DE GRUYTER Open Geosciences 2020; 12: 1736–1749

Research Article

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Effects of oil viscosity on waterflooding: A case study of high water-cut sandstone oilfield in Kazakhstan

https://doi.org/10.1515/geo-2020-0218
received October 13, 2020; accepted December 02, 2020

Abstract: After a sandstone oilfield enters the high water-cut period, the viscosity of crude oil has an important influence on remaining oil distribution and waterflooding characteristics under the same factors of, e.g., reservoir quality and development methods. Based on a comprehensive interpretation of the waterflooded layers in new oil wells, physical simulation experiments, and reservoir numerical simulations, we analyzed the waterflooding laws of a high water-cut sandstone reservoir with different oil viscosities in Kazakhstan under the same oil production speed, and we clarified the remaining oil potential of reservoirs with different viscosities and proposed corresponding development measures. The results show that low-viscosity oil reservoirs (1 mPa s) have uniform waterflooding, thick streamlines, small waterflooding areas, and low overall waterflooding degrees because of their homogeneous oil–water viscosities. However, within waterflooded areas, the reservoirs have high oil displacement efficiencies and high waterflooding degrees, and the remaining oil is mainly concentrated in the unwaterflooded areas; therefore, the initial production and water cut in new oil wells vary significantly. High-viscosity oil reservoirs (200 mPa s) have severe waterflooding fingering, large waterflooding areas, and high overall waterflooded degrees because of their high oil–water mobility ratios. However, within waterflooded areas, the reservoirs have low oil displacement efficiencies and low waterflooding degrees, and the remaining oil is mainly concentrated in both the waterflooded areas and the unwaterflooded areas; therefore, the differences in the initial production and water cut of new oil wells are small. Moderate-viscosity oil reservoirs (20 mPa s) are characterized by remaining oil distributions that are somewhere in between those of the former two reservoirs. Therefore, in the high water-cut period, as the viscosity of crude oil increases, the efficiency of waterflooding gradually deteriorates and the remaining oil potential increases. In the later development, it is suggested to implement the local well pattern thickening in the remaining oil enrichment area for reservoirs with low viscosity, whereas a gradual overall well pattern thickening strategy is recommended for whole reservoirs with moderate and high viscosity. The findings of this study can aid better understanding of waterflooding law and the remaining oil potential of reservoirs with different viscosities and proposed corresponding development measures. The research results have important guidance and reference significance for the secondary development of high water-cut sandstone oilfields.

Keywords: Kazakhstan, high water-cut sandstone reservoir, oil viscosity, waterflooding, remaining oil, development measures

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1 Introduction

After sandstone oilfields enter the stage characterized by high water cut and high recovery degree, their remaining oil distribution patterns become complex, and the controlling factors are diverse [1–6]; therefore, accurate prediction of the remaining oil distribution is the key to improving oil recovery [7–14]. Essentially, the distribution of the remaining oil in an oilfield is mainly controlled by internal and external factors. The internal factors include reservoir quality (physical properties and heterogeneity), reservoir type, and crude oil viscosity, whereas the external factors include development methods, well patterns, development layer series accuracy, and oil production speed. For high water-cut sandstone oilfields, when the development methods are determined, the internal factors control the remaining oil distribution.

In consideration of the results of previous research, most studies have focused on reservoir heterogeneity and its impact on remaining oil distribution for high water-cut sandstone oilfields, and achieved fruitful results. Based on the oilfield outcrops, the reservoir architecture characterization was carried out [12–22], three-dimensional architecture models of different types of sand bodies were established [23–26], and the control effect of sand body architecture on waterflooding [27–29] and remaining oil distribution pattern [30,31] was clarified, which pointed out the direction for the formulation of reasonable development technical measures during the high water-cut period of sandstone oilfields. Examining current research, there are relatively few studies on the influence of crude oil viscosity on waterflooding sweep characteristics.

In the research of crude oil viscosity and waterflooding sweep, previous work has mainly focused on heavy oil reservoirs, including the waterflooding characteristics of heavy oil reservoirs [32], as well as the influence of crude oil viscosity on oil recovery [33–35] and its production degree [36]. In addition, in recent years, several scholars have also studied the influence of crude oil viscosity on oil recovery prediction [37], but there are few comparative studies on waterflooding and sweeping of reservoirs with different crude oil viscosities. This article compared the actual development effects of high water-cut sandstone oilfields in Kazakhstan with different viscosities, analyzed the impact of crude oil viscosity on waterflooding characteristics and waterflooding sweep under similar development methods and oil production speed, clarified the remaining oil potential of reservoirs with different viscosities, and proposed corresponding development measures. Our research results provide important guidance and a reference for the secondary development of high water-cut sandstone oilfields.

In the high water-cut sandstone oilfields in Kazakhstan, as the viscosity of the crude oil increases, the difference in the initial production and water cut of the new wells gradually decreases, indicating that during the high water-cut period, the waterflooding characteristics and the remaining oil distributions of the three types of reservoirs are quite different (see Figure 1). Therefore, it is necessary to analyze the waterflooding sweep laws of reservoirs with different crude oil viscosities to clarify their remaining oil distributions. Based on the waterflooding analysis data of new wells and the results of reservoir numerical simulation and physical simulation experiments, the waterflooding characteristics of reservoirs with different

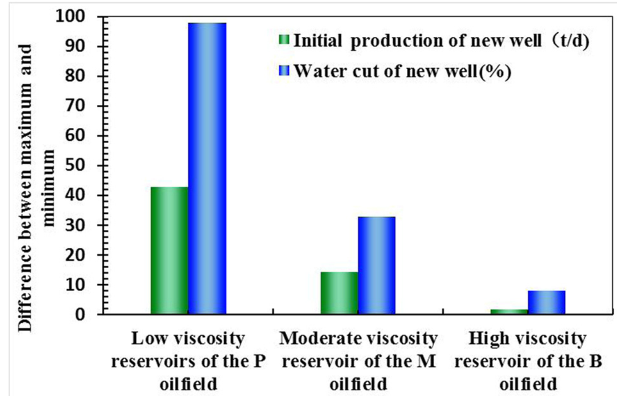

Figure 1: Differences in the initial production and water cut of new wells in reservoirs with different crude oil viscosities.

crude oil viscosities were analyzed, and the main processes are detailed as follows: First, the geology and development characteristics of the three high water-cut sandstone oilfields with different crude oil viscosities in Kazakhstan are presented. Then, based on the drilling data of new wells, the waterflooding characteristics of single sand bodies are analyzed, the waterflooding patterns are summarized, and the thickness ratios of different waterflooding levels are quantitatively calculated in these oilfields. Third, using actual parameters of the oilfields to establish a three-dimensional geological model and carry out the reservoir numerical simulation, the waterflooding analysis results are verified. Fourth, physical simulation experiments are carried out to further verify the results of reservoir numerical simulation. Finally, reasonable measures for tapping the remaining oil in these oilfields with different crude oil viscosities are proposed.

2 Geology and development characteristics of the high water-cut sandstone oilfields in Kazakhstan

The main sandstone oilfields in Kazakhstan have all entered the high water-cut and high recovery degree stage, with rapid decreases in production. The typical old sandstone oilfields in this area mainly include the P oilfield, the M oilfield, and the B oilfield (see Figure 2). The comprehensive water cuts of the oilfields are 90.6–95.4%, and the recovery degrees of the geological reserves are 9.4–54%.

Figure 2: Location of high water-cut sandstone oilfield in Kazakhstan.

The P oilfield is structurally located in the Aryskum depression in the South Turgay Basin. The main strata include a continental river–delta–lake sedimentary system. The main reservoirs are the point bar sand and overflow sand of a meandering river, the central bar sand and channel sand of a braided river, and the underwater distributary channel sand, estuary bar sand, and lateral sheet sand of a delta front [27,28]. The M oilfield is structurally located in the northwestern part of the North Ustyurt Basin. The main strata were developed by river-delta front deposition, and the main reservoirs are underwater distributary channel sand, bar bodies, bar edges, and sheet sand [38]. The B oilfield is structurally located in the western part of the North Ustyurt Basin, and the main strata are fluvial delta deposits. The main reservoirs are distributary channel sand, bar bodies, and bar edge sand [39].

The three reservoirs are all moderate-high porosity and high permeability reservoirs, but the oil properties are very different. The P oilfield produces a low-viscosity crude oil with an average crude oil viscosity of 2.1 mPa s; the M oilfield produces a moderate-high-viscosity crude oil with an average crude oil viscosity of 20.5 mPa s; and the B oilfield produces a high-viscosity crude oil with an average crude oil viscosity of 196 mPa s (Table 1).

In the development of the three types of reservoirs with high water-cut and high recovery degree, under the conditions of similar external factors of, e.g., oil recovery speed and development method, the development effects of new oil wells are quite different. The initial productions of the new oil wells in the low-viscosity reservoirs of the P oilfield are 0.1–43 t/day and the water cuts are 0–98%. The initial productions of the new oil wells in the moderate-high-viscosity reservoirs of the M oilfield project are 5.8–20 t/day and the water cuts are 52–85%. The new oil wells in the high-viscosity reservoirs of the B

Table 1: Geological and development characteristics of sandstone reservoirs with different viscosities in Kazakhstan

Reservoir type	Crude oil viscosity (mPa s)	Average porosity (%)	Average permeability (10^{-3} μm^2)	Comprehensive water cut (%)	Recovery degree of recoverable reserves (%)	Oil production speed (%)	Initial production of new well (t/day)	Water cut of new well (%)
Low-viscosity reservoirs of the P oilfield	1.1	21	541	95.4	79.3	1.0	0.1–43	0–98
Moderate-viscosity reservoir of the M oilfield	20.5	26	696	90.6	64.6	0.95	5.8–20	52–85
High-viscosity reservoir of the B oilfield	196	28	2020	93.8	43.5	0.85	7.2–8.9	56–64

oilfield have initial productions of 7.2–8.9 t/day and water cuts of 56–64%.

3 Waterflooding characteristics of sandstone reservoirs with different viscosities

Using the comprehensive well logging interpretation method for waterflooded formations, the new oil wells in the waterflooded areas of sandstone oilfields with different viscosities were divided into unwaterflooded layers (water cut of less than 10% and resistivity of greater than 8 Ω m), weak waterflooded layers (water cut of 10–40% and resistivity of 4–8 Ω m), and moderate-strong waterflooded layers (water cut of greater than 40% and resistivity of greater than 4 Ω m) [26]. Based on this division, by analyzing the waterflooding characteristics within and between single sand bodies in sandstone reservoirs with different viscosities and by quantitatively determining the thickness ratios of the waterflooded layers of the different grades, the waterflooding laws of oilfields with different crude oil viscosities were revealed.

3.1 Waterflooding characteristics inside single sand bodies in sandstone reservoirs with different viscosities

The single sand body in the low-viscosity P oilfield has been waterflooded by vertically injected water overall, and thus, weak and moderate-strong waterflooded layers have developed, and unwaterflooded layers are no longer present (see Figure 3a). Among them, the proportion of strong waterflooded zones is higher than that of weak waterflooded zones, indicating that the low-viscosity oil reservoir was uniformly affected throughout the water injection process, and the waterflooding degree and waterflooding efficiency are high.

The single sand body in the moderate-viscosity M oilfield has been primarily affected by vertically injected water, and thus, unwaterflooded, weak waterflooded, and strong waterflooded layers have all developed (see Figure 3b). Among them, the proportions of weak waterflooded layers and unwaterflooded layers are higher than that of the moderate-strong waterflooded layers, indicating that in the water injection development process

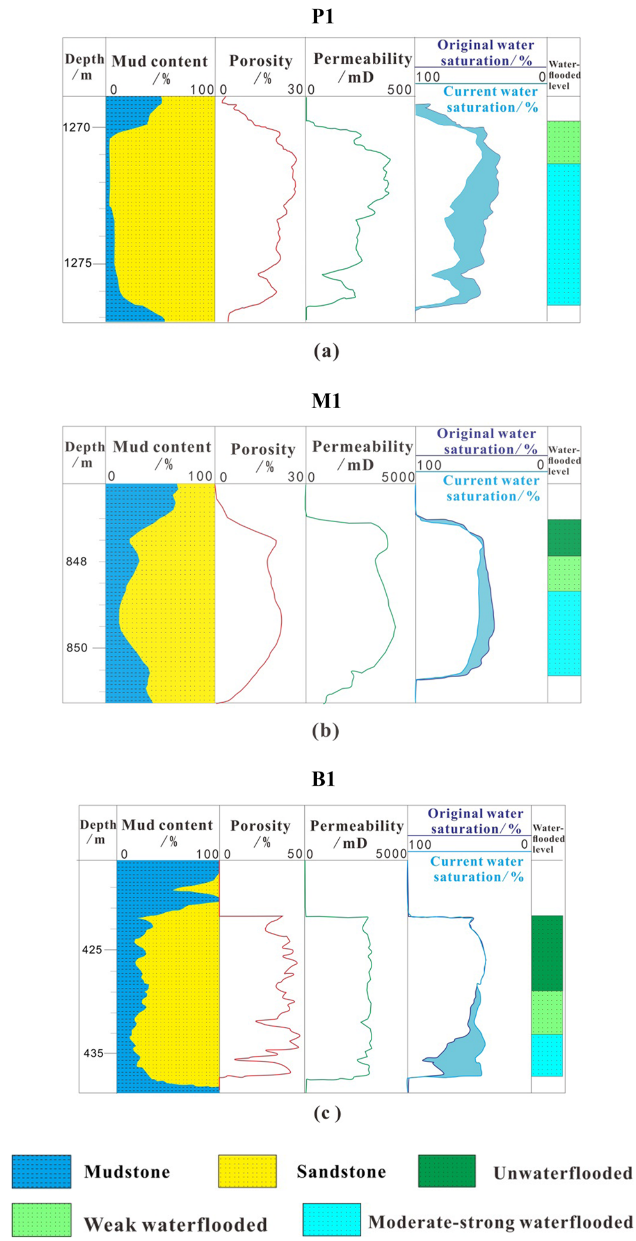

Figure 3: Waterflooding characteristics of a single sand body of a sandstone oilfield with variable viscosity: (a) low-viscosity oil reservoir, (b) moderate-viscosity oil reservoir, and (c) high-viscosity oil reservoir.

of moderate-viscosity reservoirs, compared with that of low-viscosity reservoirs, the spread of the vertical waterflooding is relatively uneven, the waterflooding efficiency is lower, the waterflooding degree is weaker, and the proportion of unwaterflooded layers in the waterflooded area is relatively high.

The waterflooded characteristics of a single sand body in the high-viscosity B oilfield are similar to those of the moderate-viscosity reservoir. Vertically, the unwaterflooded, weak waterflooded, and strong waterflooded layers are developed, among which, the development of unwaterflooded layers increases and the development of moderate-strong waterflooded layers decreases (see Figure 3c), indicating that as the viscosity of the crude oil increases, the extent of the vertical waterflooding becomes worse, and the waterflooding efficiency decreases significantly.

3.2 Waterflooding patterns of sandstone oilfields with different viscosities

Based on the vertical waterflooding characteristics of single sand bodies in the waterflooded area, using the waterflooding evaluation results of the new oil wells in the waterflooded areas, the waterflooding patterns of the single sand bodies in the sandstone reservoirs with different viscosities were analyzed.

In the low-viscosity P oilfield, the vertical single sand bodies are all affected by the injected water to varying degrees. The oil layers are mainly moderate-strong waterflooded layers and weak waterflooded layers; and in the lateral direction, the injected water mainly advances along with the middle and lower parts of the sand body. There is little difference between the waterflooding fronts at the top and bottom of the reservoir. The sand bodies in the waterflooded area are basically all waterflooded, and the unwaterflooded layers are mainly distributed in the unwaterflooded area, exhibiting an overall moderate-strong waterflooding pattern (see Figure 4a).

In the moderate-viscosity M oilfield, compared with the low-viscosity reservoirs, vertically, the waterflooding degree is weaker, and the unwaterflooded layers are developed in areas far from the water injection well. Horizontally, the injected water also advances along the bottom of the reservoir, but the waterflooding range is significantly increased, and the advancement speed of the waterflooding front in the middle and lower parts of the reservoir is higher than that in the top of the reservoir, resulting in obvious differences in the waterflooding characteristics of the middle and lower parts of the reservoir. Moreover, the unwaterflooded layers are mainly distributed at the top of the reservoir and far away from the water injection well, exhibiting a partly moderate-strong waterflooding pattern (see Figure 4b).

In the high-viscosity B oilfield, as the viscosity of crude oil increases, the sand body waterflooding characteristics change significantly. Vertically, the unwaterflooded layers are generally developed in the different well areas, and the thickness ratio increases, whereas the moderate-strong waterflooded layers are mainly developed at the bottom of the oil layer. Horizontally, similar to the low- and moderate-viscosity reservoirs, the injected water advances along the middle and lower parts of the reservoir, but the waterflooding area becomes larger, and the waterflooding efficiency decreases, exhibiting a local moderate-strong waterflooding pattern (see Figure 4c).

Therefore, the qualitative comparative analysis of the waterflooding patterns in reservoirs with different crude oil viscosities shows that as the viscosity of the crude oil increases, the vertical waterflooding range of the reservoir decreases, while the horizontal waterflooding range increases, and the development of the unwaterflooded layers increases. The waterflooding effect becomes worse, and the remaining oil potential in the waterflooded area increases.

3.3 Effect of waterflooding on sandstone oilfields with different viscosities

By comparing and analyzing the waterflooding characteristics of new oil wells in three types of reservoirs and by calculating the thickness ratios of different waterflooded layers, the effect of waterflooding on reservoirs with different crude oil viscosities was quantitatively analyzed.

The statistical analysis of the thickness ratios of the waterflooded layers in 367 new oil wells in the low-viscosity P oilfield's delta sand bodies shows that the thickness ratio of the unwaterflooded layer of different types of single sand bodies is higher than those of the weak waterflooded layers and the moderate-strong waterflooded layers. The thickness ratio of the unwaterflooded layers is as high as 58.3% and that of the moderate-strong waterflooded layers is 32.6% (see Figure 5a). This shows that the waterflooding characteristics of the new wells are very different. In the waterflooded area, the oil layers in the new wells are basically all waterflooded, whereas in the unwaterflooded area, the oil layers in the new wells are weakly waterflooded or even unwaterflooded. This is also the fundamental reason for the large differences in initial production and water cut of the new oil wells in the low-viscosity reservoirs.

The statistical analysis of the thickness ratios of the waterflooded layers in 192 new wells in the moderate-viscosity M oilfield's delta sand bodies shows that compared with the low-viscosity reservoirs the thickness ratio

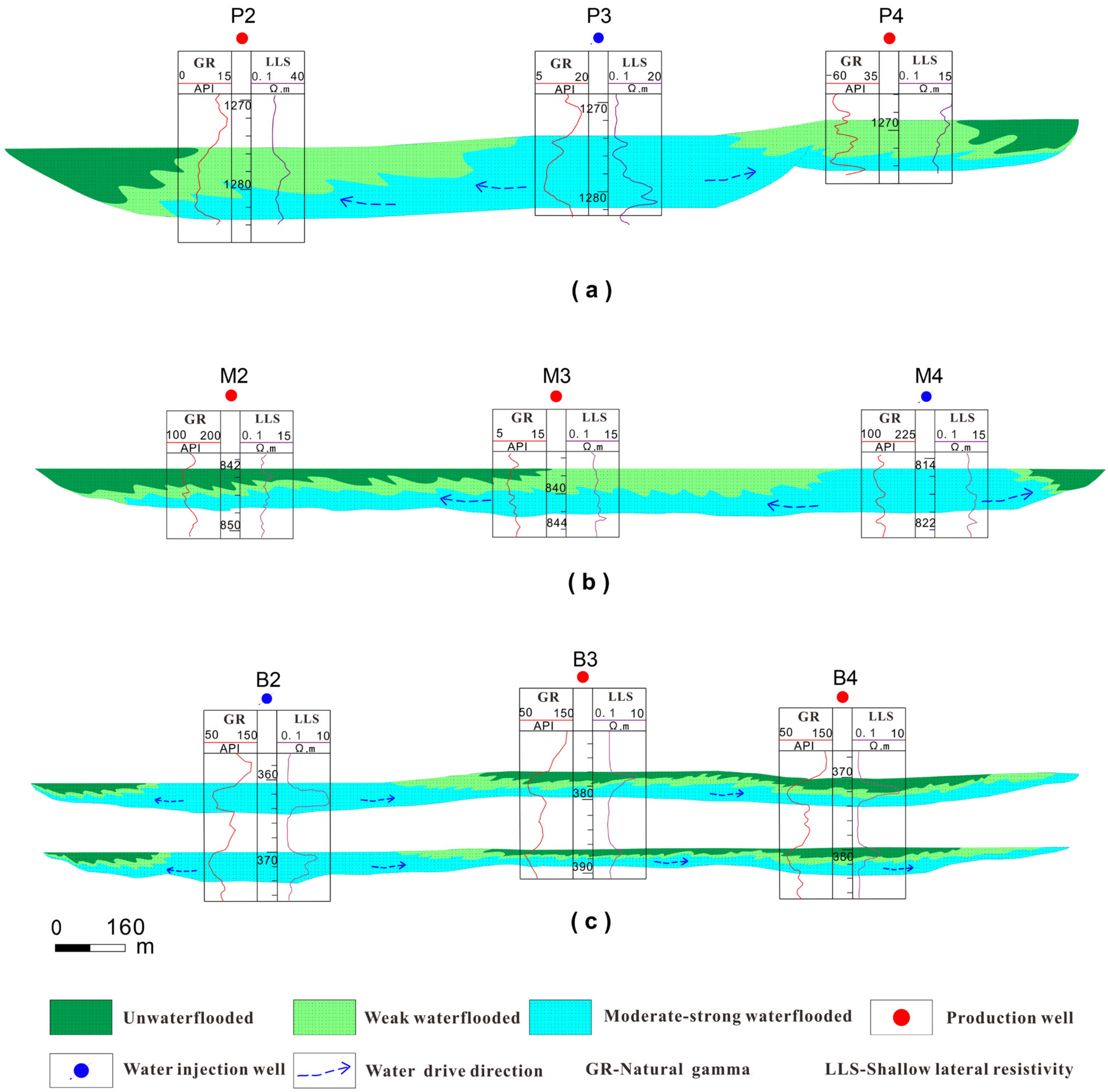

Figure 4: Waterflooding patterns of a sandstone oilfield with variable viscosity during high water-cut: (a) waterflooding characteristics of low-viscosity reservoir, (b) waterflooding characteristics of moderate-viscosity reservoir, and (c) waterflooding characteristics of high-viscosity reservoir.

of the strong waterflooded layers in different types of single sand bodies is higher, whereas the thickness ratio of the unwaterflooded layers is lower. Overall, the thickness ratio of the unwaterflooded layer decreases to 38.9% and the thickness ratio of the moderate-strong waterflooded layer increases to 48.7% (see Figure 5b), which shows that most of the new oil wells are distributed in the waterflooded areas, the overall waterflooding degree of the reservoir is high, and the differences in the initial production and water cut gradually become smaller.

The statistical analysis of the thickness ratios of the waterflooded layers in 120 new oil wells in the high-viscosity B oilfield's delta sand bodies shows that compared with the low- and moderate-viscosity reservoirs, the thickness ratio of the strong waterflooded layers in the different types of single sand bodies is significantly higher, whereas the thickness of the unwaterflooded layers is significantly lower. Overall, the thickness ratio of the unwaterflooded layer is only 24.6% and the thickness ratio of the moderate-strong waterflooded layer is

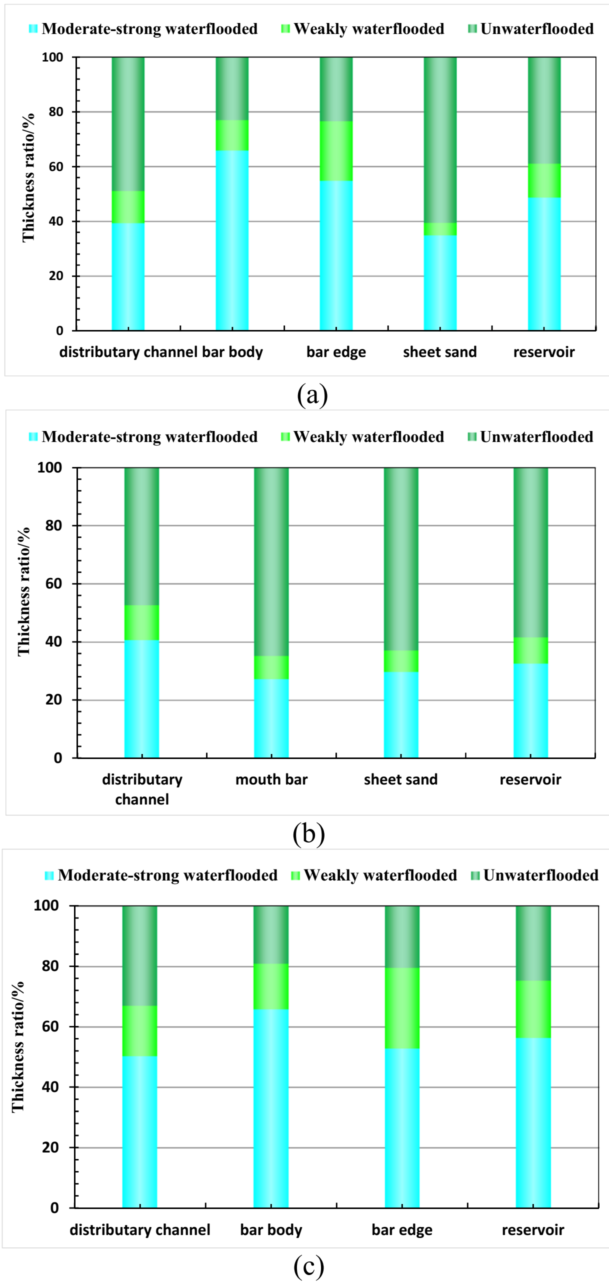

Figure 5: Statistical chart of the thickness ratio of waterflooded layers of new oil wells in reservoirs with different viscosities: (a) low-viscosity reservoir, (b) moderate-viscosity reservoir, and (c) high-viscosity reservoir.

56.4% (see Figure 5c), which shows that most of the new oil wells are distributed in the waterflooded area, the oil reservoirs are basically all waterflooded, and the initial productions and water cuts are quite similar. The results of the quantitative analysis of the waterflooding effect provide reliable evidence for the differences in the development effects of new oil wells in different-viscosity reservoirs.

4 Waterflooding laws and remaining oil development measures for sandstone oilfields with different viscosities

To further clarify the influence of crude oil viscosity on waterflooding characteristics and to reveal the waterflooding laws of sandstone reservoirs with different viscosities, three-dimensional numerical simulations were conducted using actual well group in different-viscosity reservoirs, and physical waterflooding simulation experiments were used to verify the results. Based on the results of these experiments, specific measures for tapping the remaining oil are proposed.

4.1 Reservoir numerical simulation of sandstone oilfields with different viscosities

Based on comprehensive consideration of the actual geological data of the three types of reservoirs, a three-dimensional geological model of the actual reservoir well group is established. The porosity, permeability, and shale interlayers in the model are all actual data, and the influence of structure, physical properties, and shale interlayers on waterflooding characteristics are fully considered. The planar grid accuracy is 25 × 25 m, and the vertical grid accuracy is 0.25 m. In the reservoir numerical simulation, the underground crude oil density, high-pressure physical property, and phase permeability curve are all actual parameters and are basically similar. The viscosity of crude oil is 2 mPa s (low viscosity), 20 mPa s (moderate viscosity), and 200 mPa s (high viscosity), and the oil production speed is 1.5%. Meanwhile, the historical matching rate of the production data of, e.g., daily oil production, the cumulative oil production, and the comprehensive water cut is greater than 90%.

The reservoir numerical simulation results show that in the high water-cut stage, the low-viscosity reservoirs have high oil displacement efficiencies, good water drive sweep, small water drive swept areas, planar oil–water transition zones, and obvious oil–water boundaries, and the remaining oil saturation value of the waterflooded areas is low, with an average of 22%. The movable remaining oil is relatively concentrated and is mainly distributed in the unwaterflooded areas (see Figure 6a). Vertically, the waterflooded intervals have high production degrees and low remaining oil saturations, whereas the unwaterflooded intervals have low production degrees and high remaining oil saturations, with an average value of 63% (see Figure 7a). In the high-viscosity reservoirs, because of the large difference in the oil–water viscosity and the large oil–water mobility ratio, the water has a greater mobility. During the waterflooding process, severe waterflooding fingering occurs on the plane, the waterflooding area becomes larger, the oil–water boundary becomes worse, and the two-phase area becomes wider. In the waterflooded area, the oil displacement is not thorough, the oil displacement efficiency is low, the waterflooding is uneven, and the remaining oil saturation is high, with an average of 38% (see Figure 6c). Vertically, because of the difference in the oil–water viscosity and gravitational influence, the bottom of the reservoir exhibits significant advancement and high degree of development of the dominant water drive channel, resulting in a worse vertical production degree; and in the waterflooded intervals, the remaining oil is enriched in some intervals, with an average oil saturation of 67% (see Figure 7c). For the moderate-viscosity reservoirs, the remaining oil distribution is between those of the low- and high-viscosity reservoirs because of the intermediate viscosity of the crude oil. The average remaining oil saturation in the waterflooded area on the plane is 30% (see Figure 6b), and in the vertically waterflooded interval, it is 64% (see Figure 7b).

The quantitative statistics of the remaining oil saturation distribution range at the same water cut (90%) during the high water-cut period of the different-viscosity reservoirs shows that when the volume of the remaining oil saturation is less than 45%, the remaining oil saturation distribution range of the low-viscosity reservoir is 56%, that of the moderate-viscosity reservoir is 48%, and that of the high-viscosity reservoir is 21%. When the volume of the remaining oil saturation is between 45 and 65%, the remaining oil saturation distribution range of the low-viscosity reservoir is 24%, that of the moderate-viscosity reservoir is 25%, and that of the high-viscosity reservoir is 26%. When the volume of the remaining oil saturation is greater than 65%, the remaining oil saturation distribution range of the low-viscosity reservoir is 29.3%, that of the moderate-viscosity reservoir is 37.2%, and that of the high-viscosity reservoir is 53%. For the average remaining oil saturation, the remaining oil saturation distribution range of the low-viscosity reservoir is 29.3%, that of the moderate-viscosity reservoir is 37.2%, and that of the high-viscosity reservoir is 49.8% (see Figure 8). Therefore, as the viscosity of the crude oil increases, the remaining oil potential gradually increases.

By comparing the numerical simulation results of the reservoirs with different viscosities, it was determined that the low-viscosity reservoirs have high oil displacement efficiencies within the waterflooded areas, and the remaining oil is mainly concentrated in the unwaterflooded areas. The distributions of the remaining oil in the moderate- and high-viscosity reservoirs are basically similar. Except for the remaining oil being enriched in the unwaterflooded areas, there is still greater potential for the remaining oil to be found in the waterflooded areas; and as the viscosity increases, the remaining oil potential of the waterflooded areas gradually increases. The reservoir numerical simulation results are basically consistent with the waterflooding results of the new oil wells. The numerical simulation results of the reservoirs with different viscosities show that when the viscosity of the crude oil is close to that of water, the injected water spreads uniformly with a small waterflooding range and an overall waterflooding degree; and when the viscosity of the crude oil is higher than that of water (e.g., 10 times greater), the fingering phenomenon becomes severe

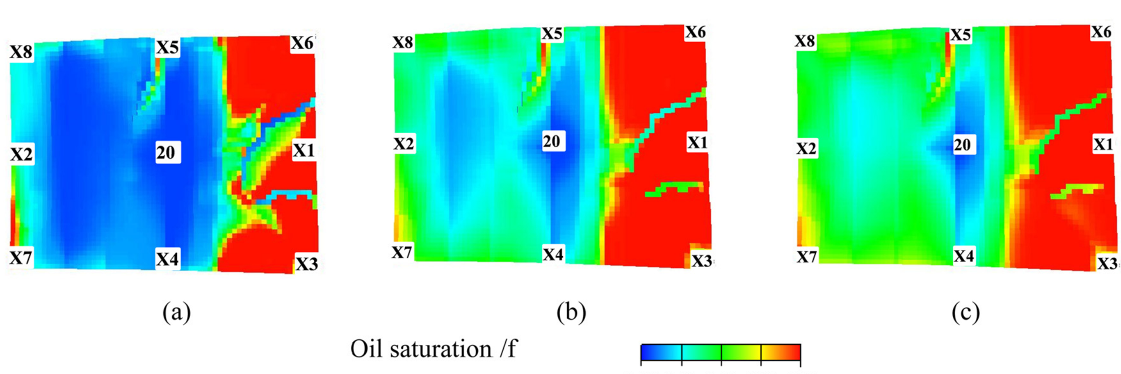

Figure 6: Planar distribution of the remaining oil in reservoirs with different viscosities with a high water cut (water cut being 90%): (a) low-viscosity reservoir, (b) moderate-viscosity reservoir, and (c) high-viscosity reservoir.

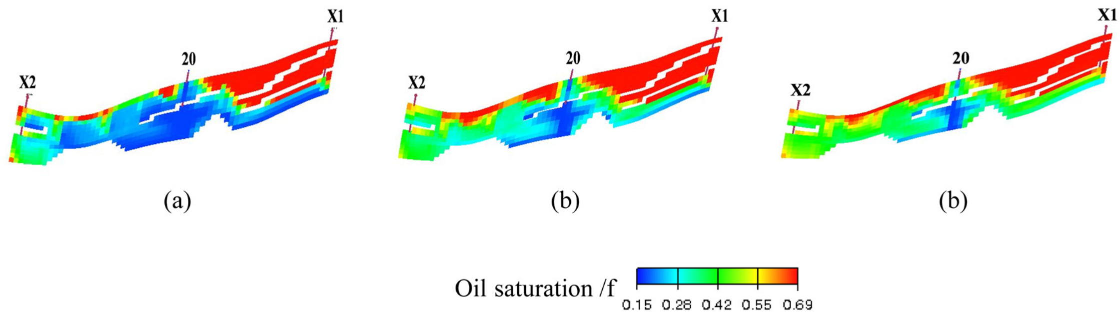

Figure 7: Vertical distribution of the remaining oil in reservoirs with different viscosities with a high water-cut (water cut being 90%): (a) low-viscosity reservoir, (b) moderate-viscosity reservoir, and (c) high-viscosity reservoir.

during the waterflooding process, the waterflooding area is large, and the overall waterflooding degree is high.

4.2 Waterflooding physical simulation experiment

To further confirm the rationality of the difference in waterflooding sweep effects in the numerical simulation of reservoirs with different crude oil viscosities, a waterflooding physical simulation experiment was designed to carry out the research on the influence of crude oil viscosity on waterflooding sweep under the same oil production speed. The apparatus used for the physical simulation experiment was designed to simulate the waterflooding characteristics of homogeneous reservoirs with different viscosities (see Figure 9a) [40], to analyze the influence of different crude oil viscosities on the waterflooding sweep laws at the same oil production speed. In the physical simulation experiment, the reservoir was composed of moderate porous, high-permeability quartz sand and the viscosity of the injected water was 0.5 mPa s. Based on the numerical simulation results of the moderate- and high-viscosity reservoir, the remaining oil distribution law for these viscosities is similar; therefore, in the waterflooding physical simulation experiment, the crude oil used was kerosene with a viscosity of 0.5 mPa s (low viscosity) and 10 mPa s (moderate-high viscosity), the injected water was dyed with Sudan red, and the injection-production well pattern is a quarter-inverse nine-point well pattern; that is, one water injection well and three oil production wells are located at the four corners of the apparatus. To more accurately reflect the actual development effect, the physical simulation experiment used the actual oil production speed of the

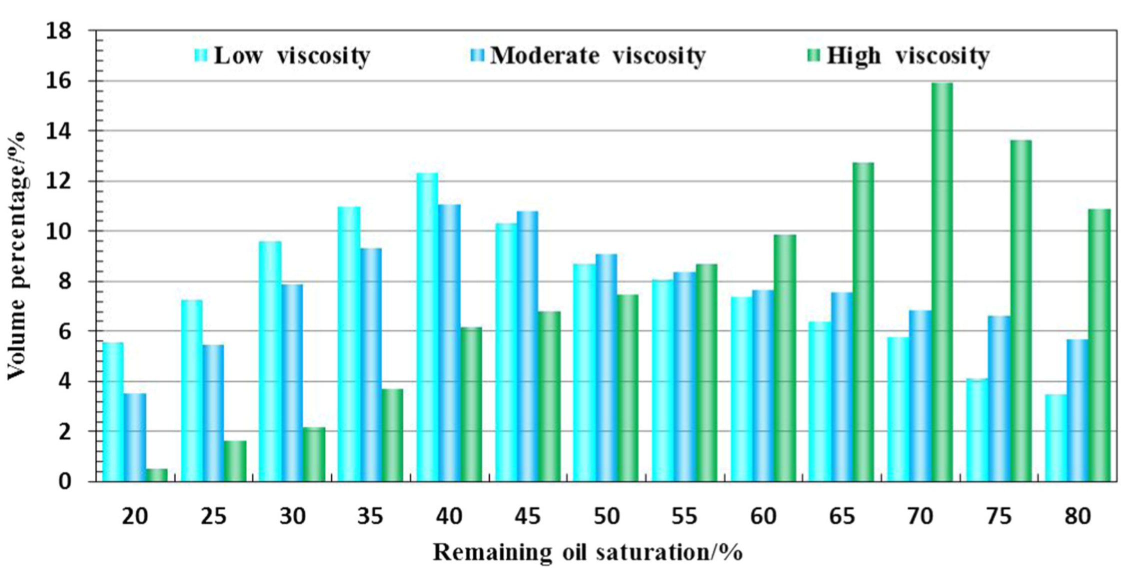

Figure 8: Histogram of the remaining oil saturation distribution in reservoirs with different viscosities with a high water-cut.

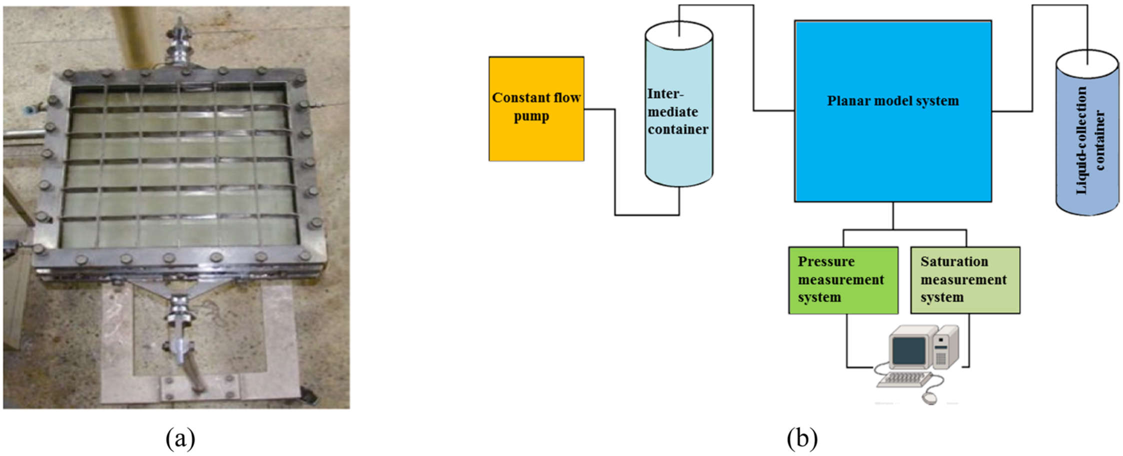

Figure 9: Waterflooding physical simulation experiment for reservoirs with different viscosities: (a) apparatus of physical simulation experiment and (b) flow chart of physical simulation experiment.

reservoir (1% oil production speed for constant pressure production) and the records of the water injection, oil production, and liquid production. When the water cut reached 100%, the experiment ended. The physical simulation experiment's design is shown in Figure 9b.

The results of the waterflooding experiments show that for the same development method, during the high water-cut period, the waterflooding characteristics of the reservoirs with different oil viscosities are quite different. During the waterflooding process in the low-viscosity reservoir, because the viscosity of the crude oil is consistent with that of the injected water, the waterflooding front is relatively straight and advances evenly on the plane. The waterflooding area is relatively small, but the waterflooding efficiency is high. There is little difference in the water spreads at the top and bottom of the reservoir (see Figure 10a). During the displacement process in the moderate-viscosity reservoir, because the viscosity of the crude oil is much higher than that of the injected water, the fingering phenomenon is obvious, the waterflooding front advances quickly, and the range is wide, but the waterflooding efficiency is low. There is a significant difference in the water spread at the top and bottom of the reservoir (see Figure 10b).

In addition, based on the statistical results, the differences in the waterflooding sweep coefficients of the reservoirs with different viscosities at the top and bottom of the reservoirs for different recovery levels and different water cuts show that in the early and middle stages of development of the low-viscosity reservoirs (the recovery degree is less than 30% and the water cut is less than 40%), the difference in the waterflooding sweep between the top and bottom gradually increases with increasing oil recovery and water cut, whereas in the middle and late stages of development (the recovery degree is greater than 30% and the water cut is greater than 40%) the waterflooding sweep difference gradually decreases. When the water cut is 90%, the waterflooding sweep coefficient difference is 30%. During the entire development process of the moderate-high-viscosity reservoir, the waterflooding sweep difference between the top and bottom increases gradually with increasing oil recovery degree and water cut. In particular, when the water cut is 90%, the difference in the waterflooding sweep coefficient is as high as 68% (see Figure 11).

Therefore, during the high water-cut period, the remaining oil potential of the low-viscosity reservoirs is low in the waterflooded area, and the remaining oil is enriched in the unwaterflooded area, resulting in large differences in the initial production and water cut of the new oil wells. However, the remaining oil potential of the high-viscosity reservoirs is high in the waterflooded area, and the remaining oil is enriched throughout the entire reservoir, resulting in small differences in the initial production and water cut of the new oil wells. The results of the waterflooding physical simulation experiments are consistent with the results of the reservoir numerical simulation and the waterflooding characteristics of the new oil wells.

4.3 Remaining oil development measures of the sandstone oilfields with different viscosities

For the same development method, the waterflooding sweep characteristics, remaining oil distributions, and

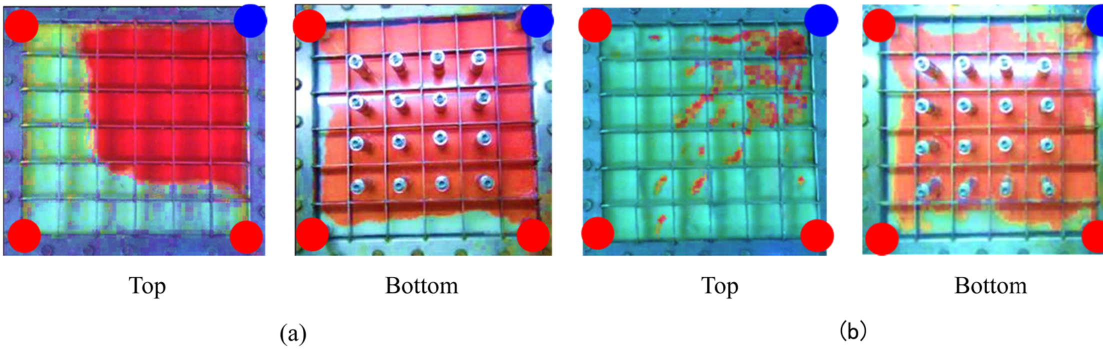

Figure 10: Top sweep characteristics of homogeneous reservoirs with different viscosities during a high water-cut period: (a) sweep characteristics of waterflooding in low-viscosity reservoirs and (b) sweep characteristics of waterflooding in high-viscosity reservoirs.

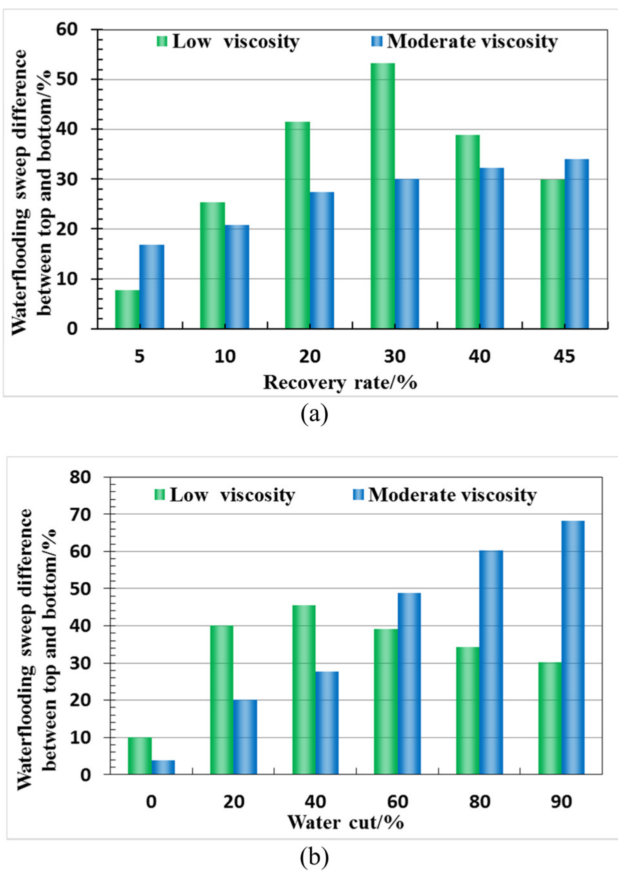

Figure 11: Waterflooding sweep differences for different recovery rates and water cuts of homogeneous reservoirs with different viscosities: (a) different recovery rate and (b) different water cut.

remaining oil development measures of the reservoirs with different viscosities during the high water-cut period are quite different. (1) On the plane, the low-viscosity reservoirs have high oil displacement efficiencies in the waterflooded area, and the remaining oil is mainly concentrated in the unwaterflooded area. Local well pattern thickening should be implemented, focusing on the remaining oil enrichment area to improve the control of the waterflooding reserve. The moderate-high-viscosity reservoirs have low oil displacement efficiencies in the waterflooded area, and the remaining oil is distributed throughout the entire reservoir. A gradual overall well pattern thickening strategy is recommended throughout the entire reservoir to improve the degree of the waterflooding reserve production. (2) Vertically, for the unwaterflooded intervals, for all three types of reservoirs, layer adjustment and re-perforation should be implemented to increase the vertical production degree, whereas for the waterflooded intervals profile control and water shutoff should be implemented to prevent a single layer from intruding and to avoid the invalid circulation of the injected water. Especially for the high-viscosity reservoirs, hot water injection should be implemented to improve the oil–water mobility ratio and to improve the waterflooding effect.

5 Discussion

The advantages of this study are that the waterflooding data of the new wells in different-viscosity reservoirs are derived from the actual oilfields, the amount of the data is large, and the data for waterflooding characteristics analysis are highly reliable, which has good guidance for the actual production of the oilfield. At the same time, the study makes full use of reservoir numerical simulation and physical simulation methods to carry out forward analysis of the reservoir, and further reveals the waterflooding law and remaining oil distribution of different-viscosity reservoirs, and the results of waterflooding analysis, reservoir numerical simulation, and physical simulation experiment are basically similar. The research results have good reference value for the development of other similar oilfields.

The limitations of this study are because of the extremely complex characteristics of the underground reservoirs. On one hand, it is very difficult to establish a three-dimensional geological model consistent with the actual reservoir, causing a certain error between the reservoir numerical simulation results and the actual reservoir development. On the other hand, the waterflooding physical simulation experiment cannot accurately reflect the heterogeneity characteristics in the actual reservoir scale. However, from a research perspective, the results of this study can basically reflect the difference in waterflooding development effects of reservoirs with different crude oil viscosities.

Later improvements are (1) improving the accuracy of the 3D geological model and reservoir numerical simulation model and (2) establishing the physical simulation experiment close to the reservoir scale in heterogeneity.

6 Conclusions

(1) The sandstone reservoirs with different oil viscosities have different waterflooding characteristics. The low-viscosity reservoirs have a weakly overall degree of waterflooding, but in the waterflooded areas, the reservoirs have high oil displacement efficiencies and high degrees of waterflooding, with an overall moderate-strong waterflooding pattern. The unwaterflooded zones are mainly distributed in the unwaterflooded areas, and the initial oil productions and water cuts of the new oil wells vary significantly. The high-viscosity reservoirs have a stronger overall degree of waterflooding because of the increased crude oil viscosity and water mobility, but the waterflooding is uneven. In the waterflooded areas, the reservoirs have high oil displacement efficiencies and high degrees of waterflooding, with a local moderate-strong waterflooding pattern, with widely distributed unwaterflooded layers and small differences in the initial oil production and water cut of the new oil wells. For the moderate-viscosity reservoirs, the waterflooding characteristics and the differences in the initial oil productions and water cuts of the new oil wells are intermediate between those of the low- and high-viscosity reservoirs, and they have a partially moderate-strong waterflooding pattern.

(2) The differences in the waterflooding sweep laws and the remaining oil in the reservoirs with different viscosities are significant. The results of the reservoir numerical simulations and physical simulation experiments reveal that the low-viscosity reservoirs exhibit uniform waterflooding and small waterflooding areas. In the waterflooded areas, the reservoirs have high oil displacement efficiencies, and the remaining oil is mainly concentrated in the unwaterflooded areas. The high-viscosity reservoirs have severe waterflooding fingering, large waterflooding areas, and a high degree of overall waterflooding because of their high oil–water mobility ratios. However, in the waterflooded areas, the reservoirs have low oil displacement efficiencies and low degrees of waterflooding, and the remaining oil is mainly concentrated in both the waterflooded areas and the unwaterflooded areas. The moderate-viscosity reservoirs have waterflooding characteristics and remaining oil distributions that are between those of the former two reservoirs.

(3) Targeted measures should be implemented for reservoirs with different viscosities to efficiently develop the remaining oil. On the plane, for the low-viscosity reservoirs, local well pattern thickening should be implemented, focusing on the remaining oil enrichment area. For the moderate-high-viscosity reservoirs, a gradual overall well pattern thickening strategy should be implemented throughout the entire reservoir. Vertically, for the unwaterflooded intervals, layer adjustment and re-perforation are suggested to increase the vertical production degree; and for the waterflooded intervals, profile control and water shutoff should be implemented to prevent a single layer from intruding and to avoid the invalid circulation of the injected water.

Acknowledgments: This work was supported by the Major Program of China (2017ZX05030-002) and the Major Program of PetroChina (2019D-4409). We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

Conflict of interest: The authors declare no conflicts of interest.

Disclosure: The authors are solely responsible for the content.

Author Contributions: Wang Jincai proposed the innovative points, conceived the study, and wrote the paper. Fan Zifei proposed the key research methods. Zhao Lun designed the physical simulation experiment. Chen Li carried out the reservoir numerical simulation study. Ni Jun, Wang Chenggang, and Zhang Xiangzhong established the 3D geological model and counted the water-flooded data of new wells.

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