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ORIGINAL PAPER - PRODUCTION GEOLOGY

Distribution of remaining oil based on fine 3-D geological modelling and numerical reservoir simulation: a case of the northern block in Xingshugang Oilfield, China

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Abstract As the Xingshugang Oilfield is in the late stage of development, a conventional geological model could not meet the needs of further enhancing oil recovery, and the establishment of a fine 3-D geological model, namely the 3-D reservoir architecture model, is urgently required. The 3-D reservoir architecture model has a strong advantage in the detailed characterization of the distribution of various architectural elements and flow baffles and barriers in 3-D space. Based on the abundant data from close well spacing, in combination with the understanding of sedimentary facies and reservoir architecture, this study builds the 3-D reservoir architecture model to show the spatial distribution of different architectural elements and intercalations (mud drapes) under the control of third-, fourth- and fifth-order bounding surfaces. The study then establishes the property model under the control of sedimentary facies (architectural elements). Subsequently, based on the fine 3-D geological model, the distribution of remaining oil is obtained after the numerical reservoir simulation. The remaining oil primarily lies in the port of channel bifurcation, the parts blocked by intercalations and abandoned channels, and the edges of different facies. This observation provides a theoretical basis for further development and adjustment.

Keywords Fine 3-D geological model · Close well-spacing · Reservoir architecture · Numerical reservoir simulation · Distribution of remaining oil

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Introduction

A reservoir geological model is the comprehensive integration of oil and gas field production geology. It reflects sedimentary features, reservoir heterogeneity, reservoir physical properties and fluid characteristics in a 3-D view (Wu and Li 2007). The model emphasizes prediction for inter-well reservoirs through methods of multidisciplinary integration, 3-D quantitative characterization and visualization (Qiu 1990; Jia 2011). Therefore, it is significant for reservoir evaluation, reservoir development and management and 3-D numerical reservoir simulation.

Different stages of exploration and development require different models (Mu 2000). During the early and middle stages of development, the model is established based on the interpretation of sedimentary microfacies that control the distribution of remaining oil (Huo et al. 2007). However, in the late stage of development, a conventional geological model is not able to meet the needs of production in the oilfield in that the reservoir architecture has been the main factor influencing the distribution of remaining oil. Hence, fine 3-D geological modelling is required for fine characterization of the spatial distribution of various architectural elements and flow baffles and barriers (Yue et al. 2008; Bai et al. 2009).

Currently, the northern block of the Xingshugang Oilfield is in the late stage of development and is facing problems due to the scattered distribution of remaining oil and difficulty in development adjustments. Nevertheless, the abundant well data and close well-spacing are the advantages of this period (Miall 1985); the average well spacing is less than 100 metres and some are within 30 metres. Therefore, based on the results of sedimentary facies and reservoir architecture, combined with abundant well data, the 3-D model of the study area is established.

This model allows the detailed characterization of different architectural elements and flow baffles and barriers. Based on fine 3-D geological modelling, reservoir simulation is conducted for the quantitative prediction of the distribution of the remaining oil and the analysis of the controlling factors of the remaining oil. This provides a theoretical foundation for the next adjustment of well patterns and tapping potentials.

Geological setting

The Xingshugang Oilfield, located in the middle of Changyuan Oilfield in Daqing, Northeast China, belongs to the central depression of Songliao Basin, and the study area of this paper lies in the north development zone of the Xingshugang Oilfield (Fig. 1). The layer series of development of the oilfield are the Saertu, Putaohua and Gaotaizi oil-bearing groups in Songliao Basin. The depth of the oil layer is from 800 to 1200 m and the main reservoirs, which develop the subfacies of delta plain, are distributed in the Putaohua Formation. These sub-layers are P111, P112, P1211, P122, P131, P132, P1331 and P1332. The non-main reservoirs, which develop the subfacies of delta front, are distributed in other oil layers of Putaohua and the Saertu oil layers. This paper focuses on the layer group of S2, comprising S215, S215-1, S215-2 and S216 layers.

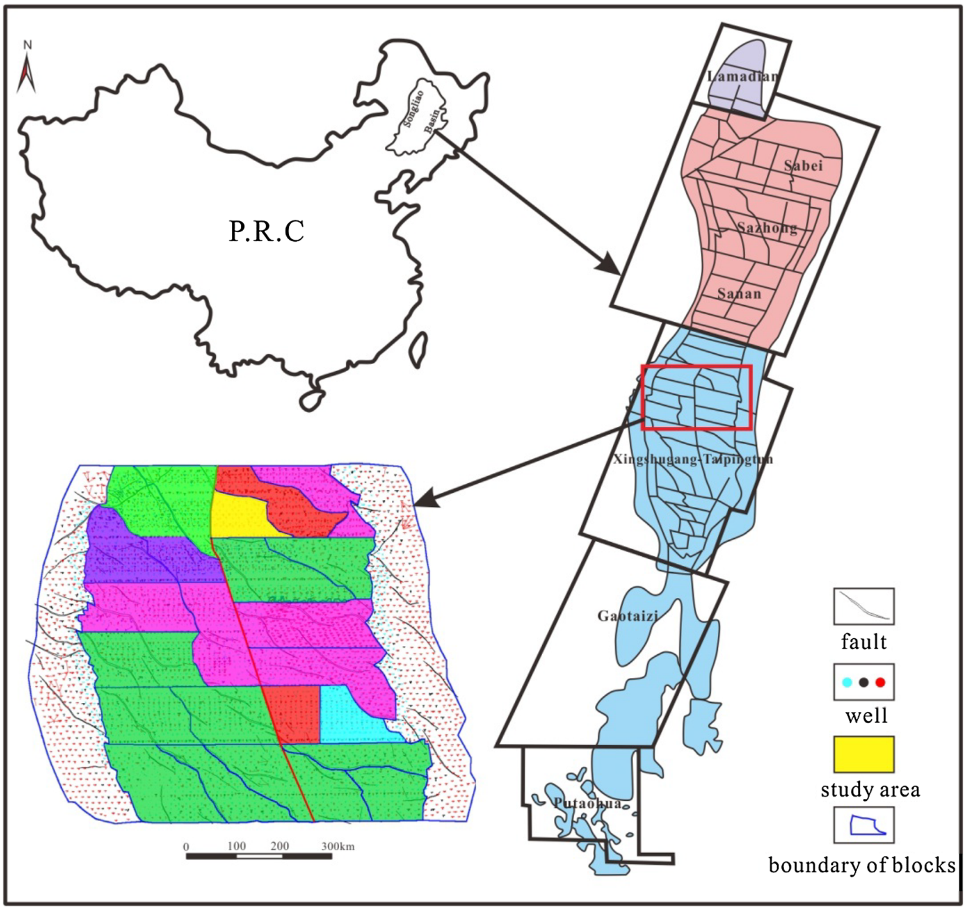
Establishment of 3-D geological models

Data preparation and quality control

In the process of geological modelling (Fig. 2), data preparation and quality control are of fundamental importance. They lay a strong foundation for the establishment of precise and accurate models. The data collected comprise two aspects:

1. Basic data: This mainly consists of wellhead data, well-top data, wire-line log data and reservoir data. The details of each are as follows:
    - (a) wellhead data: including coordinates, kelly bushing, well deviation.
    - (b) well-top data: including top and bottom depth of layers, gross pay and net pay thickness of layers, etc.
    - (c) wire-line log data for all wells.

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



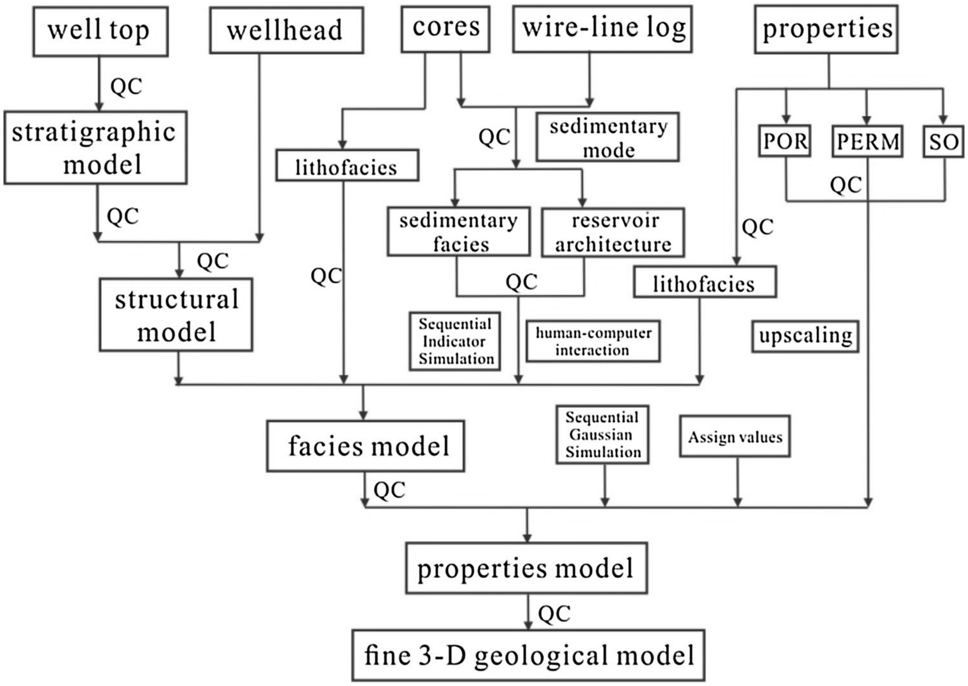


Fig. 2 The workflow of fine 3-D geological modelling. QC refers to quality control. POR, PERM and SO are short for porosity, permeability and oil saturation, respectively

(d) reservoir data: including facies, sandbody, porosity, permeability, oil saturation.

2. Geological research results: this includes maps of sedimentary facies and profiles of reservoir architectural elements in the study area.

The following step is quality control, which is an essential part of the process. With different visualization tools, we should guarantee that the raw data used for the geological model, especially the hard data, are accurate and reliable, as incorrect data would result in the geological model being inconsistent with geological research results. For instance, by using the 3-D visualization tools, the well trajectory can be directly examined to determine if it is reasonable. Meanwhile, the properties of the well, such as microfacies and porosity, can be shown simultaneously with the well trajectory. Incorrect data should be revised in time to guarantee that the data employed in models are correct.

Structural modelling

The structural model, which reflects the spatial framework of the reservoir, is the foundation of reservoir property modelling. The structural model of the study area is relatively simple as the faults are undeveloped. As a result, the structural model primarily consists of stratigraphic models (Fig. 3). Using the S2 layer set of the study area as an example, based on the well-top data, five stratigraphic models of the layer set are established. Subsequently, 3-D gridding is conducted and the grid dimensions of the X, Y and Z axes are set to 5, 5 and 0.2 m, respectively. Finally, the grid needs to be examined to determine whether the grid is reasonable and whether there is negative volume or not. The approach of Cell Volume in Geometrical modelling can be adopted to calculate the volume of every grid cell. If there is a negative or abnormal value, the model should be checked and then be built with the gridding method again to ensure that all grid volumes should be greater than 0.

With the steps above completed, the structural model is established (Fig. 4).

Facies modelling

The facies model is established based on the structural model, and the sedimentary facies in the model are based on the results of sedimentary facies and reservoir architecture (Figs. 5, 6). The S2 layer set in the study area mainly develops the high sinuosity distributary channel. Based on the theory of fluvial sedimentation of Miall (1985), the method of architectural elements analysis was employed to identify the hierarchy of bounding surfaces (Miall 1985; Hjellbakk 1997; Skelly et al. 2003; Long 2006), in particular, the third-, fourth- and fifth-order bounding surfaces. Different architectural elements can be separated by a different hierarchy of bounding surfaces (Miall 1988; Jones et al. 2001; Labourdette and Jones 2007). The architectural element divided by third-order bounding surfaces refers to the lateral accretion body in a

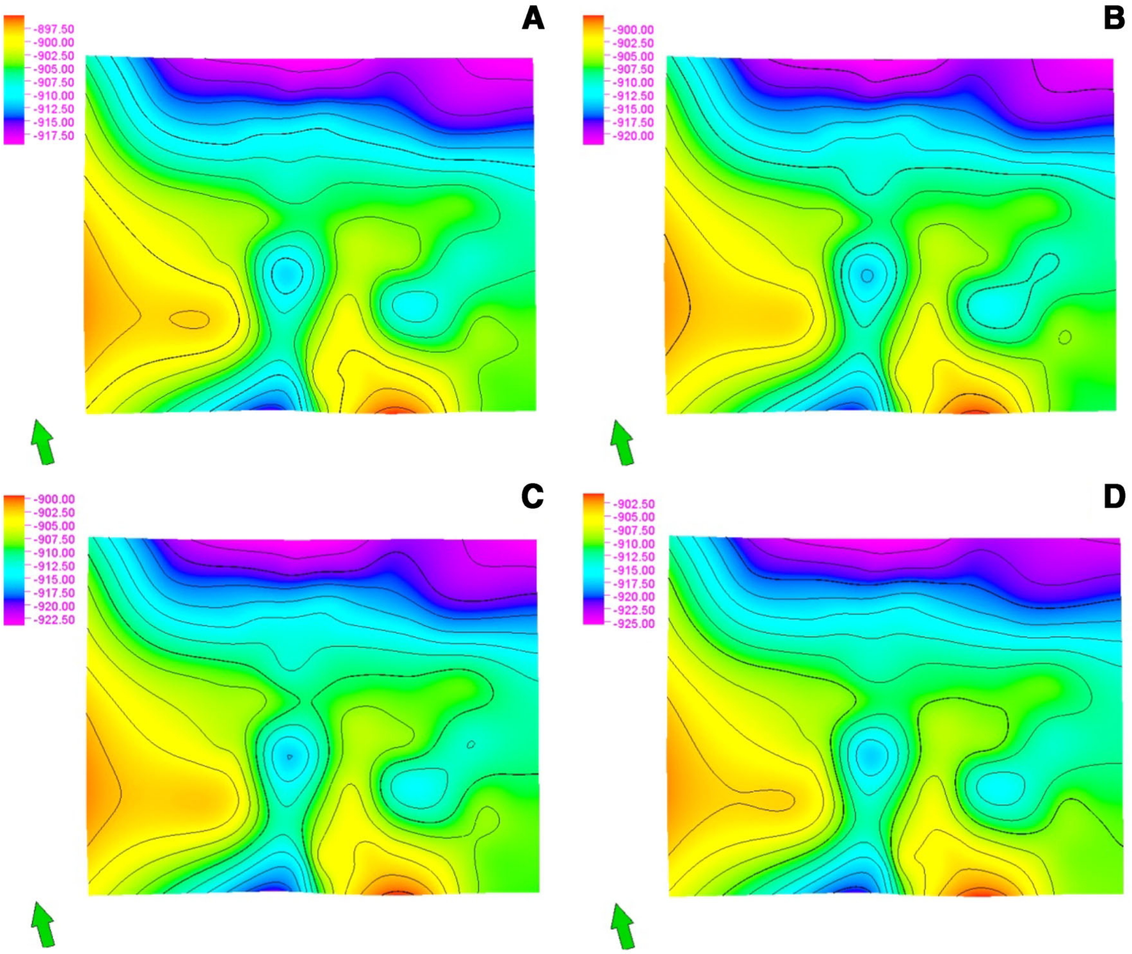


Fig. 3 The stratigraphic models of the study area. **a** The stratigraphic model of the S215 layer. **b** The stratigraphic model of the S215-1 layer. **c** The stratigraphic model of the S215-2 layer. **d** The stratigraphic model of the S216 layer

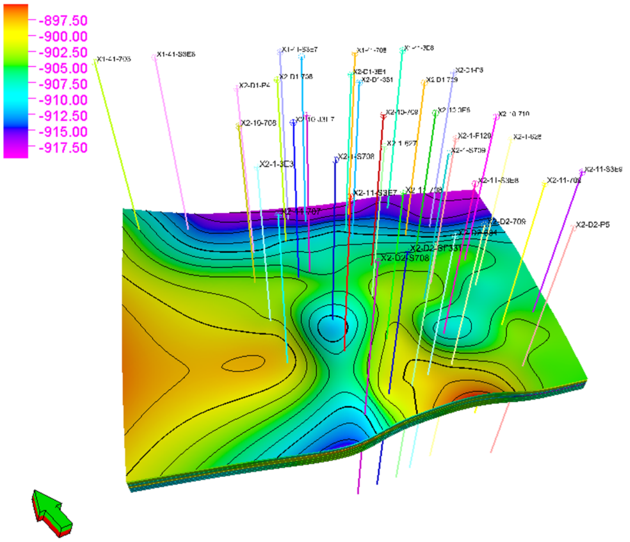


Fig. 4 The structural model of the study area

single period. The architectural elements divided by fourth-order bounding surfaces refer to channel and abandoned channel. The architectural element divided by fifth-order bounding surfaces refers to channel complexes. To satisfy the modelling requirements, the facies in the study area are classified into six groups: channel, overbank, abandoned channel, type III reservoir, mud facies and intercalation. Intercalation refers to the mud drapes on the lateral accretion surface within a point bar. Type I and Type II reservoirs refer to channel and overbank, respectively. It is noted that the Type III reservoir represents the reservoir of which the physical properties are comparatively poor and its distribution is developed on the edge of Type I and Type II reservoirs.

In addition, the logging curves require upscaling. During the process of upscaling, the facies type is confirmed by the dominant facies in the grid cell. Finally, the facies model is completed in combination with the understanding of

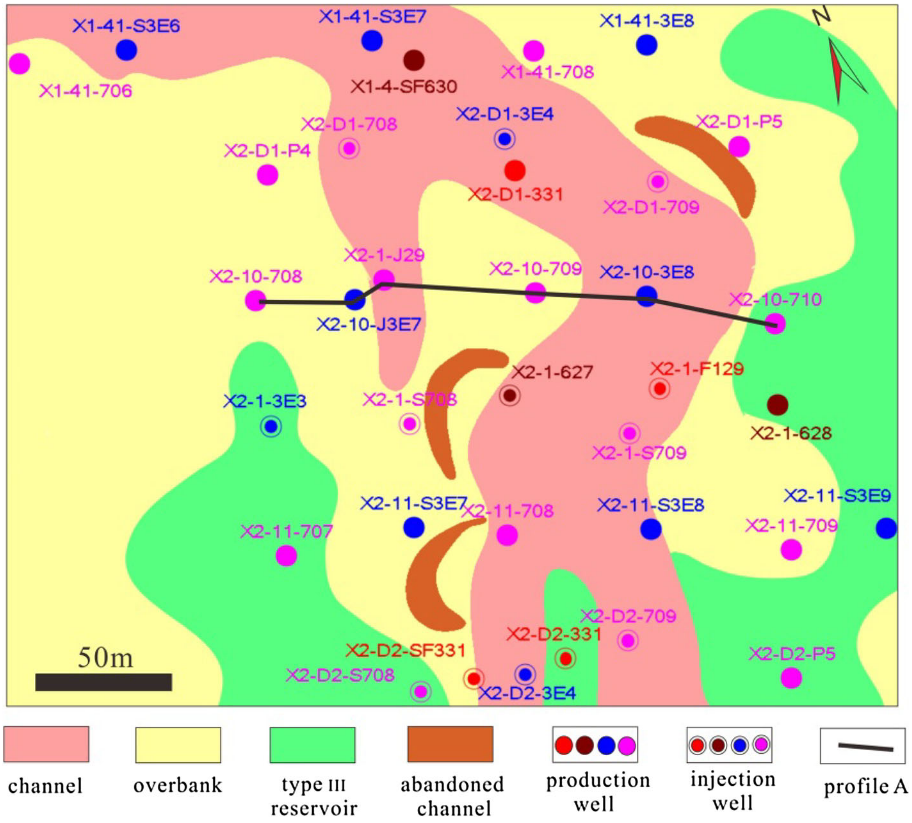


Fig. 5 Typical planar map of sedimentary facies of the S216 layer in the study area

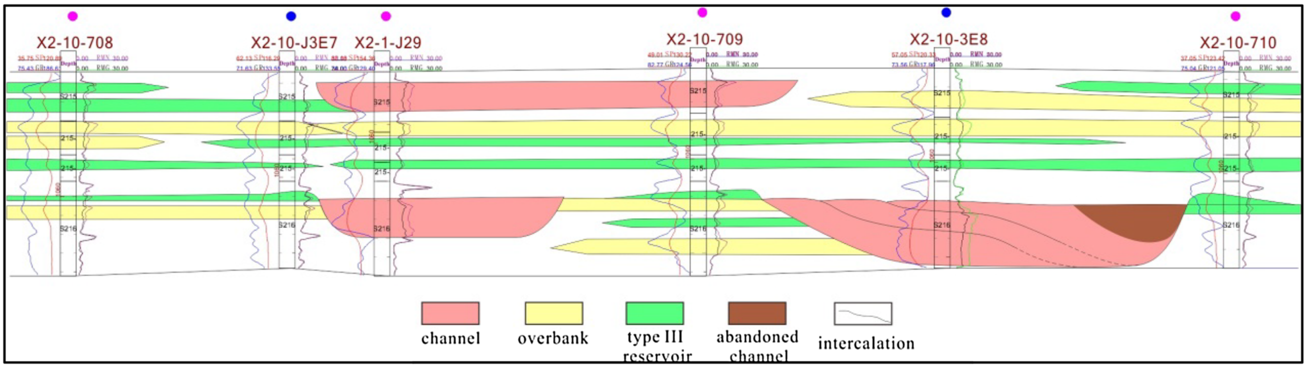


Fig. 6 Reservoir architecture of the S2 layer set of profile A in the study area

sedimentary facies and reservoir architecture. The specific procedures undertaken in this model are as follows: first, a stochastic model is built based on the lithofacies data processed through the approach of Sequential Indicator Simulation. Second, combined with the research results of planar maps of sedimentary facies and profiles of reservoir architecture, the facies in the stochastic model are edited manually in order to ensure the agreement of the facies models with the results of plane maps and profiles (Fig. 7). The facies model can be seen in Fig. 8.

Properties modelling

The properties models (petrophysical model), which mainly consist of porosity, permeability and oil saturation, are established by the method of facies-controlled modelling; this method has the advantage of incorporating the ideas of geological understanding into the geological model, resulting in a more realistic and practical model of the spatial distribution of reservoir petrophysical properties (Li et al. 2003).

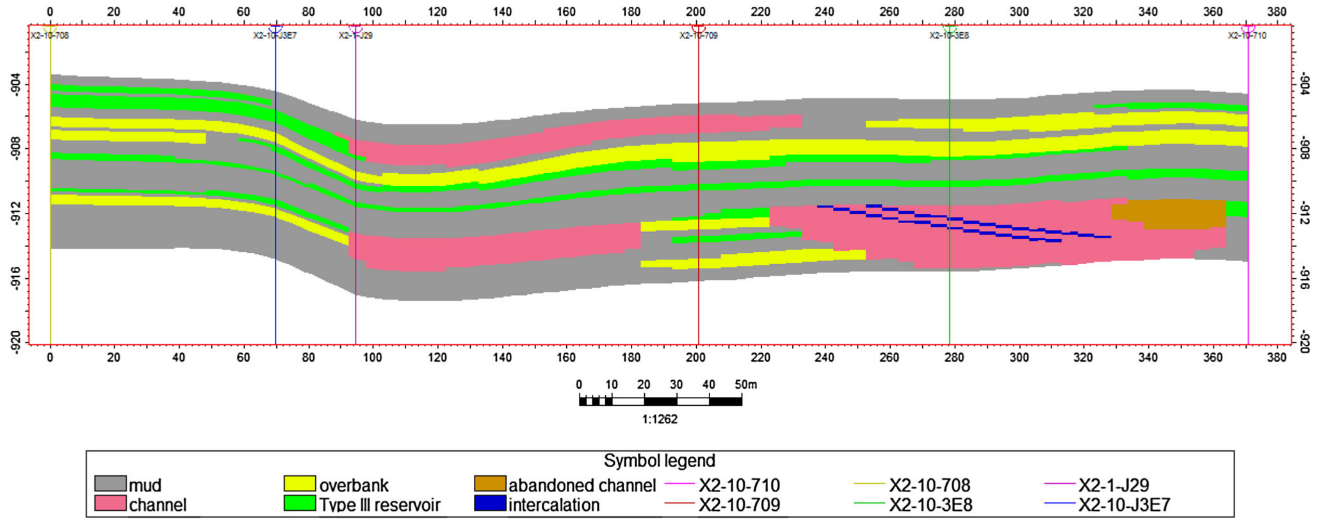


Fig. 7 Reservoir architecture model of the S2 layer set of profile A in the study area

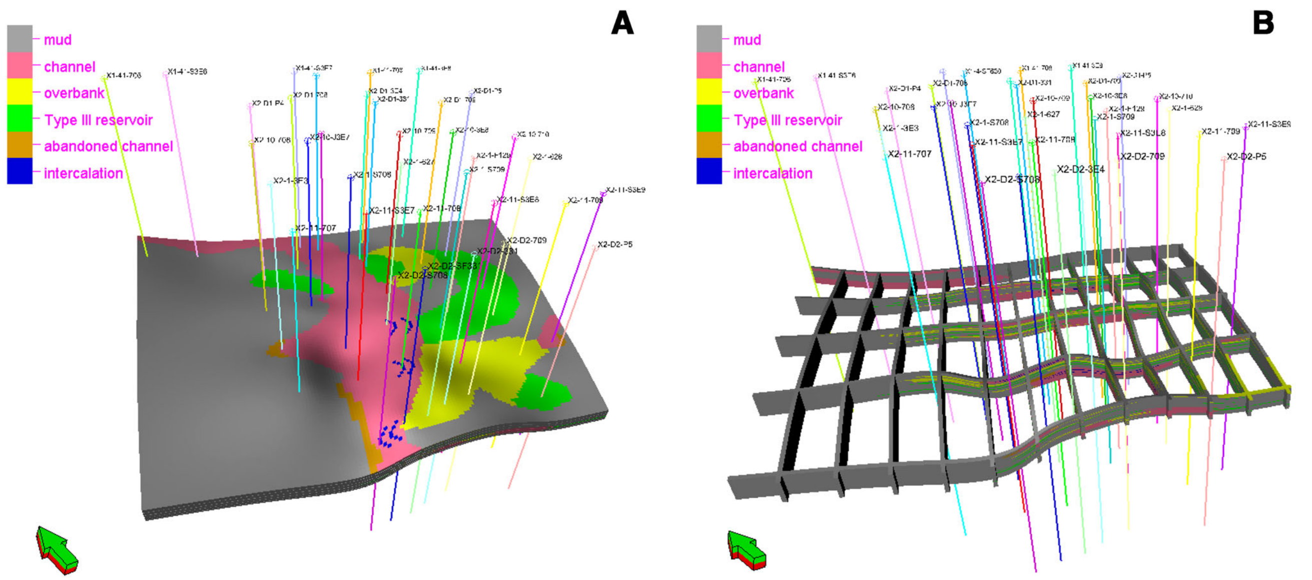


Fig. 8 Facies models in the study area. **a** Facies model of the S2 layer set in the study area; **b** facies fence model of the S2 layer set in the study area

Different physical properties are constrained by different conditions, especially in the permeability model. According to the physical data in each well, the distribution of reservoir physical parameters is controlled by data restriction under the control of sedimentary facies. For the channel, the average permeability is set to 200 md, while the maximum, the minimum and the standard deviation values of permeability are automatically calculated based on the statistical data and the set value above the channel. For the overbank, the minimum permeability is set to 70 md and the maximum is set to 100 md, while the average value is automatically calculated and the standard deviation values of permeability are set to twice that of the channel. For the Type III reservoir, the minimum permeability is set to 2 md and the maximum is set to 50 md. For the mud facies, abandoned channel and intercalation, the values are set to 10, 10 and 0 md, respectively.

Based on the properties mentioned above, the petrophysical parameters, including porosity, permeability and oil saturation, are simulated by the approach of Sequential Gaussian Simulation. Finally, the property models of the S2 layer set are established, composing the porosity model (Fig. 9), the permeability model (Fig. 10) and the oil saturation model (Fig. 11). Therefore, the fine 3-D geological modelling, namely the 3-D reservoir architecture modelling, is completed based on the above process.

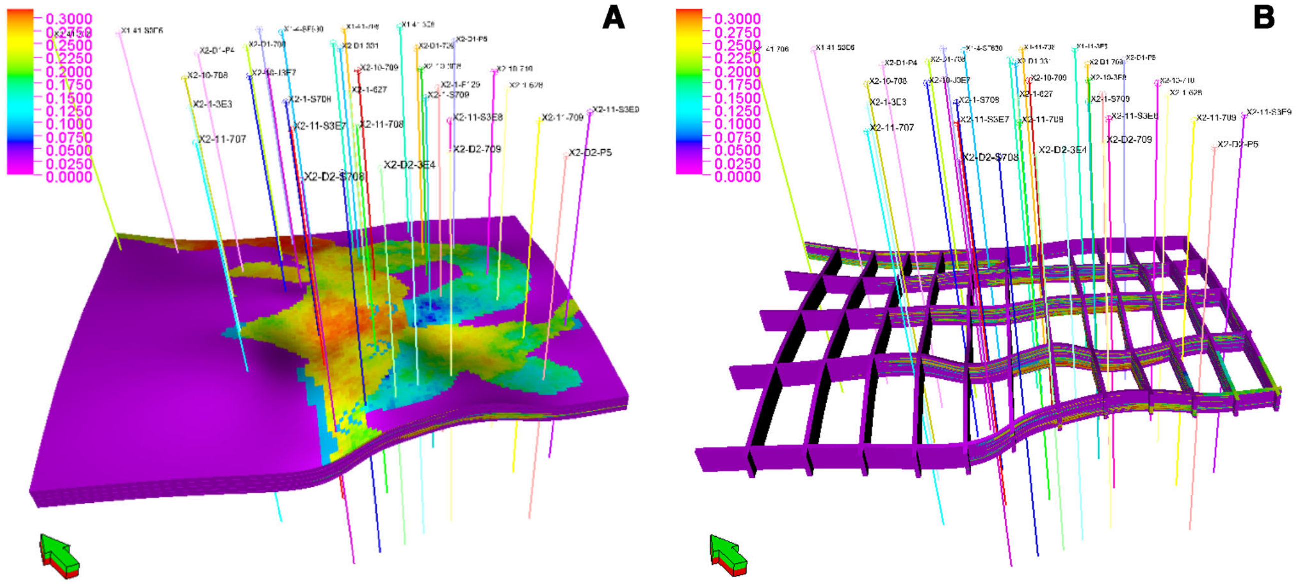


Fig. 9 Porosity models in the study area. **a** Porosity model of the S2 layer set in the study area; **b** porosity fence model of the S2 layer set in the study area

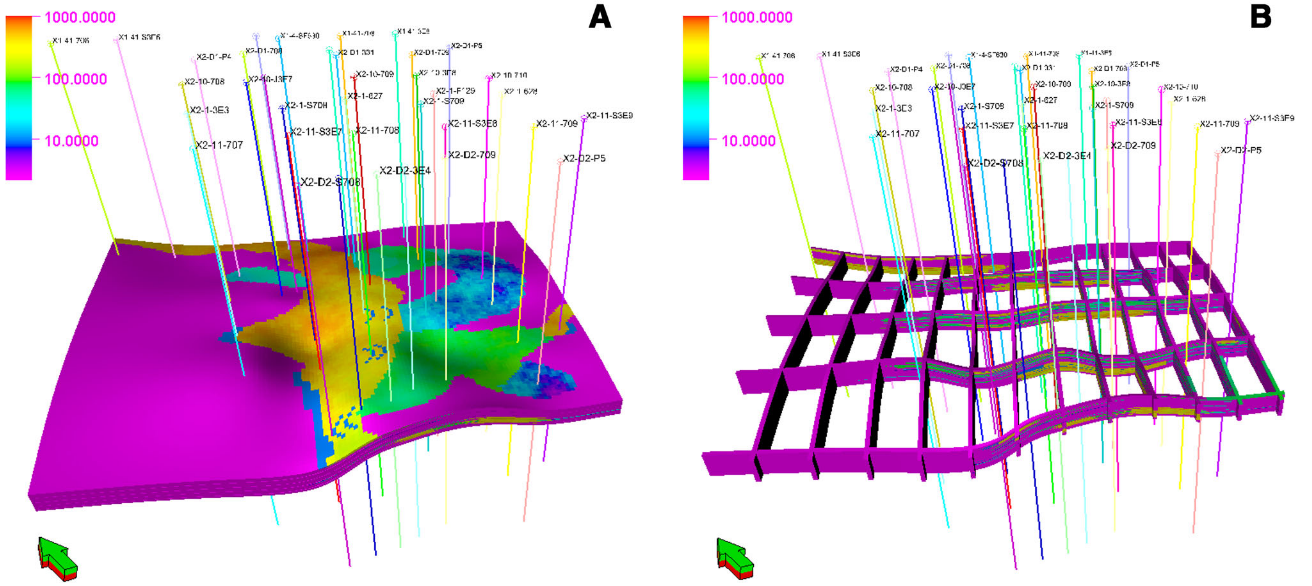


Fig. 10 Permeability models in the study area. **a** Permeability model of the S2 layer set in the study area; **b** permeability fence model of the S2 layer set in the study area

Numerical reservoir simulation based on the 3-D reservoir architecture model

Based on the 3-D reservoir architecture model, the numerical reservoir simulation is carried out. In this study, the geological model has not been upscaled to completely retain the spatial distribution of various architectural elements and flow baffles and barriers. The oil–water movement within the layer set is simulated under the control of the reservoir architecture model. As a result, the simulated distribution of the remaining oil is obtained. The remaining oil saturations of three types of reservoirs are subject to statistical analysis for the sake of obtaining the quantitative distribution of the remaining oil in the study area.

Inputs into the geological model

The geological model is imported straight into the numerical reservoir simulator (Eclipse software) without

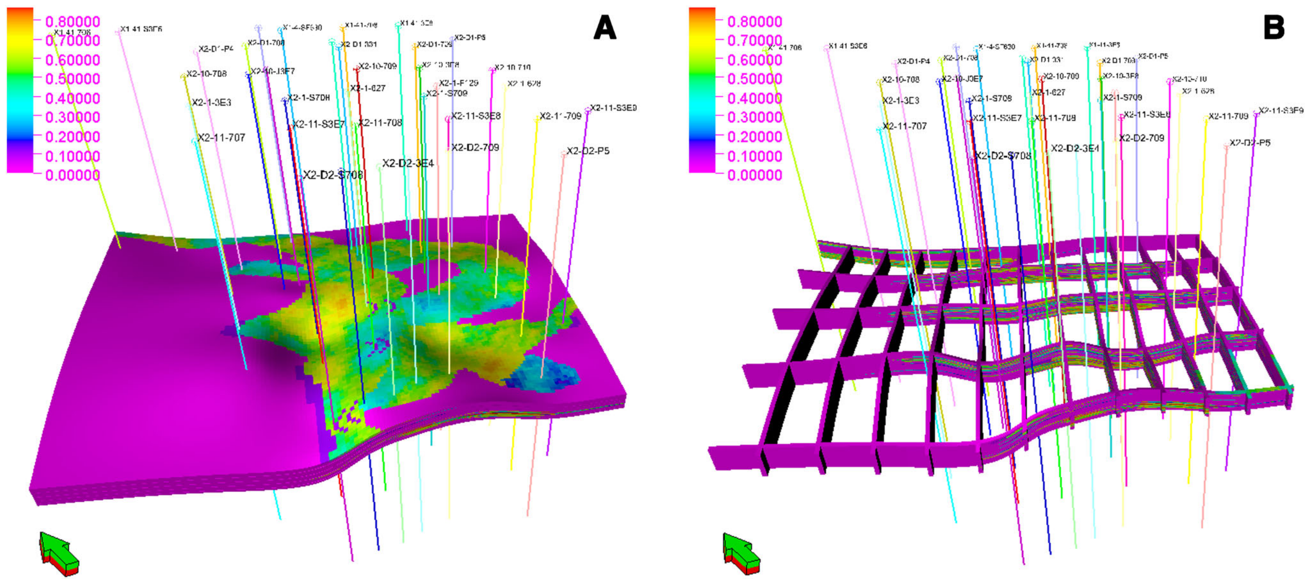


Fig. 11 Oil saturation models in the study area. **a** Oil saturation model of the S2 layer set in the study area; **b** oil saturation fence model of the S2 layer set in the study area

Table 1 The basic information of the model

Model	Layers	Grid in I	Grid in J	Grid in K	Total grid	Well numbers	Production wells/perforated wells	Water injection wells/perforated wells
S2	S215, S215-1, S215-2, S216	134	107	54	774,252	36	23/8	13/3

upscaling, and the basic information of the model is as follows (Table 1):

Reservoir parameters settings

The physical properties of reservoir and fluid are presented in Table 2.

As the seepage characteristics of different lithofacies, sedimentary facies and reservoir physical properties are well summarized in the study area, the relative permeability curve is ultimately decided according to the features of the model (Fig. 12).

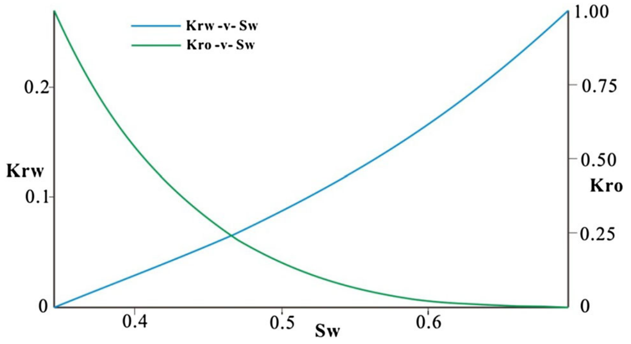


Fig. 12 The relative permeability curve selected in the simulation

Table 2 The physical properties of reservoir and fluid in the model

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

The water density and crude oil density in the above table refer to the respective densities under the ground conditions, while the remaining parameters are under the original reservoir conditions

The reservoir simulation of this study focuses on the oil–water two-phase flow, and the fluid PVT data are obtained through the analysis of high-pressure physical properties (Table 2).

Reservoir dynamics and production data input into the simulation are from the realistic oilfield data of the study area. Combined with the actual well data and perforation data, the production and injection rates have been analysed statistically, respectively. Thus, reasonable settings of production and injection rates imported into the simulator can be determined and the voidage replacement ratio is set to 1.11. The simulation is stopped until reaching the limit of water cut (fw = 98%).

Distribution of remaining oil

The reservoir of high sinuosity distributary channel, developed in the study area, is similar to the high sinuosity meandering fluvial reservoir on the sedimentary types, which are characterized by the development of point bar, channel, abandoned channel, overbank and Type III reservoir. Additionally, mud drapes (intercalations) exist among lateral accretion bodies within the point bar at different periods.

The maps of the simulation results, combined with the corresponding maps of facies model in the study area (Fig. 13a), indicate that the remaining oil is mainly distributed in the ports of channel bifurcation, the end of the Type III reservoir and the area blocked by intercalations (Fig. 13b).

From the profile of the simulation data, in combination with the related profile of the 3-D reservoir architecture model in the study area (Fig. 7), the results reveal that the remaining oil volumes are primarily distributed in the parts where the movement of oil towards the production wells is retarded by intercalations and abandoned channel, isolated overbank, margin of the channel, the end of the sedimentary bodies and the Type III reservoir (Fig. 14).

Quantitative characterization of remaining oil potentials

By importing the reservoir simulation results into the initial work area of Petrel software, the waterflooding conditions and recovery percentage of the channel, overbank and Type III reservoir are calculated statistically through the function of a property value filter. Finally, the features of the quantitative distribution of remaining oil are acquired and shown in Table 3.

Conclusions

Compared with the conventional model, the fine 3-D geological model (3-D reservoir architecture model) can provide a more accurate and fine characterization of the distribution of various architectural elements and seepage barriers and baffles to flow in 3-D space. This model can fully represent the previous geological interpretations, comprehensively show the realistic conditions of the subsurface reservoir and greatly reduce the uncertainty of the model. However, the drawbacks lie in two aspects: (1) the scarcity of data and inherent uncertainty of geological interpretation; and (2) the heavy workload during the process of human–computer interaction, the time-consumption and low efficiency. Additionally, a correct

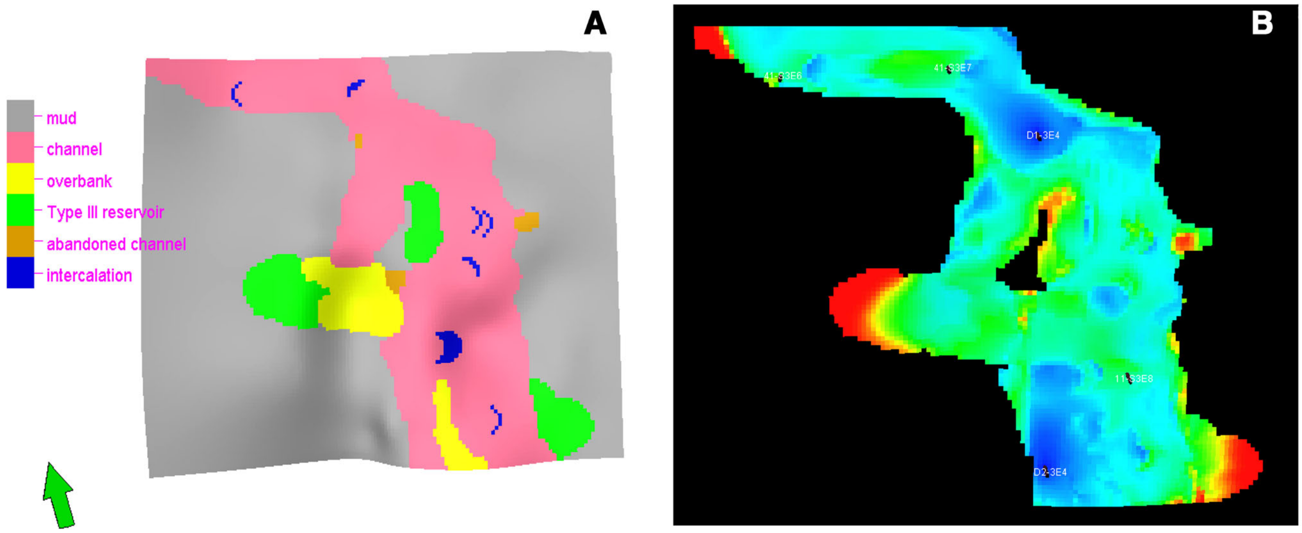


Fig. 13 The maps of the facies model and simulation result in the study area. **a** Facies model of the S2 layer set in the study area; **b** simulation result of the S2 layer set in the study area

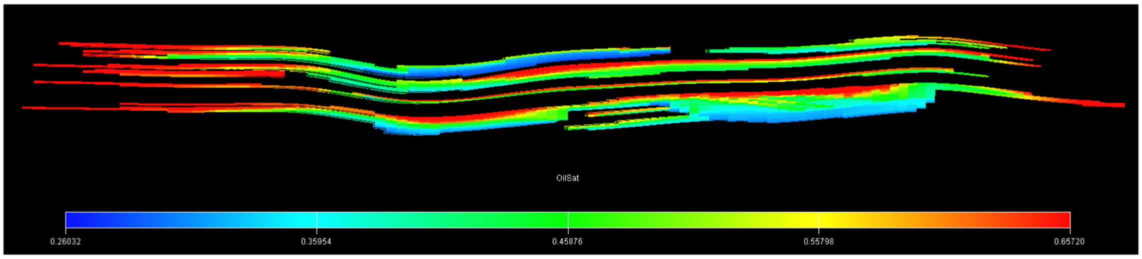


Fig. 14 The simulation result of profile A in the study area

Table 3 The recovery percentage of different facies in the study area

Model	Facies types	Average oil saturation	OOIP (m^3)	Recovery reserves (m^3)	Remaining reserves (m^3)	Recovery percentage (%)
S2	Channel	0.39	402,654	151,674	250,980	37.6686
	overbank	0.46	231,515	56,322	175,193	24.3276
	Type III reservoir	0.50	190,364	24,277	166,087	12.7529

OOIP, recovery reserves and remaining reserves in the above table refer to the reserves in standard conditions; *OOIP*, original oil in place

geological understanding is the basis for the establishment of the model.

Based on the 3-D reservoir architecture model of high sinuosity distributary channel reservoir, the numerical reservoir simulation is carried out to demonstrate that the remaining oil volumes are mainly distributed in the port of channel bifurcation, the parts blocked by intercalations and abandoned channels, and the edges of different facies. This analysis provides the theoretical basis for the next stage of the oilfield's development.

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