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Fine Correlation and Well Pattern Optimization of Extra-high Water Cut Reservoirs: Case Study of-With Fuyu Oilfield as an Example

Zhongcheng Li[1], Hongxue Wang[1], Zhenchang Jiang[1,*], Bing Yue[1] and Zhongnan Wu[2]

[1]*China Petroleum Jilin Oilfield Exploration and Development Research Institute, Songyuan 138000, China*
[2]*Department of Mechanical Engineering, University of British Columbia, BC V6T 1Z2, Canada*

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Abstract

Invalid or inefficient circulation of water injection is aggravated in the development stage of extra-high water cut reservoirs. Under current well pattern conditions, the production degree is uneven in horizontal and vertical directions, and the remaining oil distribution is highly dispersed and locally enriched. To reveal the relationship between different well pattern conditions and the remaining oil development effect, based on stratigraphic boundary division and vertical and horizontal sublayer division parameters of ultra-high water cut reservoirs, this study proposed well pattern optimization methods such as co-injection and co-production, comprehensive inter-injection and symmetrical alternation in drainage of ultra-high water-cut reservoirs. According to fine reservoir correlation principle and reservoir numerical simulation method, the original reservoir potential and production status were determined and the remaining oil development effect was evaluated. The rationality of well pattern optimization was verified by using Fuyu oilfield as an example. The results demonstrate that combining new and old wells can increase the stage production by approximately 2% in different development modes. Different cycle settings and separate injection and production combinations can decrease interlayer interference and improve the development effect. The study can provide a good reference for fine reservoir correlation and well pattern adjustment of the same type of reservoirs in the ultra-high water cut development stage.

Keywords: Ultra-high water cut reservoir, Reservoir correlation, Well pattern optimization, Numerical simulation

1. Introduction

After long-term water injection development, most onshore oilfields have been in the high water cut or extra-high water cut stage. Under existing well pattern conditions, ineffective water circulation has become increasingly serious, but remaining reserves are abundant and have great development potential [1-3]. In the meantime, the water injection effects differ considerably in each layer, which is the main study direction of fine reservoir correlation and remaining oil tap potential.

Uneven horizontal and vertical production is the common problem at the ultra-high water cut stage, and the distribution of remaining oil is highly dispersed and locally enriched [4]. Due to a long development history, well patterns have been adjusted many times, the production situation of well layers is complex, and understanding of layering is a difficult process. As a result, further tapping and adjustment of remaining oil are limited.

According to the actual data of recovery ratio at the late stage of oilfield development, the former Soviet Union proposed an empirical formula between recovery ratio and well pattern density. Despite the definitive physical meaning of the formula, the influence of water injection mode on water flooding recovery ratio was not considered. Many vertical development layers exist in Daqing Oilfield, with each layer having different physical properties that contradict the properties of other layers. Because of industrial oilfield exploitation, many large-scale well pattern adjustments have been carried out to solve problems in the development process. Through well pattern adjustment, the problems in oilfield development have been solved and good development results have been achieved. With the further development of oil fields, the production data are constantly changing, resulting in new contradictions in the extra-high water cut stage. Gangdong Development Zone of Dagang oilfield has entered the late development stage and is currently in the stage of high water cut and high recovery rate. To further enhance oil recovery, the remaining oil distribution, identification of dominant seepage channels, reasonable well pattern, and well spacing deployment were studied in Block 45, Area 2. In the meantime, the special treatment of well pattern improvement and old well maintenance was carried out and good results were achieved.

Scholars have conducted numerous studies on fine correlation and well pattern optimization of reservoirs with complex geological structure in different development stages [5-7], but the adaptability of conventional well pattern optimization methods to shallow reservoirs with a depth of 500 m in extra-high water cut stage has not been verified. Therefore, quantitative characterization of the remaining oil potential in the ultra-high water cut stage is an urgent concern, as well as carrying out prediction and evaluation of various adjustment schemes and guiding well pattern deployment optimization on the basis of defining the original potential and production status.

This study solved the existing problems of ultra-high water cut reservoir in Fuyu oilfield, and predicted the influence factors such as reservoir fine correlation, water

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injection range and development mode. The effects of different adjustment schemes were predicted to clarify the next well pattern adjustment and reorganization mode in key blocks and optimize the deployment scheme. The expectation is to provide a reference for well pattern adjustment and remaining oil tapping potential in the ultra-high water cut stage.

In this study, fine reservoir correlation and well pattern optimization of extra-high water cut reservoirs in key blocks of Fuyu oilfield were studied, including stratigraphic boundary division, interlayer development, sublayer division, and prediction and analysis of recovery factor in different well pattern deployment schemes.

2. State of the art

Most onshore oilfields are in the high water cut or extra-high water cut stage, and maintaining the existing mining system cannot achieve the remaining oil production effect. Some remaining crude oil is passively used by adjusting the mining system. Reservoir description technology, as an advanced technology applied to oil and gas exploration and development scheme adjustment, developed rapidly in the 1970s. Experts from different countries have adopted various means such as core physical simulation experiment, reservoir numerical simulation, reservoir engineering technology and logging interpretation, to analyze and compare the causes, distribution laws and utilization mechanisms of remaining oil under different exploitation modes. Moreover, effective production methods and mechanism of remaining oil have been analyzed.

Gorbunov and Li D [8-9] discussed the pore structure, physical characteristics, seepage mechanism, development characteristics and main technological measures of low permeability reservoirs. However, their study involves only a single well group, which is not universal. Fan et al. [10] planned to improve the development effect of water flooding by using profile control, profile modification and oil displacement, and studied the influence of well pattern type on the distribution of remaining oil after development. Based on the combination of profile control, profile modification and oil displacement, the seepage area of the horizontal well pattern was large. Expanding the swept volume can achieve remarkable effects, and the remaining oil saturation in each stage was lower than that of vertical and horizontal–vertical combination well patterns. However, the effect of small layers was not considered. Almajid and Kovscek [11] studied the influence of using immovable emulsified oil on geometric conditions in porous media. Under the oil-bearing condition, the influence of oil on liquid flow was simulated by adjusting the hole shape. The residual oil was asymmetric in microfluidic experiment, which had minimal influence on water injection development. Zhong et al. [12-13] took the tight sandstone reservoir of the fourth member of Yong 1 Formation as an example, and analyzed the influence of sediment source and reservoir pressure direction on well pattern deployment according to numerical simulation method and seepage theory. The well pattern parameters were optimized, but the remaining oil potential in different stages was not considered. Based on knowledge about the developed low-permeability oil and gas resources in China, Hu et al. [14] studied the development theory of low-permeability oil and gas reservoirs, summarized the key technologies of low-permeability oil and gas reservoir development, and discussed the prospects and technical directions of sustainable development of low-permeability oil and gas reservoirs. To solve the difficulty of effective development and production of ultra-low permeability and ultra-low abundance reservoirs in Daqing peripheral oilfields, Wang Y et al. [18] explored space-varying wavelet seismic inversion, independent variable analysis and virtual well prediction techniques to identify thin and narrow sand bodies based on seismic, geological, and logging data. The prediction accuracy was over 85%. The production calculation models of different well patterns based on non-Darcy seepage were established, and the optimization design method of well patterns in fractured reservoirs was proposed. Gan Y et al. [19-21] established a conceptual model and applied numerical simulation technology to study the optimization of well pattern reorganization technology. The technical policy limits during well pattern reorganization were obtained, such as well pattern adjustment mode after well pattern reorganization and pressure maintenance level of different combination strata. Moreover, the relationship between water flooding recovery ratio and well pattern density of fractured well patterns in low permeability reservoirs was compared by using the Sherkachev formula, the empirical formula of the former Soviet Union, and the empirical formula of China. However, the applicability of extra-high water cut reservoir was not evaluated. According to Liu Y et al. [15], the displacement pressure gradient should be greater than the maximum starting pressure gradient, which is the necessary condition for effective displacement of thin and poor reservoirs. Measures such as reducing well spacing, fracturing and adjustment of injection-production pressure system can effectively drive thin and poor reservoirs. However, they did not study the seepage law. Liu L [16] analyzed the control effect of different geological characteristics on the remaining oil and selected the factors with strong control effect on the remaining oil as the classification parameters of the independent off-balance-sheet reservoirs in the study area to classify and evaluate independent off-balance-sheet reservoirs. Based on the remaining oil types of various types of independent off-balance-sheet reservoirs and the distribution characteristics, the mining potential was analyzed, but the remaining oil distribution in small layers was not evaluated. Zeng L et al. [23], discussed the fracture and fracturing technology of thin reservoirs and argued that thin interlayer fracturing, balanced protection and reservoir subdivision standards can determine the effect of the measures. By using thin interlayer protection technology based on the pressure balance principle, the fracturing technology and supporting tools were optimized, and the thickness limit of the interference measures between fractures was determined. However, the production of small layers was not studied. Zeng L et al. [17] studied the influence of fractures on the development of low-permeability sandstone reservoirs. Four groups of high-angle structural fractures were in the target block. Considering the influence of the current stress field, the researchers considered that the east–west fracture had the best connectivity, largest pore diameter, highest permeability and lowest opening pressure, which were the main channels for fluid flow in low-permeability sandstone reservoirs. These fractures could influence well pattern deployment, water injection and hydraulic fracturing of low permeability sandstone reservoirs. However, they only studied the influence of reservoir physical properties and not the effect of well pattern deployment. According to Alali [22], the purpose of optimizing mixed flooding was to improve the maximum drilling rate and minimize the production time in the drilling process. The well pattern should be adjusted. Combined with numerical simulation, the recovery ratio of ultra-high water cut reservoir was improved. However, the influence of actual reservoir physical parameters was not considered. To solve the problem of difficult development of extra-high water cut reservoirs, Suranto [24] proposed the method of steam-assisted gravity drainage. The steam-solvent mixed injection should be controlled. A synthetic reservoir model was developed to study this phenomenon based on real field data sets. However, the influencing factors of well pattern deployment were not involved. Wang W [25] studied a method of joint optimization of well location and injection and recovery parameters based on machine learning for water-driven reservoirs. The optimized development effect is improved by about 12% compared with the traditional optimization method, which is only studied for a single reservoir condition and lacks adaptability analysis. Muradov [26] designed an independent water inflow control device for oil wells and the operation method, including single-phase and multi-phase flow performance and multi-phase flow of fluid in annular space. The influence on well flow performance was quantified according to geological conditions, and the optimal injection speed limit was determined.

The above studies focused on numerical simulation and laboratory experiment of equipment improvement and micro-flow, while few studies of multi-fault complex reservoirs with multiple reservoir types and multiple sets of oil-bearing strata have been published. Research on fine reservoir characterization, remaining oil potential evaluation, and well pattern optimization of ultra-high water-cut reservoirs with multi-point dome anticline with complex faults is scarce.

The rest of this study is organized as follows. Section 3 describes the principle of fine reservoir characterization and design of well pattern optimization scheme. In section 4, the stratigraphic boundary, development situation, stratigraphic correlation and recovery ratio of different well pattern deployments are predicted and analyzed. The results demonstrate that the recovery ratio of commingled injection and commingled production scheme is slightly higher. Finally, section 5 summarizes this study and draws relevant conclusions.

3. Methodology

3.1 Stratigraphic boundary adjustment principle

Based on the principle of cycle correlation, hierarchical control, and facies control constraint, the original boundary is unchanged in the correlation process and the integrity of single sand body is maintained. It is divided it into single sedimentary cycle vertically, and the integrity of the cycle is kept. The inconsistent horizons and well areas with prominent problems are unified. For the main thick sand body, the unit boundary is divided according to the sedimentary intermittent surface, and the proportion of interlayer and return is more than 80%.

After long-term water flooding development, dominant seepage channels have been formed in multi-layer reservoirs with different rock physical properties, complex well pattern deployment, and large differences in the production and remaining oil distribution of each sublayer. According to the standard of reservoir group → sandstone group → sublayer, the block closure strata are studied to realize the comparison from coarse to fine and improve the understanding of intra-layer heterogeneity. As shown in Fig. 1.

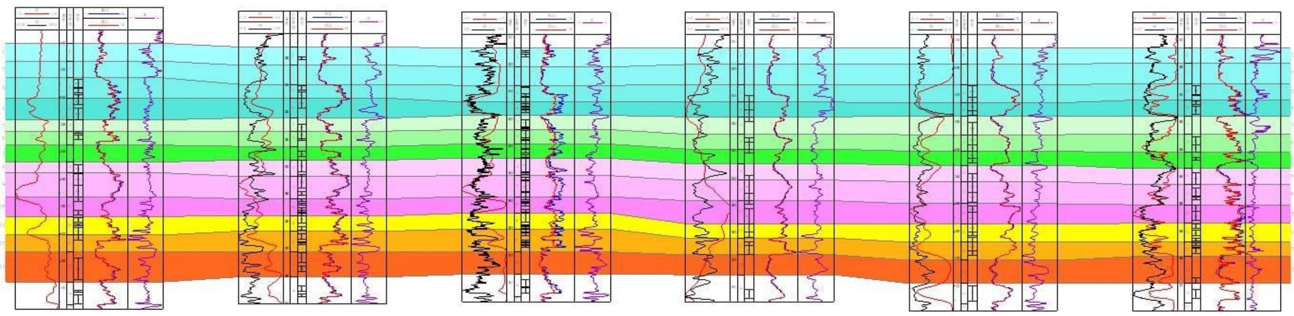


Fig. 1 Horizontal 5 comparative section

3.2 Fine reservoir correlation principle

Different correlation methods are used for different sedimentary environments. The principle of superimposition and undercutting sand bodies is used for fluvial facies deposition. Owing to diversion and river undercutting, many periods of vertical superimposition of river sand bodies have been observed, and the late sedimentary sand bodies scour and redeposit the top or whole of the early sedimentary sand bodies. However, phase-change comparison is mainly adopted for delta facies deposition. Owing to the rapid phase change of channel deposition in the horizontal direction, great lateral difference of sand body thickness occurs. In the same sedimentary time unit, even the adjacent areas can belong to different sedimentary micro dimension and the lithology and logging curve characteristics vary.

The core of coring wells is observed to find special lithologic sections that can be compared on the plane and gradually determine the marker layer in the work area. By using the core calibration logging curve, this study established the rock-electrical response model of the marker bed to guide the stratigraphic division and correlation of non-coring wells. Obvious steps are seen on the top interface and acoustic curve of the oil layer, which are distributed stably and widely in the study area. They can be used as a regional marker layer for correlation. Gamma and resistivity are low and U-shaped, and short-term cycle of lake flooding surface can be used as the standard layer between sandstone formations. Great acoustic time difference is observed at the bottom layer, gamma and resistivity are low, and the spontaneous potential mudstone baseline is clearly marked, which can be used as a local standard layer. Fig. 2 shows the marker layer identification.

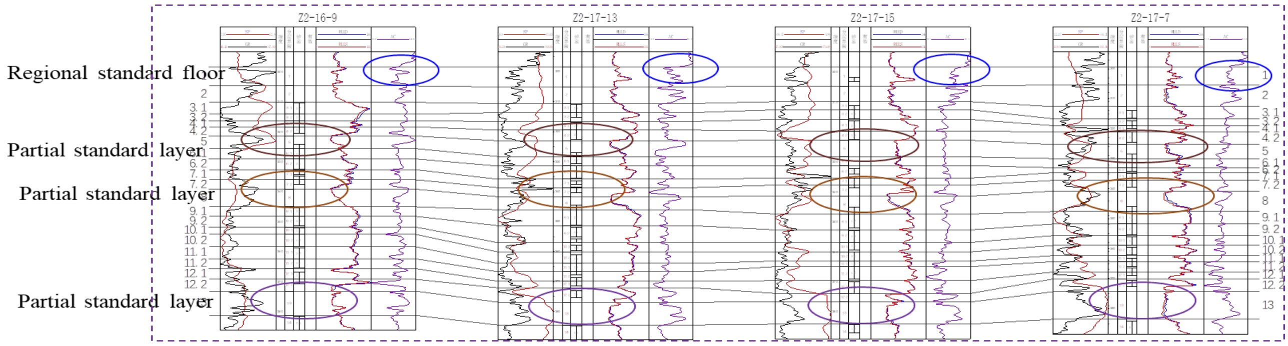


Fig. 2. Identification of marker layer

3.3 Design of well pattern optimization scheme

3.3.1 Numerical simulation model

In the process of fine geological modeling, to finely depict the detailed characteristics of reservoir physical properties in plane and vertical direction, the total amount of fine depicting grid units usually reaches tens of millions to hundreds of millions, far exceeding the scope of a simulator. The structural framework and attributes are usually coarsened to meet the needs of numerical simulation calculation, and comprehensively considering the block structure, reservoir, well pattern and simulation requirements is necessary, as well as appropriately coarsening the fine geological model. The roughing model is shown in Figs. 3 and 4.

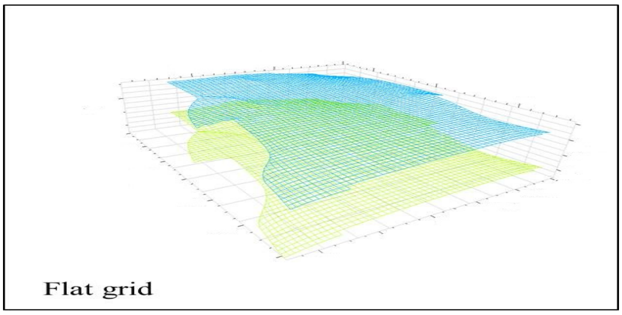


Fig. 3. Flat grid design

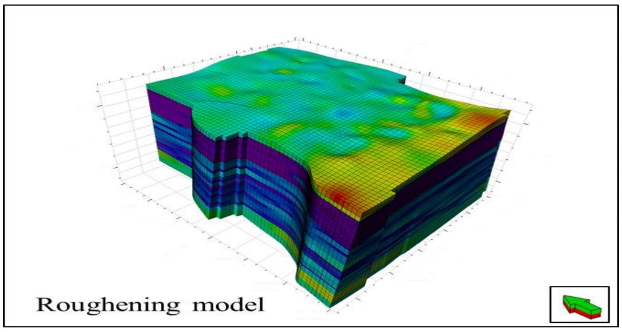


Fig. 4. Roughening grid design

In the process of attribute roughening, different processing methods were used for different attributes. Figs. 5, 6, 7, and 8 illustrates the attribute model Volume-weighted average algorithm was used in porosity and coarsening model roughening, which reflects the weight of different subdivision cells. Permeability and porosity show positive correlation. In the roughening process, in addition to volume-weighted average, porosity model constraints were added to ensure the rationality of roughening attribute distribution. Considering the structure, reservoir, well network and simulation requirements, the fine geological model was appropriately roughened. Two 20 m × 20 m block plane roughening grids were used, which were vertically roughened to subdivision units. A total of 127,500 grids were obtained after roughening.

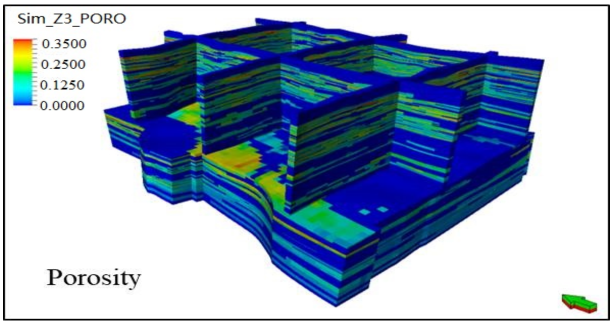


Fig. 5. Porosity model

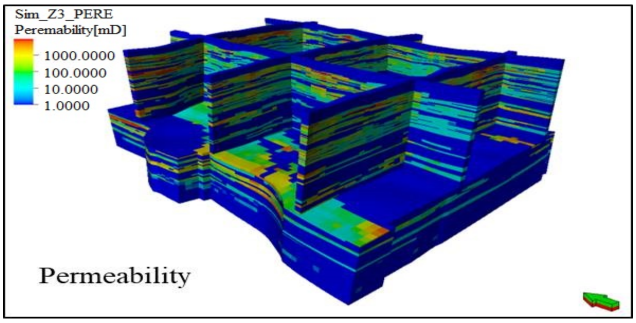


Fig. 6. Permeability model

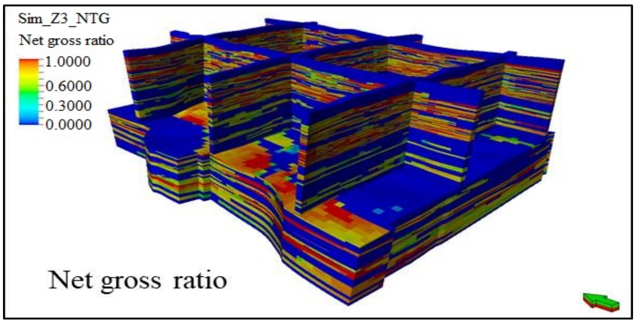


Fig. 7. Net gross ratio model

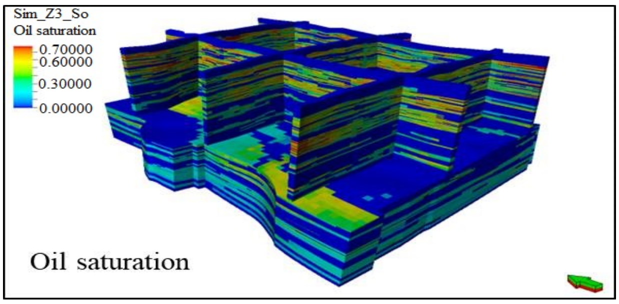


Fig. 8. Oil saturation model

3.3.2 Well pattern design

With a long history of development, the well pattern of Fuyu oilfield has been adjusted many times and its production situation is complicated, which makes potential tapping and adjustment more difficult. On the basis of fine correlation, the effect prediction and evaluation of combination reconstruction scheme under different well patterns and development modes were carried out to further improve the oilfield development effect and ensure the rationality and reliability of the design and implementation scheme. As shown in Figs. 9, 10 and 11.

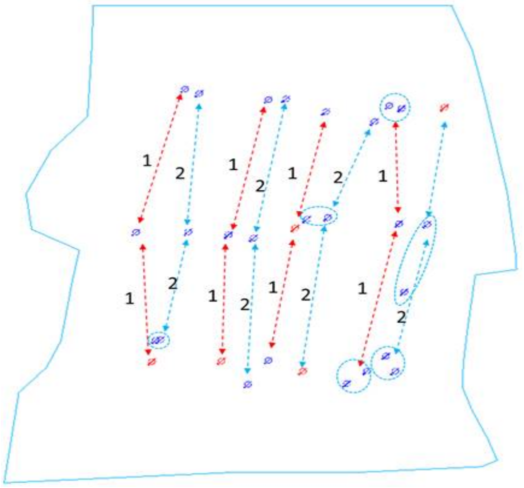


Fig.9. Symmetrical alternating water well deployment within the row

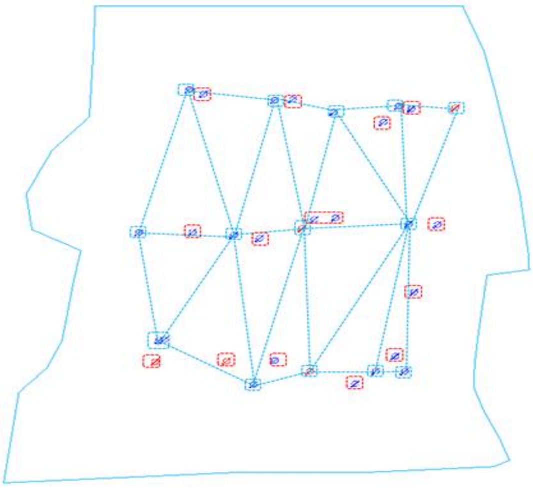


Fig.10. Triangular alternating water well scheme 1 within the row.

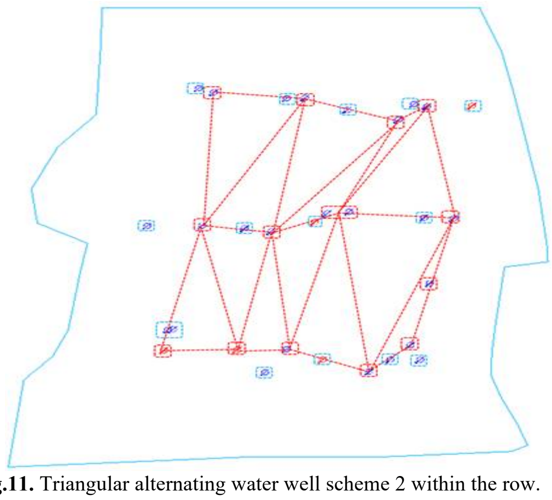


Fig.11. Triangular alternating water well scheme 2 within the row.

The development effects were comprehensively analyzed and predicted under different combination modes and evaluated in two aspects. First, on the basis of the original well location deployment, combined with the development effects after adjusting the original oil-water well pattern, a scientific basis is provided for the promotion of large row spacing water control + close well spacing liquid extraction experimental well pattern. The well network is deployed as shown in Figs. 12 and 13. Second, for vertical development layers of well pattern, plane periodic water injection effects were compared and the vertical rotation injection effect is predicted in a reasonable way. The reasonable parameters are as Table 1.

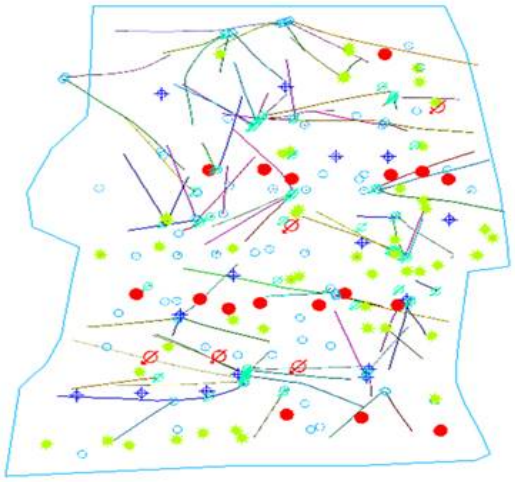


Fig.12. Deployment of new wells in delta sedimentary reservoir

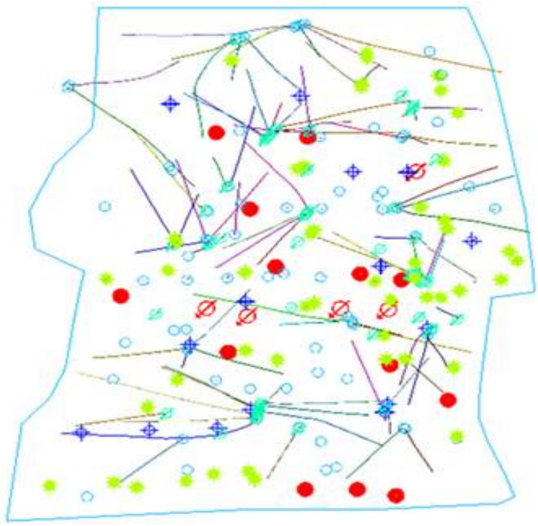


Fig.13. Deployment of new wells in fluvial sedimentary reservoir

Table 1. Combination design of different development methods

Water injection method	Injection cycle (day)	Injection fluctuations
Full inter-injection (sub-well row, not up and down)	10, 15, 30, 60, 90	0.6, 0.8, 1.0, 1.2
Symmetrical alternate water injection in the row (divided into upper and lower)	10, 15, 30, 60, 90	0.6, 0.8, 1.0, 1.2
Alternate water injection in the inner triangle of the row (divided into upper and lower)	10, 15, 30, 60, 90	0.6, 0.8, 1.0, 1.2
Longitudinal two-stage rotation injection (sub-well row, sub-up)	10, 15, 30, 60, 90	0.6, 0.8, 1.0, 1.2

4. Result Analysis and Discussion

4.1 Geological condition

With extra-high water cut oil reservoir of Fuyu oilfield as an example, the common problems of inefficient circulation of injected water, unclear potential of remaining oil and decrease of development effect under the current well pattern condition of the old oil field in extra-high water cut stage were solved by using the well pattern optimization scheme design in section 3.3. According to the core and logging data, based on the relationship between rock and electricity, the mudstone sensitive curve was searched and the interlayer identification chart was established. The reservoir was vertically and horizontally compared and analyzed, and the development of the reservoir was determined. Numerical simulation was conducted to predict different development modes.

Fuyu oilfield is located in the eastern margin of the central depression in the south of Songliao Basin, on Fuyu III structure of Huazijing terrace, which is a multi-high dome anticline complicated by faults, steep in the north, and gentle in the south. The boundary line is -400 m and the structure amplitude is 260 m. The strata in Fuyu oilfield are Quaternary, Neogene Taikang Formation and Da'an Formation, Mesozoic Upper Cretaceous Nenjiang Formation, Yaojia Formation and Qingshankou Formation, and Lower Cretaceous Quantou Formation from top to bottom. Fuyu oil layer (Quan4 member) and Yangdachengzi oil layer (Quan3 member) are developed from top to bottom in the Fuyu oilfield, and the buried depth of the oil layer is 320–500 m. The oilfield has entered the ultra-high water cut development stage with uneven horizontal and vertical production, and the distribution of remaining oil is highly dispersed and locally enriched. Block Z-3 of the Fuyu oilfield has an oil-bearing area of 1.01 km2, a geological reserve of 465.5×104t, and a total of 194 oil and water wells. At present, the comprehensive water cut is 95%, the recovery rate is 31.4%, and the predicted recovery rate is 36.8%.

4.2 Analysis of stratigraphic boundary adjustment

Based on the stratum boundary adjustment principle in section 3.1, aiming at the local serial wells, the wells with unreasonable partial splitting were adjusted. As shown in Fig. 14, the contact relationship was adjusted according to the combination characteristics of near-well curves to unify the boundary.

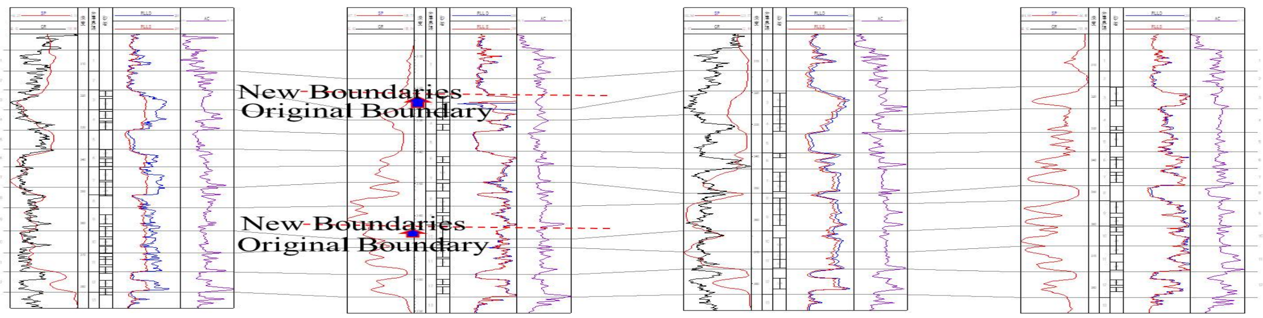


Fig. 14. Partial serial section

Based on the boundary adjustment principle in section 3.1, the logging curves are re-analyzed for complete serial wells. According to the combination characteristics of near-well logging curves, the whole stratigraphic boundary is moved down, and the small layers are fine-tuned, thus unifying the stratigraphic boundary. As shown in Figure 15.

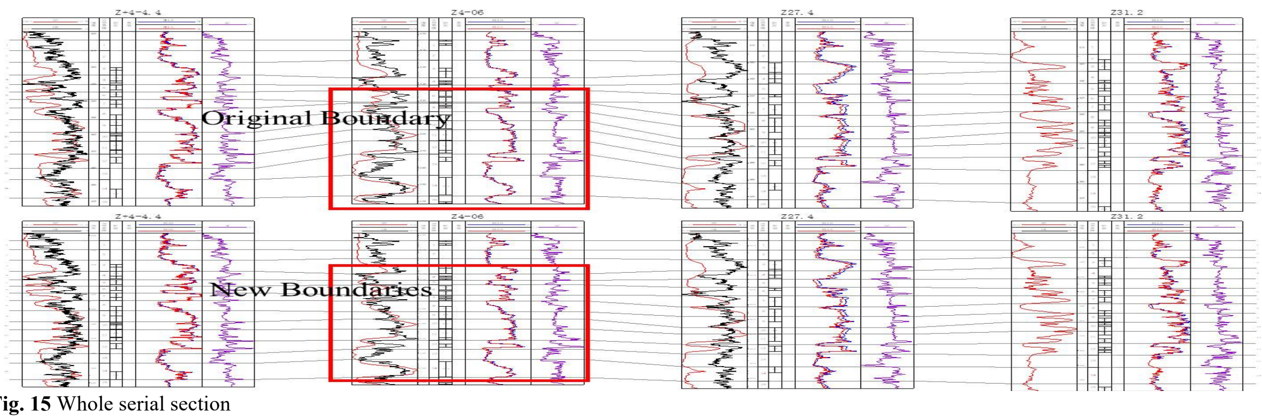


Fig. 15 Whole serial section

4.3 Fine correlation analysis of reservoirs

According to the fine reservoir correlation principle in section 3.2, on the basis of reservoir correlation and rock-electric relationship, the data on core and mud logging were used to search the sensitive curves of mudstone and the interlayer identification chart was established. As illustrated in Fig. 16.

The results show that natural gamma and deep lateral curves are sensitive to mudstone: the lithology of interlayer is mudstone with high natural gamma and low deep lateral resistivity. The natural gamma of sandstone is low, with high deep lateral resistivity. The standard for distinguishing the interlayer is as follows: natural gamma > 104 API and deep lateral resistivity < 21 Ω.m.

(1) Vertical distribution characteristics of interlayer

Figs. 17 and 18 illustrate the distribution of compartments. By analyzing the distribution of interlayer in each sublayer, we found that the thickness of the interlayer among sublayers of the fluvial sedimentary oil layer is large and the distribution is stable. The interlayer thickness of the delta reservoir is small and the interlayer of the 12/13 sublayer is stable. The interlayer of sand group 1 (4/5 sublayer) and sand group 2 (7/8 sublayer) is stable, and the interlayer distribution among other sublayers is unstable.

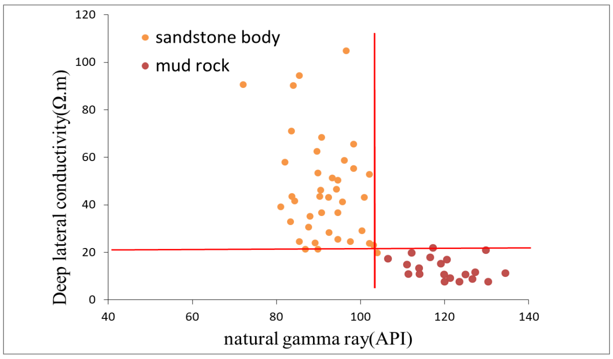


Fig. 16. Interlayer Identification

(2) Plane distribution characteristics of interlayer

By Fig. 19 analyzing interlayer distribution, we can conclude that fluvial sedimentary reservoirs consist of mainly unstable interlayers. Except for the 7/8 and 12/13 interlayers, which are stable, all the other interlayers are unstable. The fluvial sedimentary reservoir is dominated by a stable interlayer. Except for the 21/22 and 23/24 interlayers, which are unstable, all the other interlayers are stable. The proportion of compartments between 3/4 small layers and compartments larger than 2m between small layers is only 15.5%, and the distribution of compartments is unstable. Table 2 explains the distribution of status.

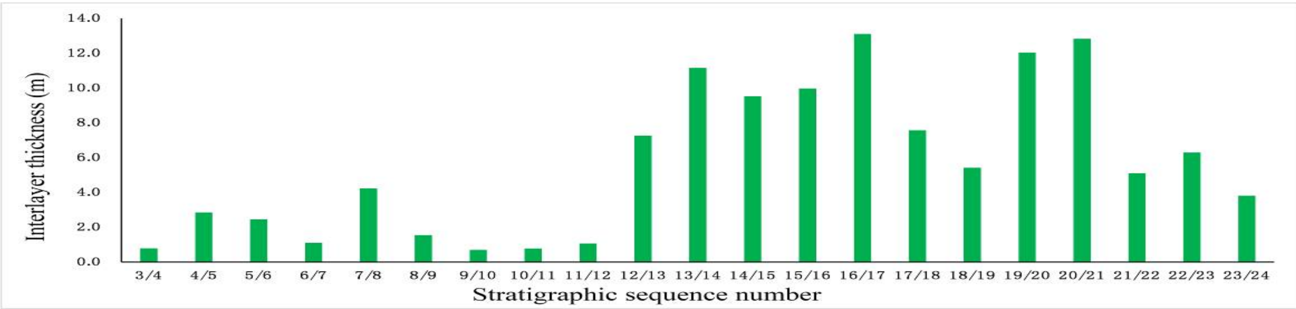


Fig.17. Histogram of small interlayer

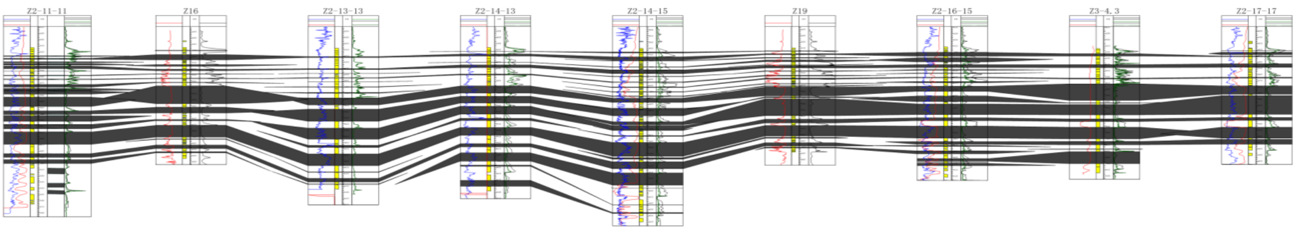
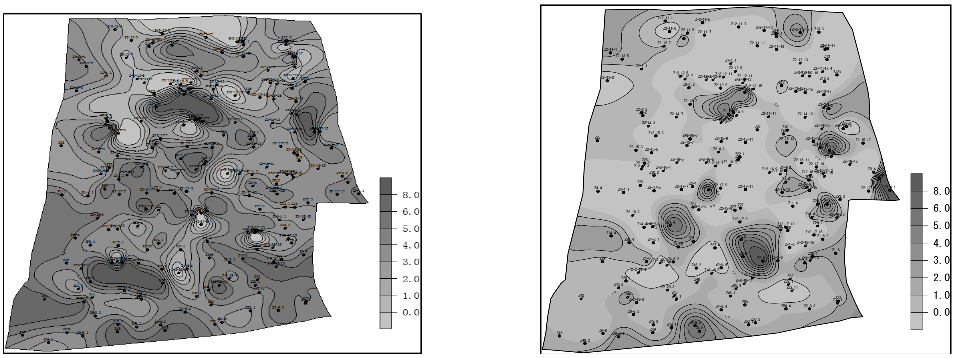


Fig.18. Interlayer distribution

Table 2. Distribution of interlayer in fluvial sedimentary reservoir

Small layer number	Partition thickness (m)			Thickness percentage		Distribution status
	min	max	ave	No compartment	> = 2 m	
3–4	0	9.4	1.0	44.8	15.5	Unstable
4–5	0	16.1	3.2	11.9	59.3	Unstable
5–6	0	18.5	2.9	23.7	44.3	Unstable
6–7	0	12.6	1.4	31.4	27.3	Unstable
7–8	0	18.5	4.7	5.7	84.5	stable
8–9	0	17.5	1.8	39.5	24.1	Unstable
9–10	0	8.2	0.8	34.9	11.3	Unstable
10–11	0	8.9	0.9	37.9	13.3	Unstable
11–12	0	10.4	1.3	25.6	21.0	Unstable
12–13	0	28.1	8.2	4.7	92.1	stable
13–14	0	30.2	12.2	4.2	93.2	stable
14–15	0	35.3	10.4	7.1	84.6	stable
15–16	0	31.1	10.4	5.7	90.2	stable
16–17	0	27.3	13.4	2.5	94.4	stable
17–18	0	23.1	8.0	10.6	80.8	stable
18–19	0	29.9	5.7	5.5	80.8	stable
19–20	0	39.1	12.5	2.1	97.9	stable
20–21	0	39.1	13.4	2.8	94.4	stable
21–22	0	29.2	5.3	22.8	51.5	Unstable
22–23	0	28.2	6.5	8.5	80.8	Stable
23–24	0	25.6	3.8	28.1	45.5	Unstable



(a) (b)

Fig. 19. Interlayer of sublayer .(a)7/8 sublayer. (b)3/4 sublayer.

(3) Sublayer division

Table 3 shows the detailed data of the small layer division. Delta sedimentary oil layer is divided into 13 sublayers, with an average stratum thickness of 7.4 m and stratum thickness ranging from 5 m to 9 m. The thickness of sandstone is mainly concentrated in the 3/4/6/7/9/10/11/12 sublayers, with an average thickness of 4.8 m. Oil reservoirs are mainly developed in the sand body. The fluvial sedimentary oil layer is divided into 15 sublayers. Compared with the delta sedimentary oil layer, the stratum thickness is large, ranging from 8 m to 13 m, with an average sandstone thickness of 3.6 m and average stratum thickness of 10.2 m .

4.4 Effect prediction and analysis of different development schemes

Based on fine reservoir correlation results and historical fitting data, different schemes are simulated and predicted. Based on the simulation of the terminal reservoir state, the restart mode is adopted for 15 years and the development effects of each scheme are analyzed and compared.

Scheme 1: On the basis of new wells, water wells are co-injected with different injection ranges and oil wells are co-produced.

Table 3. Statistical Table of Sub-layer Division

Small layer number	Reservoir thickness (m)	Sandstone thickness (m)	Small layer number	Reservoir thickness (m)	Sandstone thickness (m)
1	7.74	-	15	9.73	2.26
2	6.97	-	16	11.20	2.42
3	7.60	4.46	17	8.80	1.13
4	7.18	4.89	18	9.20	4.63
5	5.55	2.11	19	10.95	5.06
6	6.77	4.12	20	9.99	0.37
7	7.23	4.19	21	9.78	3.99
8	6.71	2.41	22	8.48	3.80
9	8.44	5.98	23	9.64	5.03
10	7.37	5.00	24	9.25	4.41
11	7.62	5.27	25	9.40	1.77
12	7.88	4.39	26	9.86	3.59
13	9.11	1.08	27	12.41	6.47
14	11.22	3.62	28	12.50	5.55

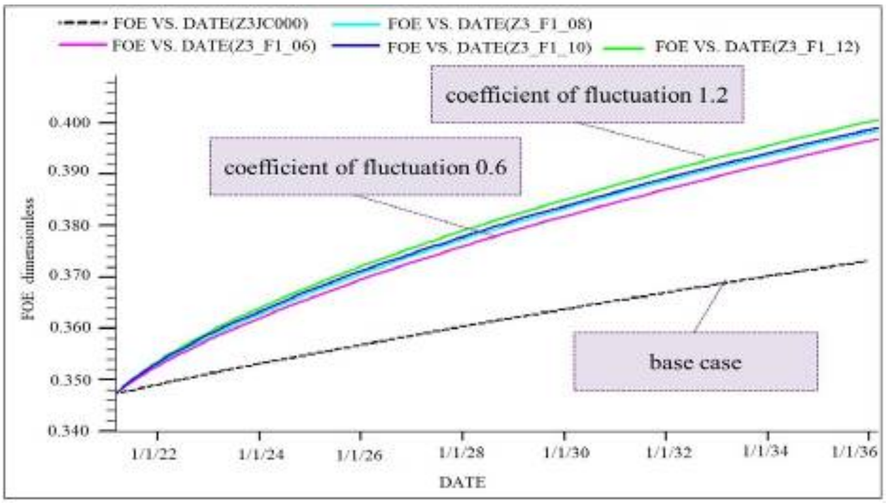


Fig. 20. Indicator prediction results of scheme 1

Table 4. Influence of different water injection fluctuation coefficients

Serial number	Package name	Recovery degree (%)	Improved recovery (%)
1	Foundation scheme	37.34	0.00
2	Flood wave coefficient 0.6	39.68	2.34
3	Flood wave coefficient 0.8	39.86	2.51
4	Flood wave coefficient 1.0	39.91	2.56
5	Flood wave coefficient 1.2	40.07	2.72

As shown in Fig. 20 and Table 4, on the baseline of the final recovery ratio of the basic scheme of 37.34%, the increase of the recovery ratio under the predicted injection range is 0.6–1.2. With the increase of injection rate, the recovery degree further increases and the recovery degree increases by more than 2%.

Scheme 2: Comprehensive inter-injection method was used for simulation and prediction. New and old water wells were injected in separate rows and sections, injecting sand groups 1 and 2 in row 1, and injecting sand groups 3 and 4 in row 2. Oil recovery was increased under the alternating conditions of different fluctuation ranges of water wells in 10-, 15-, 30-, 60- and 90-day alternating cycles.

As shown in Figs. 21 and 22, the predicted recovery degree in different modes is higher than that in the basic scheme, and the increase effect of 10-day and 15-day alternate cycles is similar under the condition of the same water injection amplitude. With the increase of alternate cycles, the improvement effect worsens, and the improvement range of the alternate cycle over 60 days shows a decreasing trend..

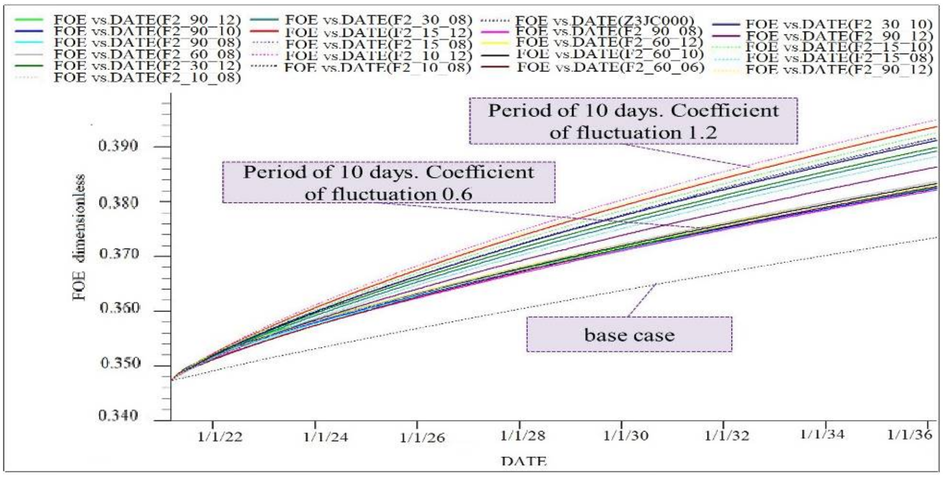


Fig. 21. Predicted results of the recovery degree of scheme 2.

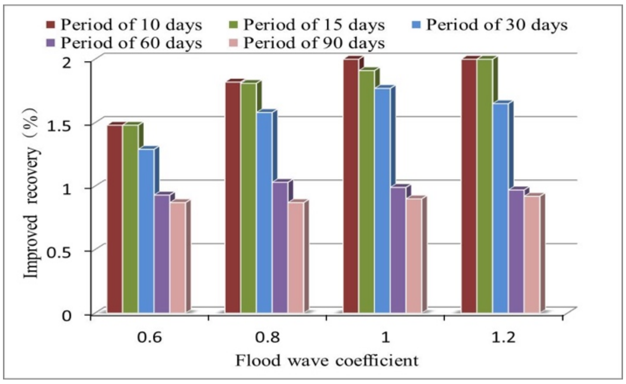


Fig. 22. Increased recovery effect of scheme 2.

Scheme 3: Symmetrical water injection mode was applied, and the delta sedimentary reservoir was divided into two sets of symmetrical well groups (including new and old wells) for alternate injection, with sand groups 1 and 2 in one group and sand groups 3 and 4 in the other group.

As shown in Figs. 23 and 24, under different alternate cycles, the recovery degree of each stage increases, and minimal difference of recovery degree occurs in different periods and amplitude stages. The recovery degree increases with the increase of injection intensity. When the injection amplitude is 0.6–0.8, the effect of continuous injection scheme is higher than that of alternate injection scheme and the effect of enhanced oil recovery is similar to the increase of injection amplitude.

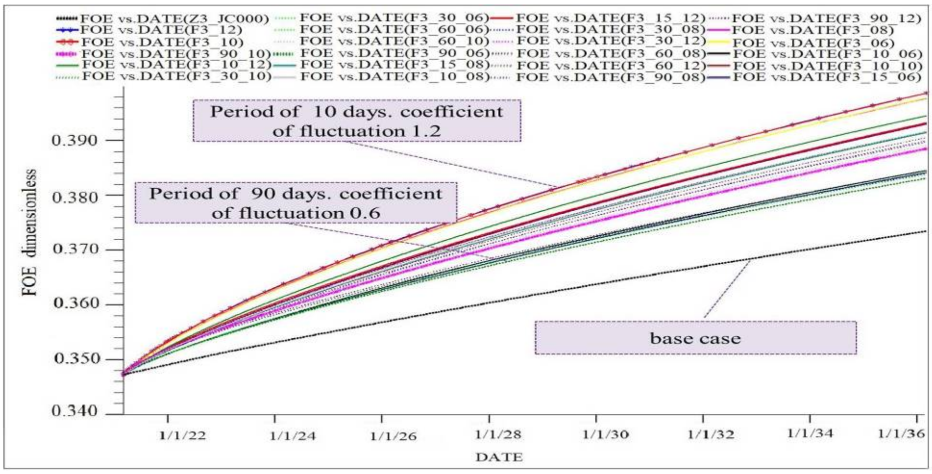


Fig. 23. Predicted results of the recovery degree of scheme 3.

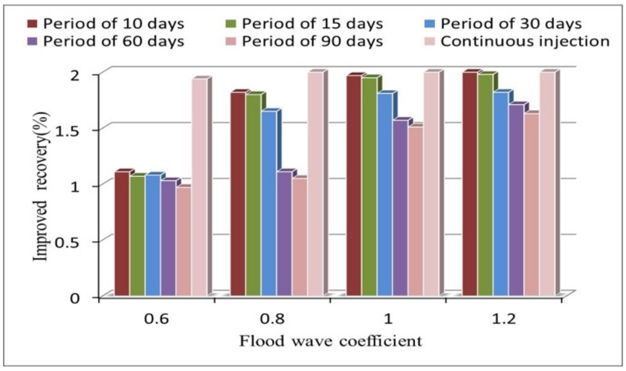


Fig. 24. Increased recovery effect of scheme 3

Scheme 4: Delta alternate mode is used for prediction and delta sedimentary reservoirs are divided into two sets of triangle well groups (including new wells and old wells) for alternate injection, with sand groups 1 and 2 in one group and sand groups 3 and 4 in the other group.

According to Figs. 25 and 27(a), with the increase of injection period, the increase degree of recovery gradually declines, and the best effect is observed when the alternating period is 10–15 days. When the injection fluctuation amplitude is greater than 0.8, the influence gradually decreases.

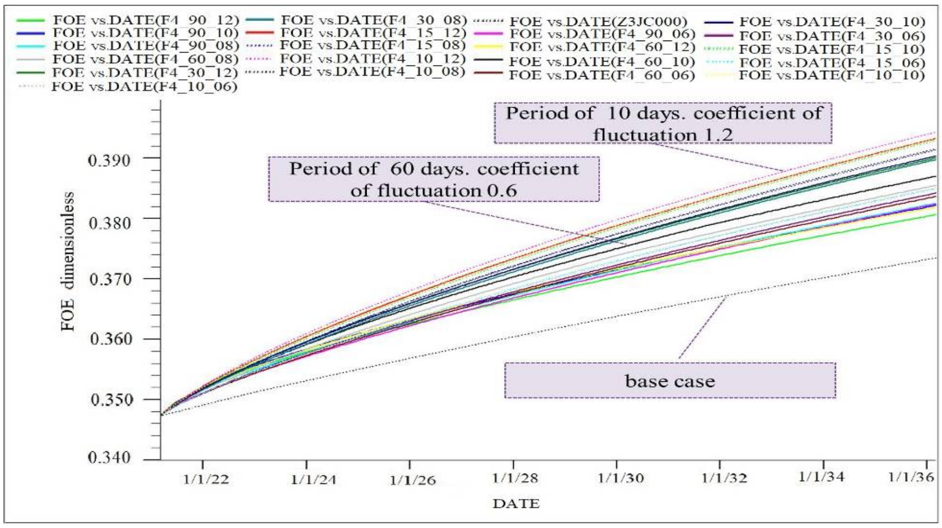


Fig. 25. Predicted results of the recovery degree of scheme 4.

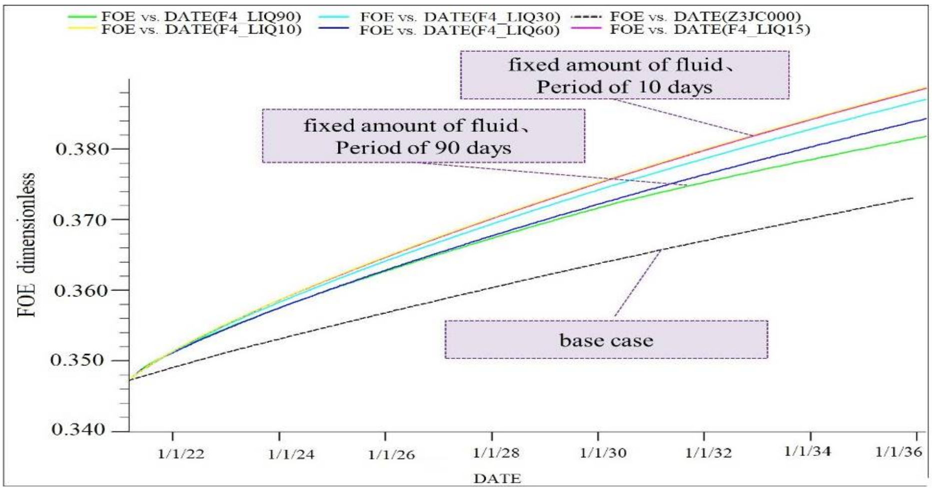
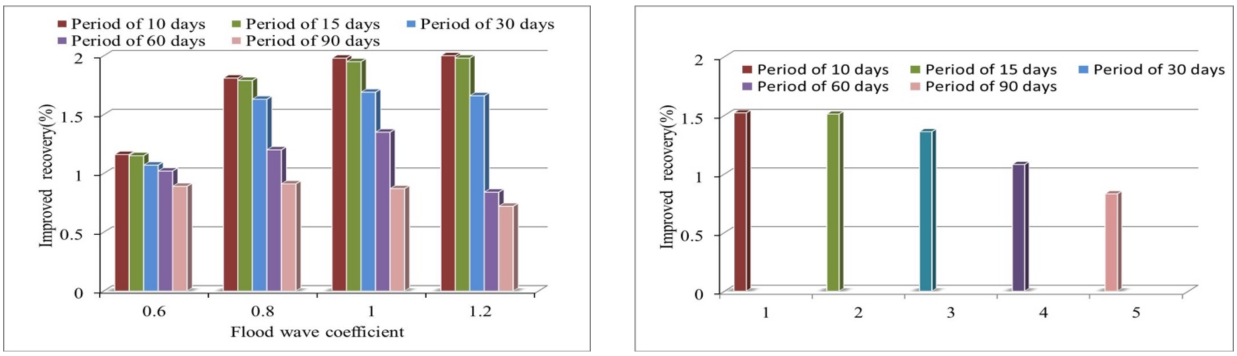


Fig. 26. Predicted results of the recovered degree of triangular alternating liquid fixation index.



(a) (b)

Fig. 27. Indicator prediction results of scheme 4 . (a) Recovery degree curve.(b)Liquid fixed index of increased recovery rate.

Fixed fluid prediction was carried out in the triangle alternating mode. The fixed fluid of oil and water wells was 12 and 25 cubic meters respectively. Two sets of triangle well groups (including new and old wells) were injected alternately, with sand groups 1 and 2 in one group, and sand groups 3 and 4 in the other group, which were injected alternately according to different cycles and fluctuation ranges.

As shown in the results in Figs. 25 and 27(b), the stage recovery degree and increase range are slightly lower than those in scheme 4.

Scheme 5: The longitudinal two-stage rotation injection mode was for prediction. All new and old wells were injected alternately according to different periods and different fluctuation ranges, with sand groups 1 and 2 in one section and sand groups 3 and 4 in the other section.

According to the results in Figs. 25 and 29, the increase of stage recovery degree is relatively balanced with a period of more than 60 d and the increase degree of stage recovery degree decreases.

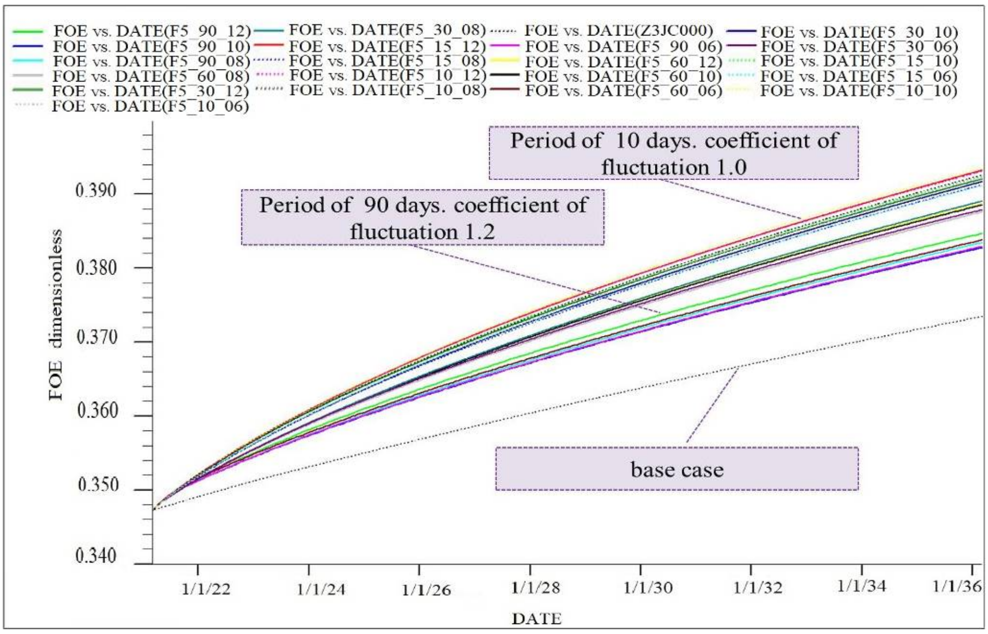


Fig. 28. Predicted results of the recovery degree of scheme 5.

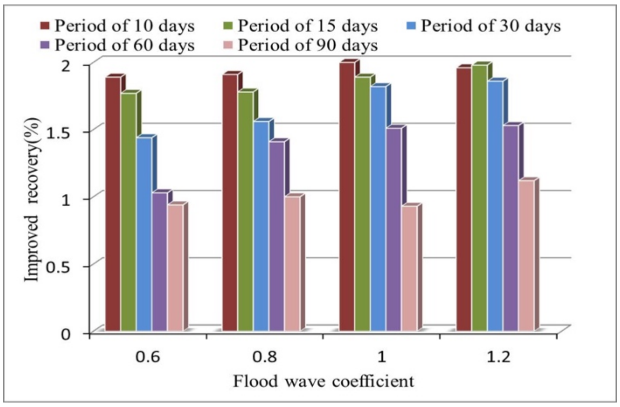


Fig. 29. Increased recovery effect of scheme 5

According to the prediction results of various schemes in Table 5 and Figs. 30 and 31, the stage recovery degree of each scheme is improved compared with that of the basic scheme. Compared with the development schemes of commingled injection and commingled production, all-round inter-injection, intra-row symmetry, triangular alternation, longitudinal rotation injection, triangular alternation of fixed liquid and intra-row symmetry, the recovery efficiency is different under the same cycle and fluctuation range of water injection. The effect of each scheme becomes worse when the cycle is more than 60 d. The development effect improves with the increase of water injection intensity. Comparing the development effects of various schemes, we can conclude that the numerical simulation prediction of commingled injection and commingled production scheme has the highest recovery rate, which can be increased by 2.72%. Moreover, the comprehensive water cut and cumulative injection amount are the largest. Therefore, commingled injection and commingled production is the best injection scheme.

Table .5. Comparative data of different injection methods

Number	Package name	Recovery degree(%)	Improved recovery(%)	Water content (%)	Loading Amount(10^3 m^3)
1	Foundation scheme	37.34	0.00	96.27	1476.36
2	Combined injection and production	40.07	2.72	97.02	1737.00
3	Full intermittent injection	39.50	2.15	96.17	1607.10
4	Symmetry in row injection	39.45	2.10	96.18	1592.31
5	Triangular alternation injection	39.43	2.08	96.49	1611.52
6	Longitudinal rotation injection	39.35	2.01	96.55	1644.75
7	Triangular alternation injection (Quantitative)	38.87	1.52	95.31	1505.71
8	Symmetry in row (Continuous injection)	39.55	2.21	96.89	1706.97

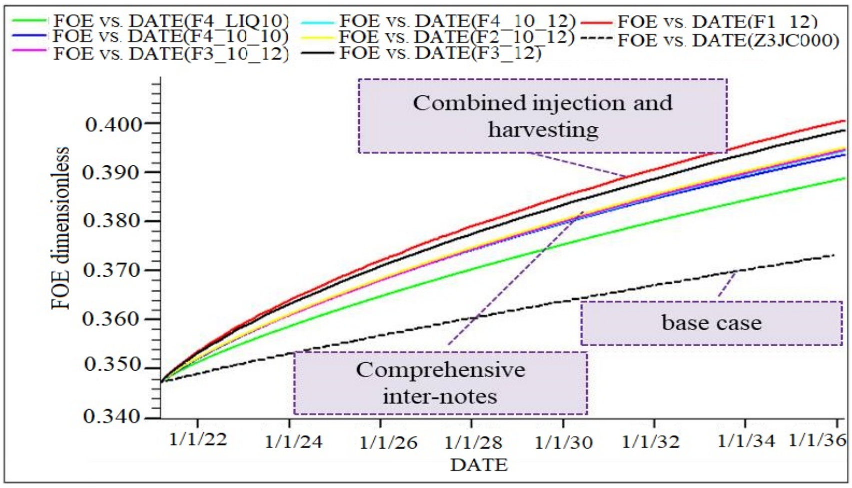


Fig. 30. Comparison of recovery degrees for the typical schemes.

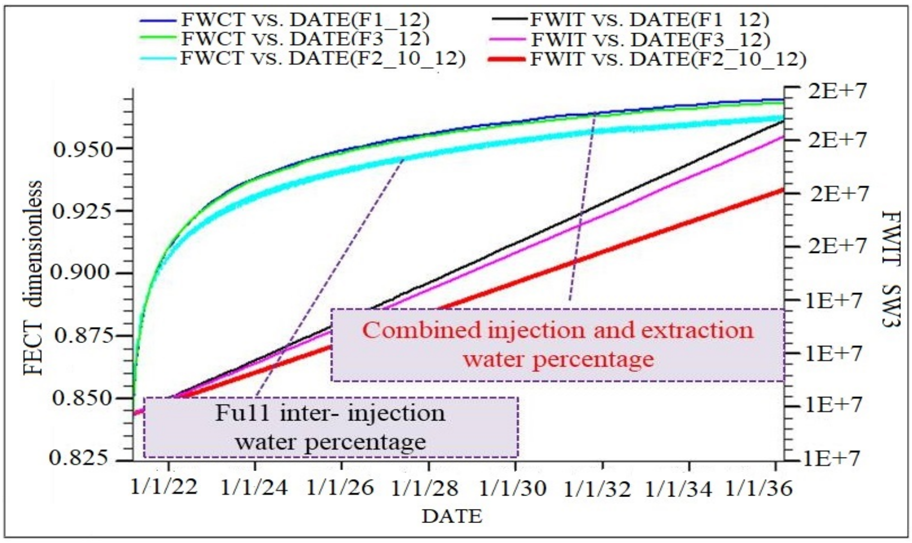


Fig. 31. Integrated water content and cumulative injection volume curves for a typical schemes.

The proposed well pattern optimization method is also applicable to well pattern adjustment in similar reservoir environments. In the process of predicting recovery rate increase of extra-high water cut reservoirs, the attribute model of rock and fluid properties was adjusted according to the reservoir properties, and different development schemes were predicted. The optimal development scheme was selected according to the recovery rate improvement effect.

5. Conclusions

The development effect of extra-high water cut reservoir is influenced by comprehensive factors such as geological characteristics, reservoir properties, well patterns, and working system. To reveal the relationship between different well pattern conditions and the development effect of remaining oil, this study used the numerical simulation method to analyze the prediction effect combined with various factors such as geology, reservoir, injection medium, well pattern deployment, and dynamic law of development scheme. The following conclusions can be drawn:

(1) Based on the interpretation of interlayer, the distribution characteristics of interlayer were analyzed. The delta sedimentary reservoir is dominated by an unstable interlayer while the channel sedimentary reservoir is dominated by a stable interlayer. The interlayer distribution is unstable, and the average thickness of the interlayer of the main sublayer is 0.41-0.83 m.

(2) As a result of sublayer subdivision, oil layers are mainly developed in sand bodies of the Fuyu oilfield. The channel sedimentary oil layers are thicker than the delta sedimentary oil layers.

(3) For typical oil layers in the Fuyu oilfield, the development schemes such as commingled injection and commingled production, all-round inter-injection, intra-row symmetry, triangular alternation, longitudinal rotation injection, triangular alternation liquid determination, and intra-row symmetry were predicted. Compared with the basic scheme, the recovery degree of each scheme has increased. Differences are observed among various well patterns, periods, and fluctuation ranges of water injection. The effect worsens when the period is longer than 60 days, and the development effect improves with the increase of water injection intensity. The recovery degree of commingled injection and commingled production scheme is slightly higher, and the comprehensive water cut and cumulative injection amount are also the largest.

In this study, the reservoirs with extra-high water cut were described and different well pattern deployment schemes were conducted to predict the increase of recovery rate. The results showed that the designed injection scheme closely conformed to the field practice, which was significant for tapping the potential of remaining oil. However, the physical properties of the reservoirs were quite different and physical simulation experimental data were insufficient. Therefore, indoor experiments were necessary according to the optimized scheme combined in future study. The mutual verification of the mathematical and physical models could help improve the development scheme of extra-high water cut reservoirs more accurately.

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References

1. Wu, Y., Wu, S., Cai , Z., "*Oil Mining Geology (3rd ed.)* ",Beijing: Petroleum Industry Press, 2005,pp.177-180.
2. Zhou ,Y., Cheng, S., Zhang, M., "Setting of variational function parameters in reservoir modeling", *Journal of Xi'an University of Petroleum (Natural Science Edition)*, 25(05),2010,pp.25-27+32+107.
3. Yang, Y., Xu, P., Wang, J., Liu, W., Wu, Y., Liu, W., Cui, C., "Techniques for regulating the zonal well network during the high water content period in broken block reservoirs ". *Oil and Gas Geology and Recovery*, 23(6),2016,pp.52-56.
4. Wu, Z., Cui, C., Yang, Y., Huang, Y., Liu, Z., "Seepage characteristics of large pore channels during high water-bearing period and quantitative description method". *Petroleum and Natural Gas Geology*, 39(4), 2018,pp.839-844.
5. Cui, C., Geng, Z., Wang, Y., Huang, Y., Liu, H., "Calculation model and application of dynamic distribution of permeability during high water-bearing period in water-driven reservoirs". *Journal of China University of Petroleum (Natural Science Edition)*, 36(4) ,2012,pp.118-122.
6. Cui C., Xu J., Wang D., Yang Y., Liu H., "Characteristic curves of new water drive in extra-high water-bearing stage". *Journal of Petroleum*, 36(10) ,2015,pp.1267-1271.
7. Fang, D., Jia, Q., Gong, J., Gao, D., Yuan, L., "Quantitative description of remaining oil based on single sand body in fan delta reservoir". *Broken Block Oil and Gas Field*, 24(4),2017,pp:529-535.
8. Gorbunov, A. T., "*Anomalous oil field development .Translated by Zhang Shubao*". Beijing: Petroleum Industry Press, China,1987,pp.35-47.
9. Li, D., "*Development of low permeability sandstone oil fields*". Beijing: Petroleum Industry Publishing House, China ,1997,pp.65-74.
10. Fan, H., Wang, X., Cao, W., Yan, K., Xie, K., Lu, X., He, M., "Influence of Well Pattern Type on Remaining Oil Saturation and Distribution after Development". *Energies*,15(7),2022, pp.2438-2438.
11. Almajid, M. M., Kovscek, A. R., "Pore level foam generation in the presence of residual oil in porous media".*Fuel*,324(PB) ,2022, pp.124568.
12. Liao, J., Zhang Z., Tang, H., Yang, J., Zhang, X., Wang, B., "Simulation of Fracturing and Well Pattern Optimization of Fractured Tight Sandstone Reservoirs". *Frontiers in Earth Science*, 5(10), 2022,pp.873617.
13. Li ,Q., Li, Y ., Gao, S., Liu, H., Ye, L., Wu ,H., Zhu W., An, W., "Well network optimization and recovery evaluation of tight sandstone gas reservoirs". *Journal of Petroleum Science and Engineering*, 196, 2021, pp.107705.
14. Hu, W., Wei, Y., Bao, J., "Advances in theory and technology of low permeability reservoir development in China". *Petroleum Exploration and Development*, ,45(04) ,2018,pp.646-656.
15. Liu, Y., Wang, F., Hu, C., Wang, Y., Liu, Y., "Study on oil-water seepage law in thin differential reservoirs". *Special oil and gas reservoirs*, 20(05), 2013,pp. 89-92+155.
16. Liu, L., "*Study on the characteristics of independent off-surface reservoirs and the influence on the distribution of remaining oil in the Sa, Pu and Gao oil reservoirs in Plain Apricot Six*". Master thesis of Northeast Petroleum University, China, 2020,pp.35-39.
17. Zeng, L., Liu, H., "Influence of fractures on the development of low-permeability sandstone reservoirs: A case study from the Taizhao district, Daqing Oilfield, China". *Journal of Petroleum Science and Engineering*, 72(1), 2010, pp.120-127.
18. Wang, Y., Ji, B., Guo, W., "Research on the development technology of Daqing peripheral extra-low permeability and extra-low abundance oil field". *Journal of Petroleum*, (06), 2006,pp.70-74.
19. Gan, Y., Zhang, S., Chen, L., Miao, H., Zhang, S., "Optimization design of irregular well networks for fracturing complex block reservoirs". *Journal of Petroleum*, (04),2006,pp.81-84+88.
20. Sun, G., "Optimization of well network reorganization technology in the Shengtuo oilfield during the extra high water content period". *Oil and Gas Geology and Recovery*, (03),2005,pp.48-50+85.
21. Jiang, R., "Exploration on the relationship between water-driven recovery and well network density in fractured well networks of low-permeability reservoirs". *Daqing Petroleum Geology and Development*, (02) ,2002,pp.19-20+75.
22. Ravela , S., Alali , A. M. , Abughaban, M. F. , Hybrid Data Driven Drilling and Rate of Penetration Optimization". *Journal of Petroleum Science and Engineering*, 200(6527) ,2020,pp.108075.
23. Zeng, L., Li, X., "Fractures in sandstone reservoirs with ultra-low permeability: A case study of the Upper Triassic YanChang Formation in the Ordos Basin, China". *AAPG bulletin*, 93(4), 2009, pp.461-477.
24. Suranto, A. M.; Permadi, A. K., Bae, W,. Park, Y., Son, D. T., "Controlling the hybrid steam-solvent injection for increasing recovery factor and reducing solvent retention in heterogeneous reservoirs". *International Journal of Oil, Gas and Coal Technology*,11(4) , 2016,pp.370-386.
25. Wang, W., Shi, M., Zhuang, X., Bu, Y., Su, Y., "A joint optimization method of well location and injection and extraction parameters based on machine learning". *Journal of Shenzhen University (Science and Technology Edition)*, 39(02), 2022, pp.126-133.
26. Muradov, K., Sefat, M. H., Moradidowlatabad, M., "Fast optimization of packer locations in wells with flow control completions". *Journal of Petroleum Science and Engineering*, 205, 2021 ,pp.108933.