Distribution of remaining oil based on a single sand body analysis: a case study of Xingbei Oilfield

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Abstract

The description of a single sand body for remaining oil predictions is critical to the enhancement of oil recovery of an old oilfield. Taking the fluvial facies of the Xingbei Oilfield as an example, a single sand body can be divided into four categories—"tabulated reservoir", "untabulated reservoir", "single channel sand body" and "abandoned channel"—using the reservoir architecture analysis method. The boundary surface of each type may be mud barriers or only an erosion surface, which was traced by careful anatomization of the single sand body. Then, a fine single sand body reservoir geological model was constructed using a combination of a determined modelling method and stochastic modelling method. The numerical simulation is executed using the constructed geological model to forecast the remaining oil distribution quantitatively. The results show that the remaining oil was distributed in the bottom parts of the abandoned channel, top part of the point bar, tabulated reservoir, and channel edges. The movements of the injection water were mainly controlled by the mud barrier and superimposed styles of single sand body, which determines the formation of the remaining oil. This research has important guidance for oilfield development in the late stage, whose reservoir is composed of single sand bodies.

Keywords Reservoir architecture · Single sand body modelling · Remaining oil distribution · Numerical simulation

Introduction

The concept of single sand body, a relatively independent sand body element with related geological genesis in its development that reflects the sedimentary characteristics of sand body, the characteristics of waterflooding development and the distribution of remaining oil to an extent, has been widely used (Miall 1985, 1988). Specifically, two conditions are necessary: (1) an obvious link of sedimentary origin, the same source and the same water system in a single period of sedimentary sand body period, or the same water system in a multi-stage sand body erosion superimposed sand body; and (2) independence in development and a separate seepage unit with connectivity in different stage sand bodies of the single sand body (Hjellbakk 1997). The effective transmission of pressure can be realized in the process of

water injection development, and there are good interlayer conditions between the different sand bodies, which can effectively close and block the fluid spillover (Qiu 1990). Traditional reservoir modelling, mainly based on well data and seismic data, predicts the distribution of single sand bodies between wells, which reveals the spatial superposition patterns and distributing law of different single sand bodies (Zhou et al. 2010; Wu and Li 2007). However, in the later stage of development, the remaining oil in single sand is an important research object, especially in a reservoir with a thin interlayer and serious heterogeneity (Li et al. 2003; Zhang et al. 2013). It is important to develop a method to quantitatively anatomize the single sand body and reveal its control on the remaining oil (Zhao et al. 2016; Yue et al. 2008). This paper uses the Xingbei Oilfield as the research object to propose a workflow for single sand body anatomization and numerical simulation to forecast the distribution of remaining oil, which can lead to a further solution for the enhancement of oil recovery.

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Geological setting

The Xingshugang Oilfield is located in the middle of the Daqing Oilfield in northeast China, which is part of the central depression area of the Songliao basin. The research area is located in the North Development Zone of the Xingshugang oilfield (Fig. 1). The development layer of the oilfield includes the Saertu, Putaohua and Gaotaizi oil-bearing groups in the Songliao Basin. The main oil reservoirs are distributed in the Putaohua oil group and formed in the environment of the delta plain. The small layers are mainly P111, P112, P1211, P1212, P122, P131, P132, P1331 and P1332; the average single well drilling sandstone thickness is 11.49 m; and the average single well drilling in the effective thickness is 7.93 m. Non-main reservoirs are mainly distributed in other reservoirs of the Putaohua and Saertu reservoirs, which are formed in a delta front. The average single well-drilling sandstone thickness is 62.39 m, and the average single well drilling in the effective thickness is 20.05 m. After several rounds of encryption, the well space reached 30 m, which provides rich and accurate data for model establishment.

Fig. 1 The map of regional geographic location of study area

Fig. 2 Curve characteristics of abandoned river channel

Internal structure anatomy of single sand body modelling

Underground oil–water movement is affected by the structural characteristics of sand bodies (Yin et al. 2013). However, the digging of residual oil controlled by the sand body configuration in the underground reservoir has become the major goal of oilfield development and adjustment after the sandstone reservoirs entered a later stage of development (Lin et al. 2013). The representation of the sand body configuration features are composed of three parts: (1) making a fine stratigraphic comparison of the logging curves of various sections in the work area; (2) explaining and analysing the logging lithofacies of the single well and dividing the sandstone phase and the mudstone phase; and (3) establishing the subsurface reservoir configuration model by the multi-well fitting of the configuration model.

The classification of the configuration in the research area is to divide the single channel in the composite channel based on the sedimentary microfacies research. There are mainly four ways to identify different single channels: (1) finding inter-river sediments along channels, including overflowing sediments; (2) identifying abandoned channels by logging curve characteristics (representing the end of point dam development and river diversion signs) and then determining the point dam boundaries; (3) identifying different river thicknesses; (4) different channels have different sedimentary paleotopographies, which have different sediment-carrying capacities, where the logging response characteristics will be different.

The abandoned channel can be summarized as a sudden abandonment type or a gradual abandonment type (Fig. 2). It is seen in the single well that the bottom of the abandoned channel and the bottom of the channel sand body are filled with sand, and there are two different filling methods in the upper part. The logging response characteristics of the upper part of the abandoned channel in the sudden abandonment type is where the SP curve is close to the baseline and the abandoned channel in the gradual abandonment type shows that the SP curve has toothed features.

Therefore, after analysing the internal structure of the S21-1 sub-layer in the five types of facies (channel has perfect reservoir quality, tabulated reservoir has favorable

reservoir quality and untabulated reservoir has poor reservoir properties) in the Xinger Middle Area, the composite channels are divided into single channels and the abandoned channels; point bars are identified; and the internal structure of the point bars are depicted. The lateral mezzanine is identified, and the fine dissection of the reservoirs of the high bending by-channel is completed (Fig. 3).

Internal structure modelling of single sand body

The model established by the conventional stochastic modelling technique often differs greatly from the reality, so it is difficult to accurately predict the distribution of an oil-bearing single sand body. In the middle and late stages of oil and gas field development, a single sand body can clearly characterize the superimposition of multi-stage sand bodies in the reservoir and reveal the distribution

and ebb and flow of single sand bodies in the three-dimensional space. Combined with the geological knowledge, a single sand body provides a more reliable basis for the development of oil and gas. Therefore, single sand body modelling technology is the key to establish an accurate geological model. However, the fine description of the single sand body requires higher well density and high-resolution reservoir studies and is not suitable for highly heterogeneous carbonate reservoirs. Based on the high-density well pattern and single sand body configuration research in the Xingbei Research Area, this research applies the single sand body modelling technology to model the single sand body structure and the physical property distribution of the space in the research area (Fig. 4 shows the technical route), which lays the foundation for a correct numerical reservoir simulation.

Fig. 3 Profile 1 of reservoir architecture set in study area

Fig. 4 The workflow of single sand body modeling

Single sand body structure modeling

According to the identification requirements of Petrel software on the data identification, the data in the work area are organized as follows: (1) collect well position data, well track data, stratified data and logging curve data; (2) check and input the well position data, well track data and stratified data; (3) check and input all types of logging curve data; (4) select the appropriate grid size to guide the establishment of the model according to the geological conditions in the research area and the later numerical simulation requirements.

The tectonic frame model is the foundation of single sand body modelling. This modelling is in the S21-1 work area of a high bending meandering stream, covering an area of 3.1 km² and has four layers with an average thickness of approximately 2 m. To better represent the interlayer morphology and reservoir heterogeneity, the grid density in the Xinger Middle Area is designed to be 5 m × 5 m according to the actual geological condition and the well density, and the average thickness of a single grid in the vertical direction is 0.2 m. Based on the operation load of the numerical modelling and taking the geological contour line map in the research area as a template, the fine single sand body tectonic framework model is established.

Sedimentary facies modelling of a single sand body

As most oilfields follow a sedimentary microfacies plan, conventional modelling does not describe the conformation sufficiently. In particular, the prediction of the single sand body reservoir and the anisotropy of the interlayer and point bar will enrich the remaining oil. Therefore, the configurational heterogeneity is particularly important in the model. According to the research of the single sand body configuration, the major seven sections in this work area can accurately show the vertical single sand body structure

across the space of the plane display phase. The sedimentary facies modelling can digitize the configuration model and then assign the parameters to the construction framework model, resulting in a reliable configuration model (Fig. 5).

Through Petrel software, the single sand body structure is subdivided by a human–computer interaction in the structural model: (1) using the top–bottom data of sand body, divide the structure into two lithofacies of mudstone facies and sandstone facies; (2) according to the sedimentary facies distribution law, select the appropriate variation function, and the software automatically obtains a random model with rough lithofacies distribution in the sequential indicator stochastic simulation method; (3) based on a random model and according to the plane sedimentary microfacies figure, confirm the distribution range of the channel sand body with the brushing tool of petrel software and then depict the sedimentary facies model as done in the explained results according to the fine single sand body configuration interpretation section (Fig. 6).

Facies-control property modeling of single sand body

The three-dimensional heterogeneity model reflects the spatial distribution of the intragranular pore of reservoir, permeability and other physical property parameter fields in the form of a parameter entity. The porosity and permeability characterize the reservoir capacity and seepage capacity of the reservoir. The main purpose of facies-control modelling is to more accurately reflect heterogeneity. However, it is difficult for the fitting of the variation function to reflect the spatial variation law of the geological conditions (the variation law of sedimentary facies and the spatial distribution of channel sand bodies, etc.). Therefore, based on the modelling of the sedimentary facies, this modelling is constrained by geological experience in removing the singular values. By finely

Fig. 5 Profile 1 of reservoir architecture model in study area

Fig. 6 Facies models in study area. **a** Facies model in study area; **b** facies fence model in study area

deploying the distribution of the sedimentary facies belt and channel sand body, the model can strictly analyse the physical parameter distribution characteristics of the reservoir, conduct a variation function analysis, and establish a fine porosity distribution model, permeability distribution model and fluid saturation distribution model aiming at different sedimentary facies in the stochastic modelling method of the Gaussian simulation and assignment method (Figs. 7, 8, 9).

Numerical reservoir simulation

After several decades of development and improvement, the numerical reservoir simulation technology has gradually become irreplaceable in studying the remaining oil (Guo and Liu 2014). Its purpose is to fit the dynamic process of production and to study the law of oil–water movement in a reservoir. Geological modelling is the precondition of numerical simulation. Numerical simulation is the key to geological modelling. The fine numerical simulation of reservoir is done to simulate the parameter field based on the parameter field of the fine reservoir description. The

Fig. 7 Porosity model in study area. **a** Porosity model in study area; **b** porosity fence model in study area

Fig. 8 Permeability model in study area. **a** Permeability model in study area; **b** permeability fence model in study area

Fig. 9 Oil saturation model in study area. **a** Oil saturation model in study area; **b** oil saturation fence model in study area

simulation results can accurately reflect the development process of oil and gas. The numerical simulation is mainly based on the single sand body configuration model. The reasonable grid density enables the numerical simulation to be carried out without roughening, completely preserving the fine sand body configuration interpretation and spatial distribution model of the interlayer and other seepage barriers, and it can represent the oil and water movement law of a single sand body under interlayer control; thus, the remaining oil distribution pattern in the study area can be quantitatively predicted. The simulation results are compared to the data of production wells and analysed according to the existing remaining oil distribution

pattern, proving that the conclusion can provide a potential direction for tapping the remaining oil in the research area.

Parameter setting of numerical reservoir simulation

The parameter field of numerical reservoir simulation plays a decisive role in the simulation results. Any irrational parameter setting can cause non-operation of numerical simulation and mistakes in the simulation result. The physical parameters of the reservoir and fluid are shown in the following table (Table 1).

The studies on reservoir engineering in the research area are deep, and the characteristics of the seepage of different

Table 1 The physical properties of reservoir and fluid in the model

Parameter items	Water density (g/cm ³)	Formation water volume factor	Formation water viscosity (mPa·s)	Formation water compressibility factor (KPa ⁻¹)	Rock compressibility (KPa ⁻¹)	Crude oil density (g/cm ³)
Parameter value	1.00	1.01	0.6	1.0×10^{-6}	1.0×10^{-7}	0.852

rocks have been summarized well. The phase-permeability characteristics and characteristic curves of various reservoirs according to reservoir lithology, sedimentary facies and physical properties are obtained according to the characteristics of the work area where the model is located; the appropriate phase-infiltration curves, PVT and PVDO curves are selected. The simulation uses the concept model simulation method. According to the actual well types and the perforation conditions, the range of the injection and the produced quantity of the oil wells and the water wells in the statistical model are statistically calculated. The reasonable production and injection proration (actual injection-production ratio of the block is 1.11) and the water drive simulation to the ultimate moisture content (fw = 98%) are conducted.

Numerical simulation analysis of reservoir

In the research area, high-bend distributary channel reservoirs are developed. Their sedimentary types are similar to those of high-bend rivers. There are argillaceous sides and interlayers for blocking between the bulks of point bar sides of different stages as well as abandoned channel, overbank sand and three types of reservoirs, etc. The sand body distribution model and plane simulation results of oil saturation of

typical work areas at the later stage of simulation (Fig. 10) are shown as follows:

The S21-1 model sedimentary facies model in the study area and the corresponding numerical simulation results of the plane show that the remaining oil is mainly distributed at the mouth of the channel; the ends of the three types of reservoirs and the parts blocked by the interlayer.

It can be seen from the S21-1 model profile facies model in the research area and the corresponding numerical modeling results of this section (Figs. 11, 12) that the remaining oil is mainly distributed in the obscured parts of the abandoned channel and the obscured parts of the top interlayers of the point bar, shielded offshore sand bodies and three types of facies, the edge of channel and the end of the sedimentary bodies.

Conclusion

1. In this project, a single sand body model is established by using the data of small well spacing. The space shape of the sand body is accurately characterized by a human-computer interaction method, which perfectly reflects the spatial distribution characteristics of the single sand body skeleton and physical properties. However, due to

Fig. 10 The map of facies model and oil saturation simulation result in study area. **a** Facies mode set in study area; **b** oil saturation simulation result set in study area

Fig. 11 The profile 2 of facies model and oil saturation simulation result in study area. **a** Profile 2 of facies model; **b** profile 2 of oil saturation simulation result set in study area

Fig. 12 The profile 3 of facies model and oil saturation simulation result in study area. **a** Profile 3 of facies model; **b** profile 3 of oil saturation simulation result set in study area

the lack of internal structure scale, the cross-sectional connections make the phase modes in the plane and the vertical direction contradictory. Therefore, the precision improvement of the stratum contrast and configuration classification is an important method for improving the quality of the model.

2. The distribution of the remaining oil is controlled by various geological factors and requires a fine model to characterize the single sand body structure and interlayer distribution. The small well distance data in this area not only describes the model accurately but also greatly reduces the model grid quantity, which facilitates the calculation of the numerical simulation and makes the simulation results more accurate. Therefore, the density

of the well pattern is particularly important in secondary development.

3. The residual oil flow obtained by the numerical simulation shows the effects of the single sand body configuration and interlayer on the remaining oil distribution. The residual oil pattern during the high water-containing period is obtained; that is, the remaining oil controls the oil and gas migration direction due to the interlayer, abandoned channel and other impervious layers so that oil and gas can be enriched around the channel and impervious layer. This model can provide an important theoretical basis for the adjustment of the well pattern in the oilfield and tapping the remaining oil in the next step.

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