:1226328. doi: [10.3389/fenrg.2023.1226328](https://doi.org/10.3389/fenrg.2023.1226328).

- [15] Alzahabi, Ahmed , Trindade, Alexander , Kamel, Ahmed , and Kiran Sathaye. "Optimizing Well Spacing to Maximize Horizontal Well Performance and Recovery." Paper presented at the SPE/AAPG/SEG Unconventional Resources Technology Conference, Houston, Texas, USA, June 2025. doi: <https://doi.org/10.15530/urtec-2025-4262105>.
- [16] Zhao, L.; Wang, J.; Fu, L.; Chen, L.; Jia, Z. Improve Oil Recovery Mechanism of Multi-Layer Cyclic Alternate Injection and Production for Mature Oilfield at Extra-High Water Cut Stage Using Visual Physical Simulation Experiment. *Energies* 2023, 16, 1546. <https://doi.org/10.3390/en16031546>.
- [17] Zhang L, Xu C, Zhang K, Yao C, Yang Y, Yao J. Production optimization for alternated separate-layer water injection in complex fault reservoirs. *Journal of Petroleum Science and Engineering*, 2020, 193:107409. 10.1016/j.petrol.2020.107409.
- [18] Jincal, W., Lun, Z., Angang, Z. *et al.* Well pattern adjustment of variable-injection-production-rate waterflooding in high water-cut oilfields. *J Petrol Explor Prod Technol* **15**, 152 (2025). <https://doi.org/10.1007/s13202-025-02066-9>.
- [19] Kumar, Ashish , Seth, Puneet , Shrivastava, Kaustubh , Manchanda, Ripudaman , and Mukul M. Sharma. "Integrated Analysis of Tracer and Pressure-Interference Tests To Identify Well Interference." *SPE J.* 25 (2020): 1623–1635. doi: <https://doi.org/10.2118/201233-PA>
- [20] Jacobs, Trent. "The Chow Pressure Group: Shut-In Wells Offer Case for a New Approach to Interference Testing." *J Pet Technol* 72 (2020): 27–30. doi: <https://doi.org/10.2118/0720-0027-JPT>
- [21] Cao, Lin, Xiu, Jianlong, Cheng, Hongjie, Wang, Hui, Xie, Shujian, Zhao, Hui, Sheng, Guanglong, *A New Methodology for the Multilayer Tight Oil Reservoir Water Injection Efficiency Evaluation and Real-Time Optimization, Geofluids*, 2020, 8854545, 17 pages, 2020. <https://doi.org/10.1155/2020/8854545>.
- [22] Liu, L., Wang, J., Su, P. *et al.* Experimental study on interlayer interference of coalbed methane reservoir under different reservoir physical properties and pressure systems. *J Petrol Explor Prod Technol* **12**, 3263–3274 (2022). <https://doi.org/10.1007/s13202-022-01513-1>
- [23] Emerick, A.A. Towards a hierarchical parametrization to address prior uncertainty in ensemble-based data assimilation. *Comput Geosci* **20**, 35–47 (2016). <https://doi.org/10.1007/s10596-015-9545-0>.
- [24] Lorentzen, Rolf J., Luo, Xiaodong , Bhakta, Tuhin , and Randi Valestrand. "History Matching the Full Norne Field Model Using Seismic and Production Data." *SPE J.* 24 (2019): 1452–1467. doi: <https://doi.org/10.2118/194205-PA>
- [25] Xu, Fuqiang, Song, Xianzhi, Song, Zihao, Wang, Gaosheng, and Yu Shi. "Heat Extraction and Interlayer Interference in Heterogeneous Multi-Layer Commingled Production Oil Reservoir." Paper presented at the 56th U.S. Rock Mechanics/Geomechanics Symposium, Santa Fe, New Mexico, USA, June 2022. doi: <https://doi.org/10.56952/ARMA-2022-0504>.
- [26] Guo, J., Jiang, C., Du, J., & Liu, Y. (2026). Inter-layer interference in commingled tight gas reservoirs: experiments and simulations. *Petroleum Science and Technology*, 44(14), 2358 – 2386. <https://doi.org/10.1080/10916466.2025.2517069>
- [27] Liang, L.; Cheng, Y.; Luo, X.; Qiu, L.; Tan, C. Research on Well Pattern Optimization Method for Multilayer Thin Gas Reservoir Based on DNN Algorithm. *Processes* 2025, 13, 599. <https://doi.org/10.3390/pr13030599>.
- [28] Chen J, Cai D, Zhang T, Yu L, Zhou D, Cheng S. Asynchronous Injection–Production Method in the High Water Cut Stage of Tight Oil Reservoirs. *Energies*, 2024, 17(19):4838. <https://doi.org/10.3390/en17194838>.
- [29] He, Y.; Guo, Y.; Wu, L.; Jiang, L.; Wang, S.; Ning, S.; Kang, Z. Evaluation of Development Performance and Adjustment Strategies for High Water-Cut Reservoirs Based on Flow Diagnostics:

- Application in the QHD Oilfield. *Energies* 2025, 18, 5310. <https://doi.org/10.3390/en18195310>.
- [30] Liu W, Wang J, Yang X. Optimization of Well Patterns in Offshore Low-Permeability Thin Interbedded Reservoirs: A Numerical Simulation Study in the Bozhong Oilfield, China. *Energies*, 2025, 18(2):285. <https://doi.org/10.3390/en18020285>.