Research Article

Flow Unit Model of Channel Sand Body and Its Effect on Remnant Oil Distribution: A Case Study of PI Formation in the Eastern Transition Zone of Daqing Oilfield

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To analyze the effect of various flow units in a channel sand body on remnant oil, we established a connection between various flow unit types and the remnant oil distribution. Using stratigraphic correlation and the characterization of sedimentary microfacies, we describe a single sand body, point bar, and narrow channel located at the injection-production well pattern of well B2-60-FB271 in the Eastern transition zone of the Daqing Placanticline. Architecture models of the point bar and narrow channel are also established using a series of parameters from different measurement methods. Four types of flow units (strong-current limiting, medium-current limiting, weak-current limiting, and none-current limiting) in the point bar sand body were identified, whereas one type, unshielded unit, was identified in the narrow channel. Geological parameters, such as porosity, permeability, and pore-throat radius (r_{50}), were optimized to quantitatively characterize these various flow units. Samples were obtained from well B2-60-FB271 and analyzed by the freeze-fluorescence thin section technique. According to the displacement degree, the microscopic remnant oil was divided into three types: (1) free-state remnant oil, (2) semi-free-state remnant oil, and (3) bound-state remnant oil. We found that the strong-current limiting flow unit in the point bar is the enrichment area of free-state microscopic remnant oil and that the medium-current limiting and weak-current limiting flow units also have relatively high free microscopic remnant oil. These constitute the remaining oil enrichment areas in the study area.

1. Introduction

During the late stage of old oilfield development, there is an urgent need to find remnant oil, slow down the decline of oil production, and improve oil recovery. A large amount of remnant oil can remain in a reservoir, which is mainly due to their complex architecture. When the water content reaches 96.6%, the recoverable degree becomes only 57.2% [1]. Therefore, the investigation of sand body architecture and the identification of internal flow units can provide guidelines relating to fluid-flow properties and the remnant oil distribution.

With the breakthrough in oilfield development and architectural structure theory, scholars have studied various

types of sand body architecture, outcrop measurements, modern sediment systems, underground sand bodies, and reservoir modeling [2], of which the meandering river point bar sand body is the most extensively studied ([1, 3–6]; Ji et al. 2012; [7–9]). It is widely believed that a large amount of remnant oil can exist in the upper part of a point bar sand body due to the shielding of the interlayers of lateral deposits, whereas little or no remnant oil exist at the bottom due to the erosion of the lateral accretion [10–15]. However, there are differences in flow within a channel sand body, and the remnant oil characteristics that are controlled by different flow units also differ [14, 16].

To determine the characteristics of the flow units in a channel sand body, this study takes the injection-production

well pattern of coring inspection wells in the Sabei oil-water transitional zone of the Daqing Placanticline. We dissect channel sand bodies, establish a model of flow units, and identify the different flow units in channel sand bodies. The characteristics of the microscopic remnant oil that are influenced by different flow units are obtained by quantitative analysis and by sample analysis.

2. Geological Setting

The eastern transition zone is located in the northeastern part of the Daqing Placanticline in the Songliao Basin (Figure 1(a)). The structure of the block is gentle with the dip angle of the stratum (approximately 3°), and the faults are not developed. The Putaohua Member (PI) of the Cretaceous Yaojia Formation, one of the main reservoirs in the northern Songliao Basin, is a large river-delta sedimentary system [17, 18]. Its oil-bearing area is 17.8 km^2 , and the original oil saturation is 59%. The study area was put into development in 1971, whereas the basic well pattern was put into development in 1973. The high permeability and thick reservoir were developed using the four-point injection well pattern with a well spacing of 300–350 m. In 1996, the well pattern was infiltrated and a 173–202 m four-point injection well pattern was adopted. Since March 2011, the comprehensive water cut was 95.13%. Well B2-60-FB271 is injected from wells B2-5-98, B2-6-BW75, and B2-5-BW101 in a basic well pattern, while it is injected from wells B2-61-BW274, well 2-61-BW273, and well B2-61-BW276 in secondary infilling adjustment (Figure 1(b)). Well B2-60-FB271 is a coring inspection well that was drilled in 2012 to study the remnant oil characteristics in the later stage of development (Figures 2 and 3). The core recovery rate is 99.7%. The PI layer is complete and stable. Based on fine characterization of sedimentary microfacies, PI1, PI2, PI3, and PI5+6 are all channel microfacies in well B2-60-FB271, and they are located in different positions of the channel sand bodies in the plane view. These four layers represent different types of channel sand bodies, which are of great significance for studying the characteristics of their flow units.

3. Characterization of Sand Body Architecture in Channel

Reservoir architecture includes the shape, scale, orientation, and stacking relationships of reservoir units, thus, reflecting the different spatial distributions between the reservoir unit and flow barriers [19]. Architecture analysis determines the three-dimensional arrangement of facies. Fluvial facies can be divided into six grades according to scale [3]. However, interfaces of grades 3–5 are the real reservoir architecture unit, of which the 5th grade interface is the channel, the 4th grade interface is the point bar, and the 3rd grade interface is the lateral accretion sand body [20–22].

During the later stage of development, recognizing sand bodies is insufficient to satisfy the needs of oilfield development. Based on the identification of single sand bodies in cored wells and the identification of thin interlayers in sand bodies, the spatial relationship of the 4th grade interface in

the channel sand body is first analyzed, and its internal architecture is then established, thereby resulting in flow unit divisions in the sand body of the channel.

3.1. Quantitative Characterization of Architectural Elements.

The main reservoir of meandering river facies is the channel sand body. Based on the analytic hierarchy process and the recognition of channel sand bodies by high-resolution stratigraphy correlation, point bar and narrow-channel sand bodies were identified. To establish the internal architecture of the two types of river sand bodies, it is necessary to identify their architectural elements and compare the sedimentary processes that formed them.

3.1.1. Architectural Elements of the Point Bar. The formation of abandoned river channel segments is closely related to a river's meandering style and avulsion history (Willis 1989, 1993; Bridge 2003, 2006). In floodplains, periodic floods deposit sediments on the convex bank and erode the concave bank. Thus, the river sinuosity may gradually increase over time. During a flood, the river may seek a more efficient flow path and cut through the channel bend (neck cutoff) or across the channel bar (chute cutoff). By cutting through a straighter channel, the river abandons its previous course, and the abandoned channel surrounds the point bar [23]. If the abandoned channel is determined, the end of the lateral accretion of the meandering point bar, which is its boundary, will also be determined [24]. Therefore, the identification of abandoned channel deposits is the key to understanding the internal architecture of meandering river sand bodies.

Layers PI1 and PI3 were identified as typical abandoned channel deposits, which were in the shape of “C” or “S.” To determine the internal architecture of the point bar sand body, the following architecture parameters were studied.

(1) *Channel Width.* The width of a channel is the key to its architecture and represents the distance from the levee crest across the channel perpendicular to the paleoflow. Channel width controls the preserved size of the sedimentary body. The width of the abandoned channel can represent the width of the river when the point bar was deposited. Four methods are used to calculate the channel width, the average of which is the final width (Table 1).

(2) *Scale of Lateral Accretion Body.* The point bar sand body is composed of many bed sets constituting a lateral accretion set whose scale is related to the channel width (Table 2).

(3) *Azimuth of Lateral Accretion Body.* The azimuth of a lateral accretion body can be determined by the geometric relationship between the point bar and the abandoned channel in a paleogeographic map. The azimuth is from the center of the point bar to the maximum curvature of the abandoned river (the red arrow in Figure 4). According to the detailed PI 1 sedimentary facies map, the azimuth of the apex of the abandoned river-channel bend is 332° , and the depositional-dip orientation of lateral accretion bedding is approximately the same. Similarly, the azimuth of the depositional dip

(a)

(b)

FIGURE 1: Map of the study area in the northeast of Daqing Placanticline in the Songliao Basin, eastern China. (a) Structural map of the Songliao Basin with the well locations. (b) Map of the developing well pattern of well B2-60-FB271.

FIGURE 2: Well B2-60-GB271 lithologic log in PI1 layer. The PI1 layer is in Yaojia Formation, which belongs to the Cretaceous system, one of the main reservoir in northern Songliao Basin.

orientation of the lateral accretion bedding in the PI3 stratigraphic interval is 268° (the red arrow in Figure 5).

(4) *Dip Angle of the Lateral Accretion Interlayer.* Point bar stratigraphy is formed by suspension and traction of sediment deposition during the lateral migration of a channel bend [25]. The oblique interlayer forms by periodic flow with an inclination of 3° – 20° [26, 27]. Three methods can be used to calculate the dip angle, the average of which is the final dip angle of the lateral accretion interlayer (Table 3).

(5) *Density of Lateral Accretion Interlayer.* Distribution density of the lateral interlayer includes the plane density and profile density, which are calculated using the equations in Table 4:

From the calculation results of the aforementioned architectural elements, the point-bars of PI1 and PI3 were dissected in plane map and vertical profile (Figures 4 and 5).

3.1.2. *Architectural Elements of the Narrow Channel.* Layers PI2 and PI5+6 in the study area are narrow channels with

FIGURE 3: Cores of well B2-60-GB271 from PI1 to PI5+6, 1146 m–1173 m. Siltstone is the main oil-bearing reservoir. Five interlayers are within the layer (red dotted line). The numbers on the core represent the sample numbers.

TABLE 1: Methods for calculating channel width.

Methods	Formula	Notes	PI1	PI3
Schumm [47]	$W = 255 M^{-1.08} H$; $H = h \times 110\%$	W : channel width; H : depth;	54.75 m	60.23 m
CAS	$W/H = 157 \times M^{-0.9}$	h : average thickness of channel sand body; 110%: compaction coefficient; M : percentage of shale content; L : river span.	54.88 m	60.37 m
Leopold [48]	$W = (L/10.9)^{0.99}$		52.88 m	59.86 m
Dissection of dense well pattern	Distance of two wells in the abandoned channel $< W <$ two wells from the abandoned channel to the point bar	B2-5-BW101—B2-5-P100 $< W <$ B2-60-B271—B2-60-FB271	31 m $< W <$ 108 m	$W <$ 96 m
Average	—	—	54.18 m	60.1 m

TABLE 2: Method for calculating the scale of lateral accretion body.

Methods	Formula	PI1	PI3
Schumm [47]	$W_L = 2 W/3$	36.12 m	40.1 m

widths of <300 m and thicknesses of <3 m (Figures 6 and 7). In the PI2 layer, the interlayer in the narrow channel was not found to be developed when observing the core from well B2-60-FB271. However, in the PI5+6 layer, an obvious interlayer was found in the middle part of the narrow channel. The dip of the interlayer was estimated from the spacing and stratigraphic correlation of wireline logs in the B2-60-FB271, B2-6-B76, and B2-6-B74 wells. The spacing of the B2-60-FB271 and B2-6-B76 wells is 107.32 m, and the difference between the interlayer height and the top surface height of the two wells is 0.3 m. The spacing of the B2-6-B76 and B2-6-B74 wells is 37.86 m, and the difference between the interlayer height and the top surface height of two wells is 0.1 m.

According to the formula $\tan \alpha = \Delta H/L$, the dip angle of the interlayer is approximately 0° . Both the plane maps and vertical profiles of the narrow channels in the PI1 and PI3 layers are shown in Figures 6 and 7, respectively.

3.2. Pattern of the Channel Sand Body. Based on the core description and detailed stratigraphic correlation, two types of channel sand body were identified (Table 5).

3.2.1. Meandering River Point Bar Pattern. The channel width is between 50 m and 100 m including lateral deposits. The abandoned rivers are mainly banded and swing regularly. The lateral accretion interlayer that dips from 3° to 8° is a convex/concave surface that downlaps onto the channel base. These surfaces are arcuate in the plane view and are referred to as ridge-and-swale topography.

3.2.2. Meandering River Narrow-Channel Pattern. The shape of the channel is mainly branched and striped, and its

FIGURE 4: (a) Plan view of the channel width in the PI1 layer. (b) Profile of the channel width in the PI1 layer.

development scale is small, with a width that is generally <300 m and thickness of 3 m. The narrow channel is a vertical accretion with 1–3 accretion bodies. Less interlayers with a near horizontal dip angle are developed vertically along the channel.

4. Pattern of Flow Units in the Channel Sand Bodies

4.1. Types of Flow Units Based on Architecture. Sandstone continuity in a channel sand reservoir is divided by permeability barriers into several flow units that have similar characteristics [28, 29]. The permeability barrier is formed by a nonpermeable rock such as shale interbedded with sandstone. However, their division is controlled by a sand body's sedimentary and petrophysical characteristics [30]. Similarly, flow units can be defined in the channel bar reservoirs of the Daqing field.

4.1.1. Types of Flow Units in the Point Bar. The main flow barrier in the point bar sand body is the lateral interlayer. The permeability of the beds that constitute flow barriers differ greatly from those in other parts of the channel sand body. Flow barrier lithology continuity controls the degree to which flow is restricted both laterally and vertically [31]. In the development process, the injected water flows in the point bar to form three kinds of remaining oil, which are

the (i) injection unproductive high-pressure pinch-outs remaining oil (ROI) without a drainage area, (ii) productive uninjection pinch-outs remaining oil (RO2) with inadequate driving energy, and (iii) up-dip pinch-outs remaining oil (RO3) between wells [12]. Based on the stratigraphic arrangement of permeability barriers and permeable channel-bar sandstones, four types of flow-units were identified in the channel bar reservoir (Figure 8).

Flow barriers in the channel bar conform to the lateral-accretion bedding and are best developed in the upper channel bar deposits. Here, they form barriers against the water flood from the adjacent well, which causes the shielding or trapping of oil called “unswept oil” in the upper channel bar deposits. Multiple flow barriers divide the channel sand body into several permeable and nonpermeable layers. As the shales or flow barriers approach the top of the channel bar, they merge to form nonfloodable zones. Thus, the remaining oil cannot be recovered through gravity drainage or via the waterflood.

However, in the middle of the channel, the lateral interlayers form a degree of shielding for the fluid, which makes the displacement of the middle channel sand body imperfect and forms a weak-current limiting flow unit. Due to the erosion of lateral interlayers at the bottom of the point bar, the permeability is relatively high. The fluid forms a confluence and, coupled with gravity differential subsidence of water, makes the injection water channel

FIGURE 5: (a) Plan view of the channel width in the PI3 layer. (b) Profile of the channel width in the PI3 layer.

TABLE 3: Method for calculating the dip angle of the lateral accretion interlayer.

Methods	Formula	Notes	PI1	PI3
Width-depth	$\tan \alpha = H/WL$	W_L : scale of lateral accretion body; H : depth of the channel.	6.3°	6.26°
Width-depth ratio	$\alpha = 32.966 \exp (-0.0966x)$	x : width-depth ratio	9°	7.7°
Core recognition	—	Object measurement	6°	5.1°
Average	—	—	7°	6.4°

TABLE 4: Methods for calculating the interlayer density.

Density	Formula	Notes	PI1	PI3
Profile density	$\rho_1 = \tan \alpha/d$	α : dip of lateral accretion interlayer; d : average	0.094/m	0.043/m
Plane density	$\rho_2 = 1/d$	thickness of the lateral accretion body.	0.75/m	0.3/m

and rush in. The bottom water degree of flooding is high, thus making it easy to form a none-current limiting flow unit. Therefore, in the development process, the point bar sand body is divided into four types of flow units: strong-current limiting, medium-current limiting, weak-current limiting, and none-current limiting.

4.1.2. Types of Flow Units in the Narrow Channel. For narrow-channel sand bodies without interlayers, the internal

flow unit is essentially a single, homogenous flow unit. For narrow-channel sand bodies with interlayers, the dip angle of the interlayers is approximately zero, thus offering no barrier to injection water but acting as horizontal separators for layers. Sand bodies can be separated into several individual flow units (Figure 9).

4.2. Geological Parameters of the Flow Unit in the Channel Sand Body. A flow unit is a continuous lithologic volume of

The high-pressure mercury intrusion (HPMI) capillary-pressure curve is shown in Figure 10, and a summary of the values is given in Table 6. The five samples represent different permeability levels and had different characteristics of the capillary-pressure curves, thus showing that the channel sand body is characterized by coarse pore throats and is well sorted. In Figure 11, all samples form a single peak, thereby indicating that pore-throat size distribution is concentrated [32–35]. The correlation between the median pore-throat radius and the permeability is obtained by fitting the mercury injection. This shows that under the control of the single-peak pore-throats, the permeability of the well increases with pore-throat size ($R^2 = 0.93$, Figure 12). Using the fitting formula, the pore-throat size of other samples in the well were calculated. Then, from the different flow units of the samples, the petrophysical characterization of different flow units

The strong-current limiting flow unit in a point bar is within the upper part of the channel bar, which the injection water cannot reach. Its location includes medium- and weak-current limiting flow units; therefore, the flow parameters should have the overall characteristics of both the medium- and weak-current limiting flow units. The medium-current limiting flow unit is located in the mudstone pinch-out area of the channel sand body, and it exhibits the lowest values of all parameters in the point bar sand body. The weak-current limiting flow unit is within the mudstone shelter area of the channel sand body, and its parameters are slightly larger than those of the medium-current limiting unit. The none-current limiting flow unit is located at the bottom of

FIGURE 7: (a) Plane-view of the channel patterns in the PI5+6 layer. (b) Vertical profile of the channel in the PI5+6 layer.

TABLE 5: Channel sand body pattern.

Type of channel	Representative layers	Modern sedimentation	Pattern
Point bar	PI1, PI3
Narrow channel	PI2, PI5+ 6

the channel, and numerous parameters increase significantly in a similar way to the other flow units, which have obvious differences, thereby reflecting the characteristics of high flow velocity. In the narrow channel, the unshielded flow unit has a smaller permeability and pore-throat radius, which are different from other flow units of the point bar sand body.

Overall, the geological parameters of each flow unit can be ranked in the following order according to their size (from largest to smallest): none-current limiting flow unit, weak-current limiting flow unit, medium-current limiting flow-unit, and strong-current limiting flow unit in the point bar and unshielded flow unit in the narrow channel Figures 13 and 14.

FIGURE 8: Flow units of the point-bar pattern in the development process. The injected water flows in the point bar to form three kinds of remaining oil and four types of flow units.

FIGURE 9: Flow unit of the narrow-channel pattern in the development process. The injected water flows in the narrow-channel to form an unshielded flow unit.

FIGURE 10: HPMT-derived capillary pressure curves of the five selected samples.

TABLE 6: HPMI test data.

Sample number	K ($10^{-3} \mu\text{m}^2$)	r_{50} (μm)	Pcd (MPa)
23	2688.58	14.216	0.027
66	1197.69	10.431	0.034
68	663.82	6.58	0.034
39	148.67	0.731	0.048
72	341.76	2.816	0.069

Pcd: threshold entry pressure; K : permeability; r_{50} : pore-throat radius.

FIGURE 11: Pore size distribution from the HPMI experiment.

5. Distribution of Remnant Oil in Flow Units of the Channel Sand Body

5.1. Recognition of Microscopic Remnant Oil

5.1.1. Experimental Principle of Cryopreservation Thin Section Observation. To observe both the pore structure and fluid characteristics, the position of the pore structure and internal fluid pore status were kept stable, and the samples were polished at 0.04–0.05 mm at 5°C. This method is called cryopreservation thin section, and which preserves the original state of the sample and makes the oil-water interface more visible in the microslide ([36–38]).

Fluorescence microscopic observation uses a high-pressure mercury lamp as the light source in order to analyze the occurrence and distribution of microscopic remnant oil via its luminous characteristics. Given that the different components of crude oil have different colors under ultraviolet light, the microscopic remnant oil can be identified through quantitative and qualitative analyses. Comparison of an empty microslide, microslide with water, and microslide with oil will result to the last slide exhibiting fluorescence

FIGURE 12: Scatter plot of permeability and r_{50} in the HPMI test.

(Figure 15), whereby a greater oil concentration leads to a brighter fluorescence and white to blue is the color of interest. Therefore, the microslides with fluorescence represent areas with remnant oil. Point counts were also used to determine the amount and types of microscopic remnant oil with more than 300 points for each thin section, thus lowering the standard deviation.

5.1.2. Samples of Cryopreservation Thin Section Observation. Sixteen samples with different depth, sedimentary microfacies, and oil levels were chosen from the PI1, PI2, PI3, and PI5+6 layers and their respective microslides were prepared (Table 8).

5.1.3. Types of Microscopic Remnant Oil. Microscopic remnant oil distribution patterns were constructed for the late stage of oil field development (Figure 16). Remnant oil can be divided into three types: bound-state, semi-bound-state, and free-state [39–41], and these three types can be further subdivided according to shape and distribution.

Bound-state remnant oil has a low efficiency of displacement and is adsorbed on mineral particles. It can be subdivided into the following three subtypes, where Ot means oil type:

- (i) *Adsorbed-particle-shaped (Ot1).* The oil is adsorbed in a disseminating form on the surface of mineral particles. As the oil is strongly adsorbent, oil displacement is difficult (Figure 17(a)).
- (ii) *Oil-film-shaped (Ot2).* The oil is adsorbed on the sides of mineral particles, mainly the sides of large pores in reservoirs that are characterized by the wettability of oil. In the beginning of water flooding, water is injected and breaks through from the middle of large pores. Under continuous washing, this subtype of remnant oil will gradually decrease, but it is difficult to become completely stripped clean (Figure 17(b)).

TABLE 7: Geological parameters of different flow units.

Channel type	Flow unit	φ (%)	K ($10^{-3} \mu\text{m}^2$)	r_{50} (μm)
Point bar	Strong-current limiting	25.79/23.8-28.6	297.9/48.2-539	1.99/0.26-3.06
	Medium-current limiting	26.47/23.8-28.1	297.4/48.2-425	1.98/0.26-2.87
	Weak-current limiting	25.57/27.3-28.6	298.12/58-539	2.00/1.65-3.06
	None-current limiting	27.26/21.6-30.3	1221/114-3569	9.41/0.67-29.98
Narrow channel	Unshielded	26.23/22.3-28.6	138.61/13.4-483	0.86/0.06-3.3

FIGURE 13: Scatter plot of permeability and r_{50} in different flow units.

FIGURE 14: Scatter plot of permeability and porosity in different flow units.

Semi-bound-state remnant oil, which has a medium efficiency of displacement and is situated near mineral particles, can also be subdivided into three subtypes as follows:

- (i) *Pore-center-precipitation-shaped (Ot4)*. The oil precipitates in the center of pores that primarily consist of colloids and asphaltene. Displacement is difficult due to high viscosity (Figure 17(d)).
- (ii) *Throat-shaped (Ot5)*. The oil is found in necking, sheet, or pipe throats. It is difficult for water to break through the throats as a result of capillary pressure. After the oil is displaced in large pore throats, an interconnected channel is formed among the large pore throats where water passes through; hence, this type of oil is not displaced (Figure 17(e)).
- (iii) *Corner-shaped (Ot6)*. The oil is found in the corner of a complicated pore space. On the one side, the oil attaches to the particles' contact angle. On the other side, it is in the open space with a free state. At the beginning of exploitation, a lot of corner-shaped remnant oil exists in the pores. However, after long-term water injection, the interstitial material rushes out, and both the pore and throat (without impurities) have a good connectivity and a lower contact angle; thus, this type of remnant oil decreases (Figure 17(f)).

Free-state remnant oil, which has a high efficiency of displacement and is far from the mineral particles, can be subdivided into the following four subtypes:

- (i) *Foggy-shaped (Ot7)*. When a reservoir is at a high degree of water logging, the oil is almost stripped out, and only a small amount of dissolved hydrocarbon is distributed in the pores as foggy-shaped remnant oil. This type is exclusively found during the later period of reservoir development and makes a lesser contribution to production in comparison to other types (Figure 17(g)).
- (ii) *Intergranular-adsorbed-shaped (Ot8)*. The oil is distributed in the intergranular pores wherein the mud or clay mineral content is relatively high. At the beginning of exploitation, some of the interstitial materials break and become deformed. Thus, the displacement channels become blocked, and the oil is difficult to exploit. However, after long-term water injection, this type can be displaced (Figure 17(h)).

- (iii) *Slit-shaped (Ot3)*. The oil is within the slender slits (<0.01 mm) of mineral particles, which are bundle of throats or microfractures. Due to a strong capillary force, the displacement process cannot be overcome (Figure 17(c)).

FIGURE 15: Calibration test of fluorescence microscopic observation. (a) An empty microslide. (b) Microslide with water. (c) Microslide with oil.

TABLE 8: Samples of freeze-fluorescence thin section.

No.	Porosity (%)	Permeability ($10^{-3} \mu\text{m}^2$)	Depth (m)	Color, oil-bearing grade lithology	Water flooding degree	Layer	Facies	Flow unit
15	27.3	395	1148.1	Gray-brown, oil-stain siltstone	Low	PI1	Distributary channel	Weak-current limiting
21	27.3	258	1149.42	Brown, oil-rich siltstone				None-current limiting
23	30.1	3569	1150	Brown, oil-rich siltstone				
26	28.7	2087	1150.56	Brown, oil-rich siltstone				
28	25.1	29.4	1154.45	Brown, oil-saturated siltstone	High	PI2	Distributary channel	Unshielded
34	23.8	13.4	1155.57	Gray-brown, oil-stained siltstone				
39	25	32.1	1156.41	Brown, oil-rich siltstone				
42	27.7	315	1156.81	Brown, oil-saturated siltstone				
45	28.1	425	1159.05	Brown, oil-rich siltstone	Low	PI3	Distributary channel	Medium-current limiting
47	23.8	48.2	1159.29	Brown, oil-rich siltstone				None-current limiting
52	28.4	1255	1160.12	Brown, oil-rich siltstone				
56	28	1211	1160.69	Brown, oil-rich siltstone				
66	28.4	1337	1162.56	Brown, oil-rich siltstone	Low	PI5+6	Distributary channel	Unshielded
68	25.9	335	1162.97	Brown, oil-rich siltstone				
76	28	140	1167.96	Gray-brown, oil-stained siltstone				
77	27	141	1168.43	Brown-gray, oil spot siltstone				

(iii) *Intragranular-shaped (Ot9)*: The oil exists within intragranular dissolution pores. If the intragranular pores have a good connectivity with other pores, the remnant oil will be lesser. However, if the intragranular pores have a poor connectivity, the remnant oil will be greater, but the displacement effect will be worse (Figure 17(i)).

(iv) *Cluster (Ot10)*. The oil occurs among large pores with either a cluster, mass, or bead distribution

Remnant oil with a free state exists within the pores, although some may be in the flowing state. If the pore heterogeneity is strong, greater proportion of remnant oil will be found (Figure 17(j)).

5.2. Microscopic Remnant Oil Distribution of Different Flow Units in Channel Sand Body. To determine the distribution of microscopic remnant oil in different flow units, it is necessary to quantify the microscopic remnant oil saturation. For two-dimensional images, the relative content of microscopic remnant oil can be obtained using area ratio statistics. The saturation of microscopic remnant oil is calculated as Equation (1):

$$S = \frac{Ro}{\varphi}, \quad (1)$$

where $Ro = Ao/A$, S is the saturation, φ is the porosity, Ao is the area of oil, and A is the total area of the horizon.

FIGURE 16: Microscopic remnant oil distribution patterns. G: grain; Ot: oil type; Ot1: adsorbed-particle-shaped; Ot2: oil-film-shaped; Ot3: slit-shaped; Ot4: pore-center-precipitation-shaped; Ot5: throat-shaped; Ot6: corner-shaped; Ot7: foggy-shaped; Ot8: intergranular-adsorbed-shaped; Ot9: intragranular-shaped; Ot10: cluster shaped.

The blue to white areas of the fluorescent regions in the photograph are the statistical region. However, due to human error, some foggy-oil areas could not be determined; hence, the statistics of the calculated microscopic remnant oil areas are less than the actual concentrations. The statistical results of 16 samples are presented in Table 9.

The saturation values of the samples' microscopic remnant oil (Figure 18) show that, under the control of the same injection-production pattern and injection-production time, the saturation values were different in different types of channel sand bodies. During the later stage of development, the saturation of microscopic remnant oil was $<19\%$. In the point bar sand body, the saturation in the upper part of the interlayer was higher than that in the lower part, and in the narrow-channel sand body, the saturation of microscopic remnant oil in each part was lower.

Thus, using the sand body architecture and microscopic remnant oil distribution of each flow unit, the influence of different flow units on the remnant oil distribution in the channel sand body could be determined.

5.2.1. Microscopic Remnant Oil Distribution of Different Flow Units in Point Bar. According to the division of flow units by their architecture, four types of flow units in the point bar sand body affect the distribution of remnant oil. The permeability of the none-current flow unit in the bottom of the point bar sand body channel was relatively high, thus leading to the easy displacement of injected water and a relatively low remnant oil content. Meanwhile, the permeabilities of the strong-, medium-, and weak-current limiting flow units that were affected by the interlayer were found to be relatively low. The injection water would be considerably blocked, and the remnant oil content was found to be relatively high.

In the continuous samples of the PI1 layer, sample numbers 15 and 21 belong to the weak-current limiting flow unit,

whereas samples 23 and 26 belong to the none-current flow unit. The microscopic remnant oil saturation of this layer was characterized by a high saturation of the weak-current limiting flow unit and a low saturation of the none-current limiting flow unit. The proportion of free-state remnant oil in the weak-current limiting flow unit was higher than that of the none-current limiting flow unit. At the top of the point bar sand body, the oil saturation of sample 21 was the highest due to the influence of ① interlayer. From the geological parameters of the weak-current limiting flow unit, the peak pore distribution of the sample was found to be $\sim 2\ \mu\text{m}$, (maximum value: $3.06\ \mu\text{m}$). However, easily displaced, free-state remnant oil was found in pores $>3.06\ \mu\text{m}$, thus indicating that the oil had not been displaced cleanly.

In the continuous samples of the PI3 layer, samples numbers 45 and 47 belong to the medium-current limiting flow unit, whereas samples 52, 56, 66, and 68 belong to the none-current limiting flow unit. Samples 45 and 47 had high microscopic remnant oil saturation, and the proportion of free-state remnant oil was higher than that of weak and none-current limiting flow units. This was because the medium-current limiting unit was more significantly affected by the interlayer.

Compared with the PI1 and PI3 layers, although the layers are all low flooded, the saturation and characteristics of microscopic remnant oil in different flow units were found to differ. Both the saturation of microscopic remnant oil and the ratio of free-state remnant oil were ranked as medium-current limiting unit $>$ weak-current limiting unit $>$ none-current limiting unit (Figure 18).

5.2.2. Microscopic Remnant Oil Distribution of Different Flow Units in the Narrow Channel. The PI2 and PI5+6 layers are narrow channels with only a few interlayers, most of which were observed to be vertically accumulated with a very small (or zero) value of inclination. They belong to the unshielded flow unit, and the remnant oil content in each part was found to be relatively low.

There were no interlayers in the PI2 layer. Continuous samples showed that the displacement degree of each part of the sand body was equal and that the overall performance is of high water flooding. In the PI5+6 layer, there was a nearly horizontal thin interlayer and the overall performance was also high water flooding. (Figure 18). There was no obvious difference between the upper and lower parts of the interlayer in the microscopic remnant oil saturation, which indicates that the interlayer has no shielding effect to the injection water and that the displacement degree of the unshielded flow unit varies slightly from place to place.

6. Effect of Flow Units on the Distribution of Remnant Oil

In combination with the model of the flow units and the determination of the microscopic remnant oil distribution and content, the influence of different flow units on microscopic remnant oil was found to be quite different for the same injection-production pattern and time during the development process.

FIGURE 17: Different types of microscopic remnant oil on microslides and the depths where the samples were obtained (Ot: oil type). (a) Adsorbed-particle-shaped (Ot1), No. 15-0214, 1148.1 m. (b) Oil-film-shaped (Ot2), No. 68-0074, 1162.97 m. (c) Slit-shaped (Ot3), No. 56-0147, 1160.69 m. (d) Precipitation-shaped (Ot4), No. 68-0068, 1162.97 m. (e) Throat-shaped (Ot5), No. 45-0039, 1159.05 m. (f) Corner-shaped (Ot6), No. 15-0216, 1148.1 m. (g) Foggy-shaped (Ot7), No. 23-0196, 1150 m. (h) Intergranular-adsorbed-shaped (Ot8), No. 21-0203, 1149.42 m. (i) Intragranular-shaped (Ot9), No. 47-0099, 1159.29 m. (j) Cluster (Ot10), No. 47-0103, 1159.29 m.

TABLE 9: Saturation (S) and R_o of samples.

No.	Porosity (%)	Permeability ($10^{-3} \mu\text{m}^2$)	R_o (%)	S (%)
15	27.3	395	2.48	9.08
21	27.3	258	3.95	14.47
23	30.1	3569	2.17	7.21
26	28.7	2087	2.68	9.34
28	25.1	29.4	1.28	5.10
34	23.8	13.4	1.21	5.08
39	25.0	32.1	1.34	5.36
42	27.7	315	1.72	6.20
45	28.1	425	2.63	9.35
47	23.8	48.2	3.85	16.19
52	28.4	1255	0.91	3.21
56	28.0	1211	2.15	7.67
66	28.4	1337	1.47	5.19
68	25.9	335	1.43	5.53
76	28.0	140	0.62	2.23
77	27.0	141	0.76	2.80

FIGURE 18: Saturation of microscopic remnant oil in different flow units.

In the point bar sand body, the strong-current limiting flow unit is located outside the injection-production well spacing, and the injection water cannot reach the area where the remnant oil has not been recovered [42–44]. Hence, the content of remnant oil is the highest of the study area. In the microslides, the pore was observed to

be filled with a large amount of free-state remnant oil; thus, the strong-current limiting flow unit is the key area for improving oil recovery. The medium-current limiting flow unit is strongly shielded by the lithology of the lateral intercalation. Hence, it is difficult for fluid to flow through the intercalation, and only a small amount of remnant oil

FIGURE 19: Microscopic remnant oil model of the point bar sand body flow units. White areas represent microscopic remnant oil, black to gray areas represent mineral particles; and blue areas represent foggy-shaped remnant oil. (a) Strong-current limiting flow unit microscopic remnant oil model. (b) Medium-current limiting flow unit microscopic remnant oil model. (c) Weak-current limiting flow unit microscopic remnant oil model. (d) None-current limiting flow unit microscopic remnant oil model.

in the macroporous throat with a good connectivity is displaced. The remnant oil content is high. In the microslides, the free-state remnant oil was observed in the small connected pore and had a high oil content, thereby forming an interlayer barrier of remnant oil, which is also the dominant area for extraction. The lateral intercalation of the weak-current limiting flow unit cannot completely block the injection water, but it has a restrictive effect on the flow. Numerous connected macroporous throats have been displaced, and the remnant oil content is of a medium level. In the microslides, a certain amount of free-state remnant oil was observed in small connected or poorly connected pores. During the later stage of development, the propor-

tion of bound-state remnant oil gradually becomes higher than that of free-state remnant oil. In the none-current limiting flow unit, there is no shield at the bottom of the channel, and the injection water forms a stream. The displacement is perfect, thus resulting in a high degree of flooding and low remnant oil content [45, 46]. In the microslides, a large number of free- and semi-free-state remnant oil had high displacement degrees, and very few bound-state remnant oil was found on the pore surfaces with displacement difficulty (Figures 19 and 20).

In the narrow channel, the unshielded flow unit with perfect displacement has the lowest remnant oil content because the flow capacity everywhere is comparable and

FIGURE 20: Scatter plot of saturability as a function of permeability of different flow units.

FIGURE 21: Unshielded flow unit microscopic remnant oil model in the narrow channel. White areas represent microscopic remnant oil; black to gray areas represent mineral particles, and blue areas represent foggy-shaped remnant oil.

the parallel interlayer cannot act as a shield for injection water. In the microslides, the pore separation of the narrow channel was better. During the development process, the microscopic remnant oil is displaced to a high degree, and the bound-state remnant oil in the pore is the greatest (Figure 21).

Therefore, during the development process, the flow units with strong-, medium-, and weak-flow restrictions in the point bar sand body are the favorable flow units for remnant oil recovery (Figure 22).

FIGURE 22: Histogram of saturability as a function of different flow units and types of remnant oil.

7. Conclusion

- (1) On the basis of high-resolution sequence stratigraphy contrast and characterization of sedimentary microfacies, a step-by-step study of a single sand body, point bar, abandoned channel, and thin interlayer, along with various methods of extracting internal architecture parameters of the single sand body were employed to establish the model of the point bar and narrow-channel sand bodies in each layer of the research area
- (2) Using the architecture of the sand body, four types of flow units were identified: strong-, medium-, weak-, and none-current limiting flow units in the point bar, and an unshielded flow unit in the narrow channel. Different flow units were quantitatively characterized by optimizing and calculating geological parameters. The units were ranked from large to small as the none-current limiting, weak-current limiting, medium-current limiting, strong-current limiting, and unshielded flow units
- (3) The remnant oil saturation of each flow unit was found to be different under the influence of the flow barrier. In the point bar sand body, the strong-current limiting flow unit has the most remnant oil because the injection water is difficult to reach, and the interior of the medium-current limiting flow unit is shielded by the interlayers and influenced by the gravity subsidence of injected water. The weak-current limiting flow unit is located between the injection and production wells. Although the interlayers have a shielding effect on injection water, they are not impermeable, and there is still some remnant

oil. The none-current limiting flow unit is scoured by long-term injected water during the later stage of development. Injection water flows through and intrudes into the bottom water. The degree of flooding is high and the remnant oil is less. The unshielded flow unit in the narrow channel has a uniform flow field, perfect displacement, high water flooding, and low remnant oil content

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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