Multi-Point Geostatistical Sedimentary Facies Modeling Based on Three-Dimensional Training Images

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Abstract: As an important modeling parameter in multi-point geostatistics, training images determine the modeling effect to a great extent. It is necessary to evaluate and optimize the applicability of candidate training images before modeling by multi-point geostatistics. Conventional two-dimensional training images can't describe the overlapping relation of sedimentary facies in space, and there is a deficiency in describing the event relation of single data. This paper puts forward a new training image optimization method. The basic idea is to arrange and analyze sand bodies filled with sedimentary sand bodies in point dams and river channels in different periods. The method of obtaining three-dimensional training images is to use sand thickness maps and sedimentary facies maps for spatial constraints. The simulation test shows that compared with the sedimentary facies model obtained from two-dimensional training images, the sedimentary facies model obtained from three-dimensional training images through multi-point geostatistics has high compatibility and is more in line with geological understanding. On the basis of fully understanding the development characteristics of the sedimentary system and quantitative geometry of sedimentary body in the study area, sedimentary microfacies models based on sequential indicator simulation method and target simulation method are established, respectively. By comparing and analyzing the sedimentary microfacies models established by three different methods, the results show that the multi-point geostatistics can stably present the planar distribution characteristics and overlapping spatial relationship of sedimentary microfacies and reproduce the complex spatial structure and geometric shape of fluvial facies. The model established by this method is more in line with the geological sedimentary model.

Key Words: Three-dimensional training image, Sequential indicator simulation, Target-based simulation, Multi-Point geostatistics, Dawangzhuang oilfield.

1. INTRODUCTION

Since Haldorsen et al. published the first paper on oil and gas reservoir modeling, reservoir modeling technology has been rapidly popularized and applied [1]. For example, the commonly used sequential indicator simulation method realizes the prediction of unknown areas through the statistics of the scale and law of sedimentary microfacies development and better combines qualitative geological research with quantitative statistical prediction. The range size reflects the change of regionalization variables in a certain direction and reflects the extension scale of sand body in a certain direction, predicting the scale of the sand body and the plane heterogeneity of a certain geological variable [2-3].

However, the continuity and variability of complex geological bodies cannot be characterized because of the great influence of sample representativeness, less well data, or small well pattern density [4].

On this basis, the target stochastic simulation method was proposed (Haldorsen and Lake, 1984). This method directly and clearly reproduces the spatial geometry of the reservoir by defining shape parameters, but its biggest limitation is that when there are many locally known data, it is very difficult to condition these data into the model.

In 1992, Farmer, Deutsch, and Joumel used a multi-point geostatistics method to iteratively match the statistical input parameters of simulated images [5], and Srivastava put forward an iterative post-processing method based on Gibbs sampling, specifically applying the iterative method based on Gibbs sampling. Through the obtained local conditional probabilities of unknown points, the realized simulation is iteratively modified in order to restore the statistical characteristics of multiple points [6], but it cannot be widely used due to many influences such as iterative convergence.

In 1993, Guardiano et al. proposed a non-iterative algorithm, which took the frequency of different data events obtained by scanning training images with data templates as the statistical probability of multi-points

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(data events), and then simulated the probability at unknown nodes, belonging to the category of sequential simulation. However, due to the high requirements on computer performance caused by repeated scanning of training images, it still could not be applied [7-8].

In 2005, Wu Shenghe used the multi-point geostatistics method and the sequential indicator simulation method to compare the sedimentary facies modeling of a block in the Bohai Bay Basin, and concluded that the multi-point geostatistical modeling is better than the traditional two-point statistics. The scientific modeling method has obvious advantages. The multi-point geostatistical modeling method is more faithful to the conditional data, and better expresses the complex spatial structure [9]. Based on the principle of multi-point geostatistics, Feng Guoqing used the Snesim algorithm to establish a lithofacies model of a certain block in the eastern oilfield and verified it. He believed that the multi-point geostatistical simulation method could describe the local variability and non-uniformity of sand bodies more accurately. Homogeneity [10]. Bai Hexiang analyzed the basic principles of the multi-point simulation algorithm Snesim and conducted a series of discussions on the multi-grid point simulation method. He believed that the multi-point geostatistics method could be well used for modeling complex geometric shapes and features. The multi-point geostatistics method has faster calculation speed [11]. Luo Yang believes that multi-point geostatistics combines the advantages of both the pixel-based method and the target-based method. The principle of multi-point geostatistics is used to simulate fluvial facies reservoirs, and the main problems, such as the continuity of the target body, are analyzed and discussed [12]. Li Shaohua used two methods to simulate the attribute distribution of channel sand bodies; one is the local change mean method, and the other is multi-point geostatistics. Through comparative analysis, he believes that the multi-point geostatistics method can better reflect the distribution characteristics of physical parameters in the channel than the local change mean method, but there is also the problem of discontinuity of the channel in the simulation results [13]. Han Jichao et al. simulated meandering fluvial sedimentary microfacies by using multi-point geostatistics and reproduced the complex spatial structure of fluvial facies [14].

Dr. Strebelle of Stanford University, based on the multi-point algorithm of Guardiano and Srivastava, put forward the multi-point probability obtained by scanning the training image to analyze the relationship between multiple points in space, and greatly improved the efficiency of simulating unknown nodes by using the “search tree”. This made the multi-point geostatistical sedimentary facies modeling truly popularized [15-17]. Among them, the production of training images and the selection of data templates are the key steps.

Training image is an important input parameter. Therefore, making a training image that can reflect the quantitative distribution pattern of microfacies has become the key problem of multi-point geostatistical sedimentary facies modeling. There are many ways to make training images, such as using the model obtained by the target modeling method or directly hand-drawing. Geological knowledge, sand-mudstone scale curve, and seismic inversion data volume in the study area are the main materials for making 3D training images, which can also be established first and then combined with sand-mudstone scale curve [18-19].

Zhang Wei and others modified the distribution map of sedimentary microfacies according to the geological conceptual model, and generated the training image of braided river sedimentary facies through digital processing [20]. Wang Jiahua and others made two-dimensional training images based on geological understanding and combined them with vertical sand-mudstone scale curve [21]. According to the wave impedance distribution map, Yang Lei drew the training image that meets the requirements [22]. According to geological data and related maps, Chen Tao drew two-dimensional training images [23]. Chen Gengxin et al. established a reliable braided river delta sedimentary facies model by setting parameters such as geological body shape and scale obtained from previous research, taking phase ratio curve as longitudinal constraint, adopting random simulation of target body, multiple realization methods, and making training images in different regions [24].

In this paper, a new training image optimization method is proposed. The basic idea is to sort out and analyze the sand bodies of point bar and river channel filling sediments in different periods, make relevant constraints of microfacies spatial distribution by using sand thickness map and sedimentary facies plan, and make corresponding simulation constraints on sand body simulation by using sand-ground ratio probability body, so as to obtain three-dimensional training images. The sedimentary facies model obtained by multi-point geostatistics using the three-dimensional training image can accurately reflect the plane distribution and spatial contact relationship of sand bodies in different stages, and also overcome the problem that the above methods can not accurately reflect the vertical sand body distribution characteristics.

At present, there is not enough experience and knowledge about the complex meandering river sedimentary reservoirs in the study area, the effectiveness of various sedimentary micro-modeling methods, and how to choose appropriate simulation methods to get ideal simulation results. Therefore, in this paper, the sequential indicator simulation method, target-based simulation method, and multi-point geostatistics method are used for the quantitative description of sedimentary microfacies in the study area, and the adaptability and reliability of the three methods for quantitative description of reservoir microfacies are analyzed.

2. REGIONAL GEOLOGY

Dawangzhuang oilfield in the study area is located in Suning-Dawangzhuang structural belt of Raoyang Sag in Jizhong depression (Figure **1a**). Its structural features are generally anticline structure with northwest dip and southeast lift, which is one of the most favorable areas for oil and gas enrichment in Raoyang Sag. Jizhong depression is located in the west of Bohai Bay Basin, with Taihang Mountain in the west, Yanshan Mountain in the north, and Cangxian uplift in the east. Raoyang Sag is a secondary structural unit of the Jizhong depression in the Bohai Bay Basin, and it is a Cenozoic dustpan-shaped sag with an area of about 5280km2. As an important producing area in the Jizhong depression, the Raoyang depression is very rich in oil and gas, with proven oil and gas reserves accounting for 70% of North China oilfield. From west to east, the depression is divided into a low uplift belt, western slope belt, buried hill sub-depression belt, central uplift belt, main depression belt and eastern fault step belt.

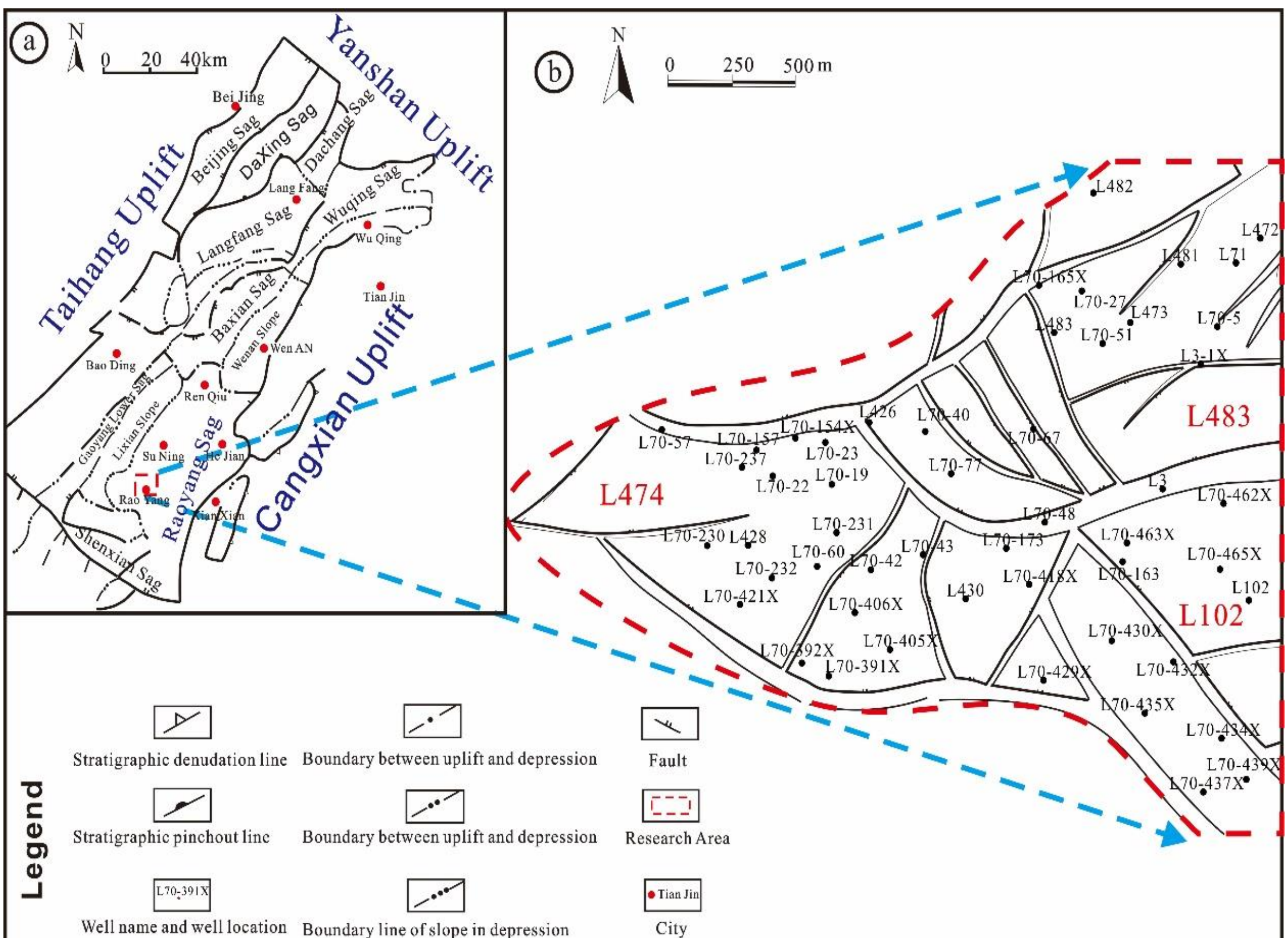


Figure 1: Regional location map of Dawangzhuang oilfield: **(a)** Outline of Jizhong sag structure; **(b)** Regional structural location map of Dawangzhuang oilfield.

Geographically located in Suning County and Raoyang County, Hebei Province, Dawangzhuang oilfield belongs to Dawangzhuang structural belt structurally, located in the central uplift belt, sandwiched between Hejian depression and Suning depression, and is a typical anticline structure of “uplift in depression”. There is a Hejian-Wobei trough in the east, Lcun bulge in the south, and a Suning-Raoyang trough in the west. This structure is a NW-trending uplift structure with good reservoir forming conditions. There are two main positive structural units, namely, the Dawangzhuang anticline and the south fault nose of the Dawangzhuang structure, and one negative structural unit in Wobei oil-generating depression.

This study area is located in the south of Dawangzhuang oilfield (Figure **1b**), bounded by the L426 fault, including the L474 well area, L483 well area, and L102 well area of the L70 fault block. The oil-bearing area is about 11km2, and the geological reserves are 1441.53×104t. It is one of the most favorable areas for oil and gas enrichment in Raoyang sag.

3. METHODOLOGY

To better understand the principle of multi-point geostatistics, the concepts of data event, training image, and search tree method are introduced in multi-point geostatistics.

3.1. Data Events

In order to make up for the defect that traditional geostatistics can only express the correlation between two spatial points, multi-point geostatistics focuses on the analysis and expression of the correlation between multiple spatial points, and defines a new concept “data event” to express the “multi-point” set. A U-centered data event Dn with a size of N is composed of N vectors and the endpoints of N vectors. The endpoints are determined as sedimentary facies, and the attribute X is represented by M different states. Figure **2a** shows that the five-point data event. It consists of a central point to be evaluated u, four vectors u1, u2, u3 and u4, and endpoints X(u1), X(u2), X(u3) and X(u4).

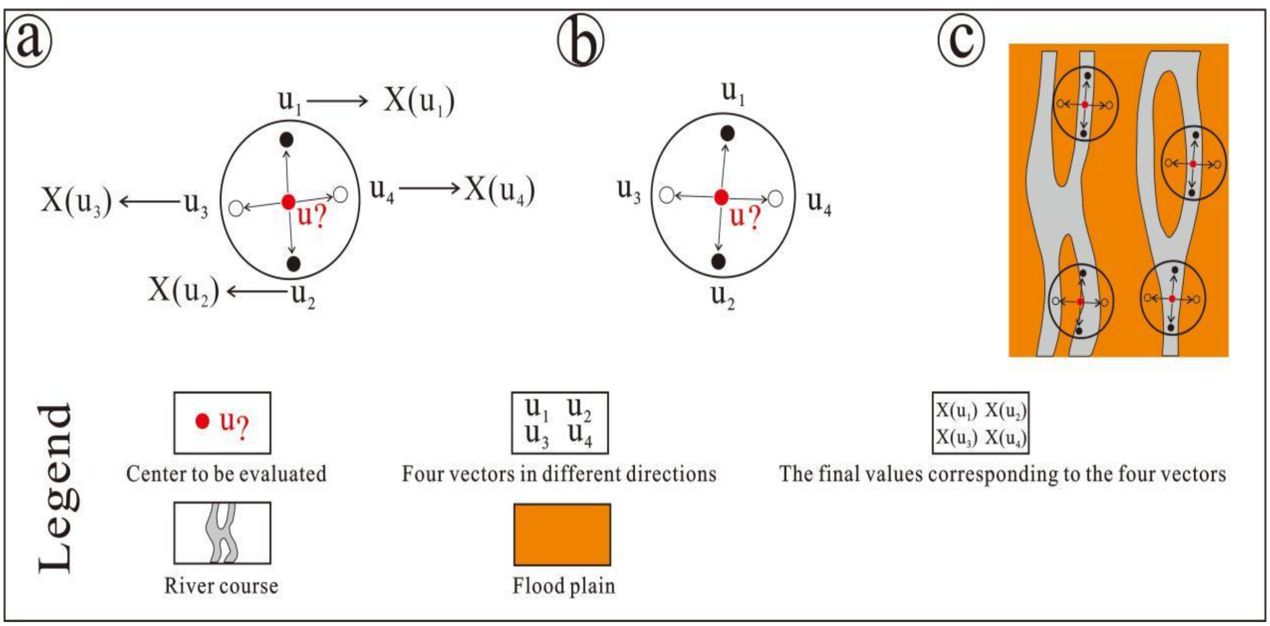


Figure 2: Estimation of conditional probability at unsampled points by training images: **(a)** Schematic diagram of five-point data events; **(b)** Data events; **(c)** Training image.

3.2. Training Image

Training image belongs to a quantitative facies model, which generally highlights the spatial distribution, morphological characteristics, and their combination and superposition relationship of different sedimentary microfacies in the sedimentary body. The geometric shape and distribution mode of each sedimentary microfacies expressed in the training image only needs to be consistent with the prior geological model, and do not have to be faithful to the well information [25-26].

Multi-point simulation is still based on pixel calculation. Under the premise of stationary assumption, the calculation formula of the local conditional probability distribution function can be obtained from the conditional probability formula as:

$$Prob[k/dn] = \frac{C_k(dn)}{C(dn)}$$

In the previous formula, k is the expected value; dn is the conditional data event; C(dn) is the number of repetitions of the conditional data event dn in the training image; Ck(dn) is the conditional constraint of the data event dn in the training image, The number of repetitions when the center point value is k. For example, Figure **2** can be regarded as a schematic diagram of using training images to estimate the conditional probability distribution function at unsampled points. In Figure **2b**, u1 and u2 are river course, u3 and u4 are flood plain, and the corresponding data events are dn={Z(u1), Z(u2), Z(u3), Z(u4)}, then the value of C(dn) should be 4. Use the data event shown in Figure **2b** to search in the training image shown in Figure **2c**. Among the 4 data that meet the conditions, u is the river course, and there are 3 repetitions, then the corresponding conditional probability is:

$$Prob[\text{River course}/dn] = \frac{\text{The center point is the river course}}{\text{Data events that meet the conditions}} = 3/4$$

U is the repetition of the flood plain, and the corresponding conditional probability is:

$$Prob[\text{River course}/dn] = \frac{\text{The center point is the flood plain}}{\text{Data events that meet the conditions}} = 1/4$$

Therefore, the probability that point u is a river course is 3/4, and the probability that point u is a flood plain is 1/4.

3.3. Search Tree Method

In the process of building the model according to the geological model expressed in the training image, it is necessary to analyze the data of the training image to obtain the local conditional distribution probability of geological parameters. In the early stage of multi-point modeling, the Snesim method was used to calculate the probability, but the simulation time was too long to be applied in the modeling process. Therefore, this paper proposes a search tree method, which is a dynamic data structure improved on the basis of the Snesim algorithm and is used to store geological patterns scanned from training images. When calculating the conditional probability of data events, it is not necessary to scan the training image repeatedly but to read it directly from the created search tree, which greatly shortens the simulation time.

As shown in Figure **3a**, there is a training image composed of 5*5 grids, with blue representing sandstone and white representing mudstone. This training image expresses the contact relationship between sandstone facies and mudstone facies on the plane. The local conditional probability of lithofacies is obtained by scanning the training image. As shown in Figure **3b**, there is the search template, which indicates that the lithofacies at U is determined by the parameter values at 1, 2, 3 and 4. The probability distribution at its center U is obtained by these four lithofacies values. The specific search and the probability calculation process is as follows:

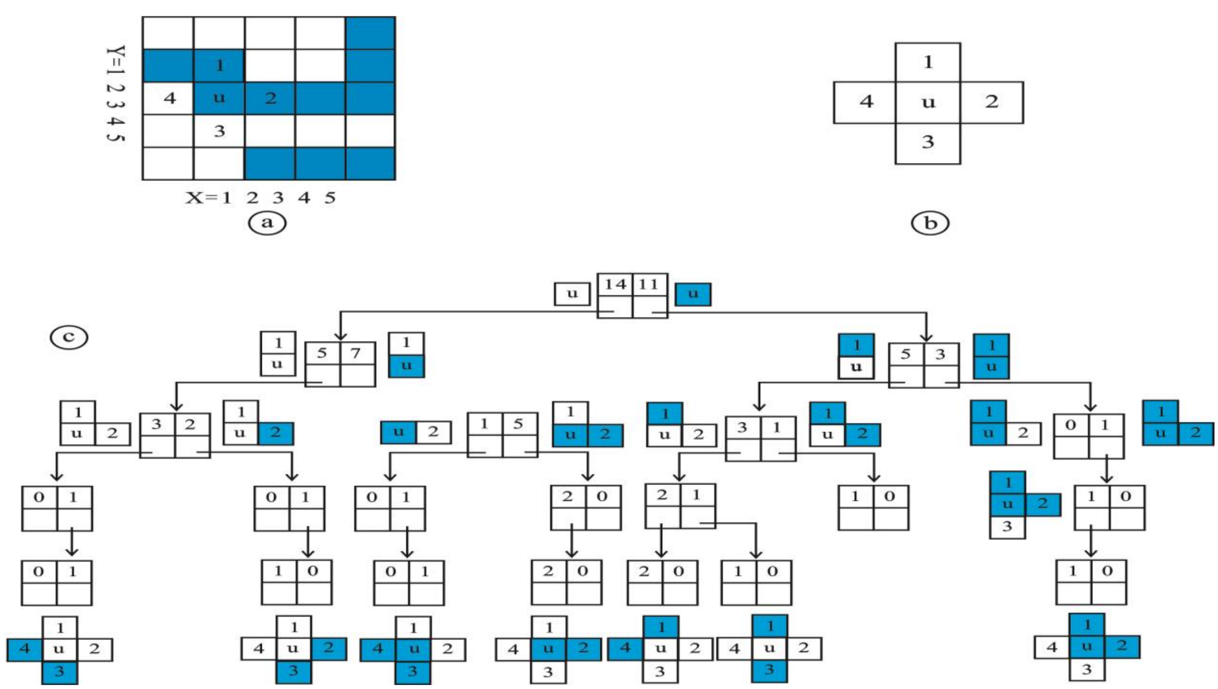


Figure 3: Search tree diagram: **(a)** Schematic diagram of 5*5 grid training image; **(b)** Schematic diagram of Search template; **(c)** Schematic diagram of search tree plain.

This search tree (Figure **3c**) is expressed in the form of a binary tree. During the search process, the lithofacies values of nodes 1, 2, 3 and 4 are searched and recorded in turn, and their probabilities are recorded. Ⅰ indicates the root node of the search tree, which is determined by the lithofacies statistics of 25 nodes (14 nodes are mudstone and 11 nodes are sandstone); Ⅱ is the scanning statistics of the lithofacies values at node 1. The lithofacies distribution at nodes 1 and U can be divided into four situations: mud, silt, sand, mud, and sand. Each situation appears 5 times, 7 times, 5 times and 3 times in the training image. Record the statistical values at nodes 1 and U, and scan the next node on this basis until all four nodes in the search template are searched and counted, and finally generate several different lithofacies. In the actual multi-point geological modeling process, the training image should reflect the spatial structure of the geological body, so it is much more complicated, and the size of the search template should be tested and adjusted according to the actual situation.

4. RESULTS

4.1. Multi-point Geostatistical Facies Modeling in The Study Area

According to the comprehensive geological analysis and outcrop data in the study area, combined with the training images obtained from sedimentary microfacies analysis, and under the constraints of logging data and geological information, the multi-point geostatistics Sensim algorithm is used to generate the sedimentary microfacies model.

4.1.1. Types of Sedimentary Microfacies

Based on the detailed observation and description of the core wells in the study area, as well as the research and analysis of the sedimentary environment, sedimentary petrological characteristics, and sedimentary structure characteristics, combined with previous research results in the study area, it is believed that meandering river facies developed during the deposition period in the study area. Divided into three subfacies: river bed subfacies, bank subfacies, and flood subfacies, and further subdivided into five sedimentary microfacies: channel filling, point sand bar, rupture fan, natural dike, and floodplain. Each microfacies types have different rock facies combinations and petroelectric response characteristics [27].

The river channel is filled with microfacies: River channel filling sediments are generally located at the bottom of river channel sediments, and there are uneven scouring surfaces under them. These sedimentary microfacies are mainly distributed in the deepwater area near the concave bank, which is the product of the flood period. The composition of retained gravels is complex, and most gravels are found in the source area. Gravel is well-rounded, has certain sorting, and is often arranged in a shingle-like orientation. The long axis is generally perpendicular to the flow direction, and the inclined direction points upstream. The spontaneous potential curve evolves from smooth box shape to toothed box shape or bell shape.

Point bar microfacies: The lithology of point bar sediments in the study area is mainly sandstone, which is mainly well-sorted sand-grade detritus. Its mineral composition is complex, with low maturity, many unstable components and high feldspar content. During the development of the point bar, the hydrodynamic cycle changes frequently and greatly, and a variety of bottom shapes and bedding types are developed. Generally speaking, the lower bedding type is a mainly large and medium-sized trough or plate-shaped cross-bedding caused by current ripple, while the upper bedding type is parallel bedding, small ripple bedding and climbing bedding. The amplitude of the spontaneous potential curve is medium-high, and the combined shape is small box, smooth funnel, toothed funnel, a medium-high small funnel, or bell. Extending from the river to both sides or the end of the river, the amplitude of spontaneous potential decreases gradually, and the curve teeth seriously.

Microfacies of crevasse fan: The sediments of the crevasse fan are mainly composed of fine sandstone and siltstone. The grain size is slightly coarser than that of natural dike sediments and gradually becomes thinner from the crevasse to the fan margin. Small cross-bedding, wavelet mark bedding, climbing bedding and horizontal bedding are developed, and scouring and filling structures are common. The spontaneous potential curves are mostly finger-shaped and cone-shaped.

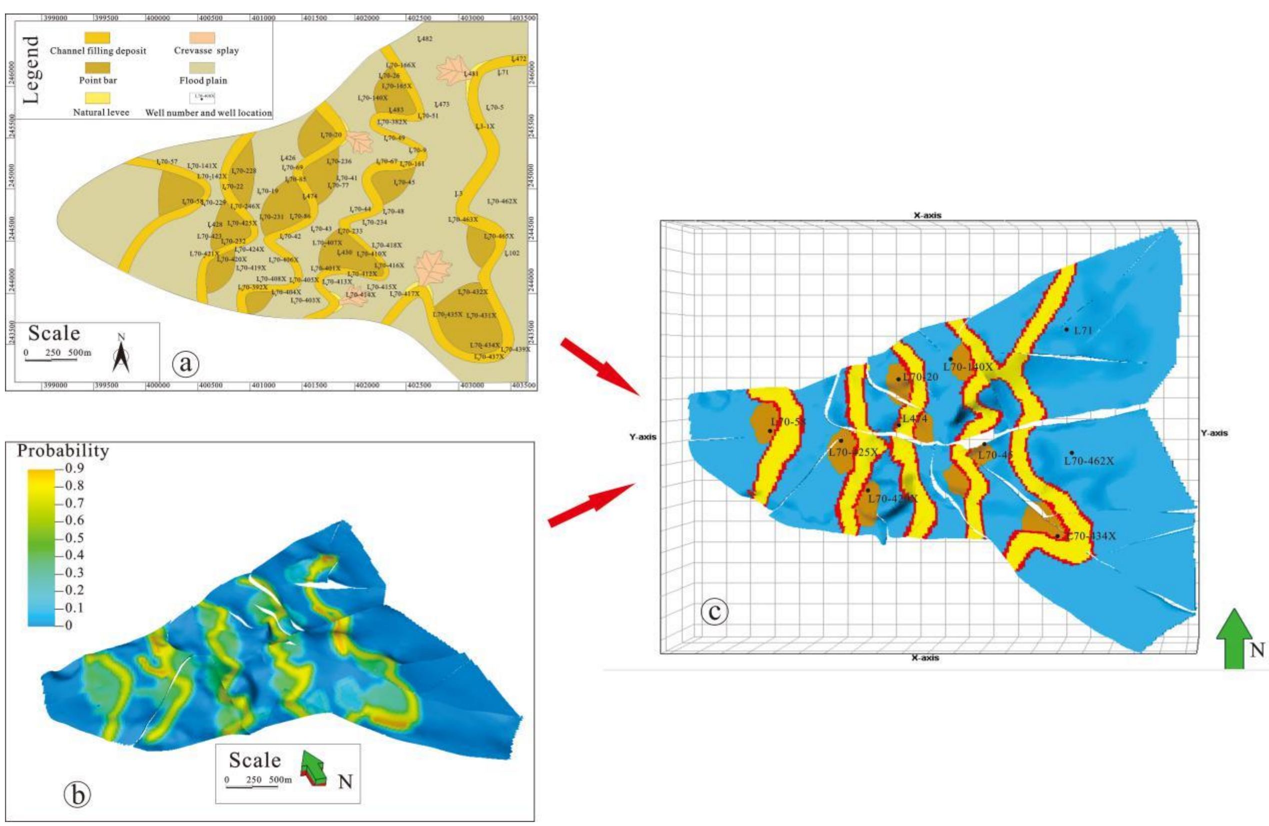
Natural dike microfacies: Natural dikes are mainly developed on the concave bank side of the meandering river, and the sediments of natural dikes are mainly thin layers composed of fine sandstone, siltstone and mudstone, with poor reservoir performance. The internal bedding structures are mainly small trough cross-bedding, wavy bedding and horizontal bedding. The combination of spontaneous potential curves is bell-shaped or toothed bell-shaped.

Floodplain microfacies: The floodplain is a flat part at the bottom of the river valley outside the riverbed, and it developed well in the middle and old age of river development. Sediments in the floodplain are mainly siltstone and clay. The bedding structure is dominated by wavy bedding and horizontal bedding. Dry cracks and raindrop imprints are often reserved in mudstone due to intermittent water exposure. The amplitude of the spontaneous potential curve is mostly medium-low, and the combined shape is zigzag, sometimes even straight, with serious teething. Most of the spontaneous potential curves in the study area are of low amplitude, and the combination shape is conical.

4.1.2. Establishment of Training Images

The quality of training images directly determines the quality of the final sedimentary facies model. For the multi-point statistical simulation of point bar microfacies in meandering river sedimentary system, the most important thing is to grasp the development form and plane contact relationship characteristics of point bar sand bodies in the same period, as well as the vertical overlapping contact relationship characteristics of point bar sand bodies in different periods [28]. In this regard, training images can usually be drawn based on artificial hand-painted phase diagrams through prior sedimentary models, but the training images obtained by this kind of method are mostly two-dimensional and lack the distribution characteristics of sand bodies in the longitudinal direction. Based on the simulation of shale content distribution, although three-dimensional training images can be obtained, it is difficult to capture the plane distribution patterns of sedimentary facies due to the lack of some characteristic statistical parameters of sand bodies in the horizontal direction [29].

The two-dimensional training image (Figure **4c**) of the target interval in this study area is obtained by the prior deposition model and hand-painted image. According to the previous geological research, the corresponding sedimentary microfacies distribution map has been made for each sublayer in the study area, which is widely used in actual production. According to the artificial phase diagram (Figure **4a**) of the Ed3Ⅲ-8 sublayer in the study area, the training image of this sublayer is drawn. When drawing the training image, the position and distribution of sedimentary microfacies refer to the artificial delineation map, and the sedimentary facies probability distribution is to sketch the sedimentary area of the whole sand body as a plan according to the sedimentary microfacies plan of each sublayer and digitize it. The digitized plan is assigned to the facies model by the assignment method, so the sedimentary facies probability distribution (Figure **4b**) can be used to make corresponding simulation constraints for sand body simulation.



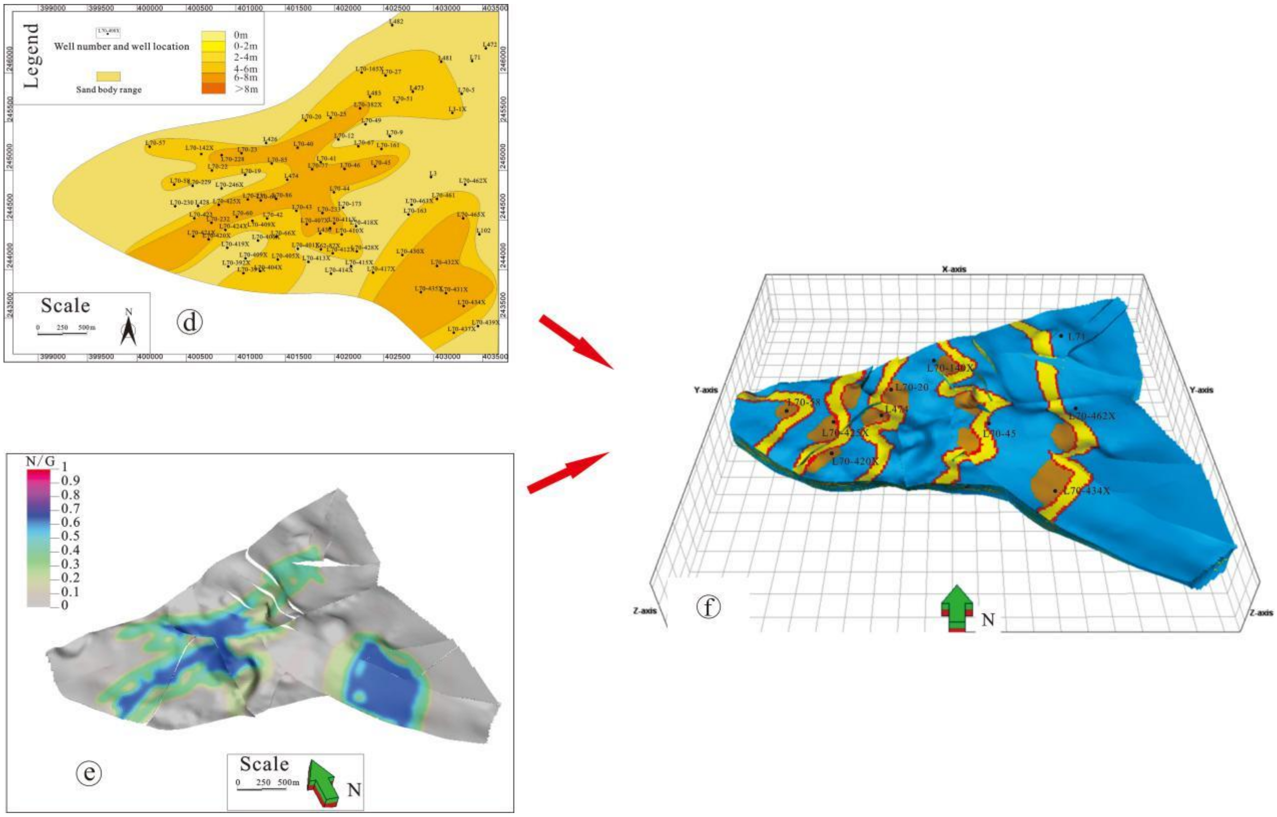


Figure 4: Generation of training image: **(a)** Sedimentary microfacies plan of Ed3Ⅲ-8 sublayer; **(b)** Probability distribution model of sedimentary microfacies; **(c)** Two-dimensional training image; **(d)** Sand thickness map of Ed3Ⅲ-8 sublayer in the study area; **(e)** Probability model of sand-land ratio in Ed3Ⅲ-8 sublayer in the study area; **(f)** Three-dimensional training image.

Based on fully understanding the position and distribution of sedimentary microfacies, the generation method of three-dimensional training image, through sorting and analyzing the sand bodies of point bar and river channel filling in different periods, uses sand thickness map (Figure **4d**) and sand-ground ratio probability body (Figure **4e**) to make corresponding simulation constraints on sand body simulation. As soft data of multi-point statistical simulation, the sand-ground ratio probability body has an effective constraint effect on the simulation of point bar sand body in both plane and vertical direction, thus obtaining a three-dimensional training image (Figure **4f**). According to the development morphology and distribution characteristics of different sedimentary microfacies in the Ed3Ⅲ-8 sublayer in the study area, the influence of two-dimensional and three-dimensional training images on the quality of the final sedimentary facies model is comparatively studied.

4.1.3. Multi-point Statistical Phase Simulation

The training images used by the Snesim algorithm add a priori qualitative and quantitative geological knowledge. It is faithful to the well point hard data that can be combined with logging and geological information, which improves the vertical resolution of the lithofacies model and increases the constraints on the cross-well large-scale structure [30-31]. The grid size of the training image is very important. At present, there is no relevant literature on the ratio of the training image grid to the model grid. Schlumberger suggests setting the number of training image grids in the horizontal direction of the river to 50-200 cells, and at least twice the size of the reservoir in the continuous direction of the river. The average scale of the point sand bar in the study area in the direction of the river is 80 meters. Therefore, a grid of 150m×150m was selected in the horizontal direction for this study; The grid in the vertical direction should be 20-40 cells. Considering that there are 69 small layers in the study area, a grid of 0.5m in the vertical direction is selected. A unified model grid parameter with a size of 150m×150m×0.5m is taken, and the search radii in I, J and K directions are 19m, 19m and 5m, respectively. According to the modeling steps of the Snesim algorithm, the sedimentary facies model based on training images of different dimensions is simulated; they are sedimentary facies models based on two-dimensional training image (Figure **5a**) and sedimentary facies model based on three-dimensional training image (Figure **5b**).

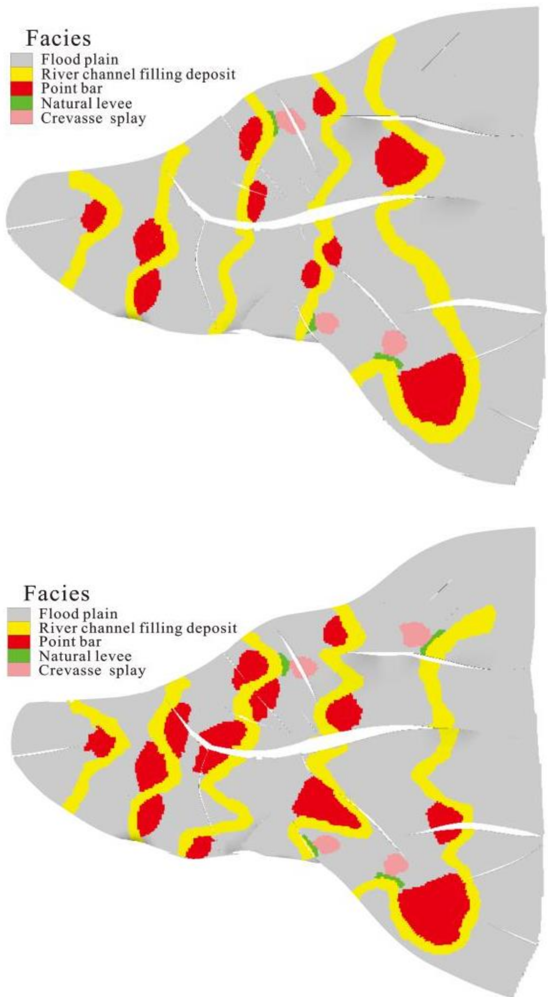


Figure 5: Sedimentary facies model map of Ed3Ⅲ-8 sublayer in the study area: (a) Sedimentary facies model based on two-dimensional training image; (b) Sedimentary facies model based on three-dimensional training image.

4.1.4. Multi-point Statistical Sedimentary Facies Model Test

When multi-point geology is used to simulate sedimentary facies, the attribute values of unknown areas between wells are predicted by a certain random algorithm according to the existing single well facies interpretation data, and the simulation data obtained from this method are uncertain. Therefore, in order to ensure the accuracy of the model, it is necessary to use the method of probability distribution consistency and well-connected profile, combined with the drilling and logging information to test the model [32].

The probability consistency test is to count the sedimentary facies probabilities among sedimentary facies models simulated by different training images, discrete data of well points, and original logging curves, and judge whether the probabilities of the three are consistent [33]. If the probability distribution trends of the three are consistent, the model has high accuracy. If the probability distribution trends of the three are quite different, the accuracy of the model is low. Comparing the statistical results of three kinds of probability data of sedimentary facies in the above two models (Figure **6**), it is concluded that the coincidence rate of sedimentary facies ratio in the sedimentary facies model controlled by three-dimensional training image is higher than that in two-dimensional training image, which is about 87%.

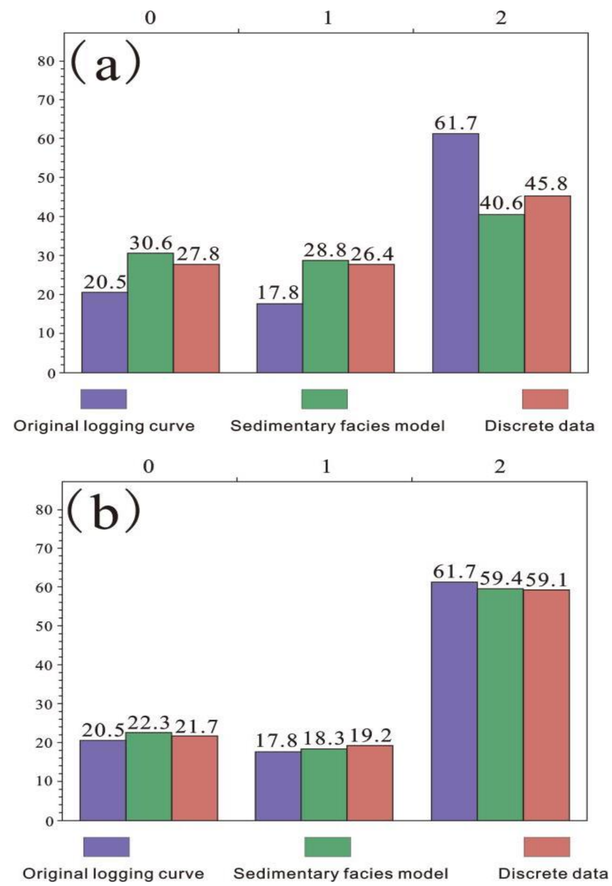


Figure 6: Statistical chart of sedimentary facies proportion of Ed3Ⅲ-8 sublayer in the study area: (a) Statistical diagram of sedimentary facies proportion based on two-dimensional training image of Ed3Ⅲ-8 sublayer in the study area; (b) Statistical diagram of sedimentary facies proportion based on three-dimensional training image of Ed3Ⅲ-8 sublayer in the study area.

In order to optimize the two-dimensional and three-dimensional training images, select a well-connected section parallel to the provenance direction and compare, analyze and judge the quality of sedimentary facies models made based on different training images.

The five selected wells parallel to the provenance direction are L70-20, L70-40, L474, L70-86 and L70-406X.

Select five wells parallel to the source direction, adopt the same simulation method, and ensure that all parameters are set unchanged during the simulation process, and establish a reservoir parameter model for inspection. From the cross-well sedimentary facies model profile, it can be concluded that: due to the lack of information on the thickness of reservoir sand bodies in two-dimensional training images, the generated model cannot reflect the vertical changes of reservoir sand bodies and the horizontal connectivity problems (Figure **7a**), which makes the simulation results less consistent with the known data; The three-dimensional training image can overcome the problems brought by the two-dimensional training image, and the sand body of the point bar in the generated model shows a certain continuity in vertical and horizontal directions and longitudinal directions, with a high degree of coincidence (Figure **7b**).

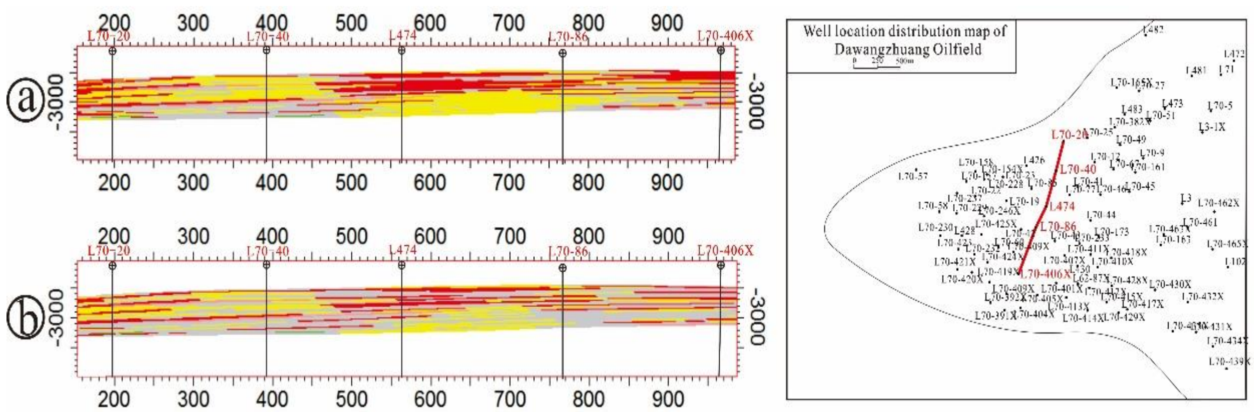


Figure 7: Sedimentary facies model profile of Ed3Ⅲ-8 sublayera: **(a)** Sedimentary facies model profile based on two-dimensional training image; **(b)** Sedimentary facies model profile based on three-dimensional training image.

To sum up, using the algorithm, the given grid parameters are reasonable, i.e., the ideal sedimentary facies model can be obtained by using three-dimensional training images with the appropriate proportion of sedimentary facies.

4.2. Three-dimensional Sedimentary Facies Modeling of Traditional Geological Reservoirs

4.2.1. simulation Based on Sequential Indication

There are four sedimentary microfacies in the study area, namely, river channel filling, point bar, crevasse fan and natural dike. There are 124 wells in the study area. Based on the logging data of these wells, the proportion of the four sedimentary microfacies in the study area is determined: the proportion of the four microfacies is 48.3%, 39.2%, 10.1% and 5.4%, respectively. The parameters of this layer are calculated according to the calculation principle of the experimental variogram, and the spherical model is used to calculate and fit the experimental variogram in many directions, and the parameter table of the experimental variogram is obtained as shown in Table 1. Figure **8** shows that the main direction of the variogram is 43°, and the nugget value is 0. The secondary direction is 135°, and the nugget value is 0. Through the calculation results in different directions, the distribution characteristics of sand bodies can be clearly seen. The main provenance direction of the L70 block in Dawangzhuang oilfield is southwest-northeast [34].

Table 1: Parameter table of experimental variogram

Direction	Search Radius/m	Steps/m	Number of Steps	Angle Tolerance	Proportion/%
Main dir of river channel filling deposit	1753.33	195.2	9	π/8	48.3%
Secondary dir of channel filling deposit	1673.33	135.7	14	π/8	
Main dir of point bar	1772.65	188.2	10	π/8	39.2%
Secondary dir of point bar	1641.37	106.7	16	π/8	
Main dir of crevasse splay	1638.66	137.8	12	π/8	7.1%
Secondary dir of crevasse splay	1637.05	145.2	14	π/8	
Main dir of natural levee	1839.33	166.8	11	π/8	5.4%
Secondary dir of natural levee	1673.33	157.5	14	π/8	

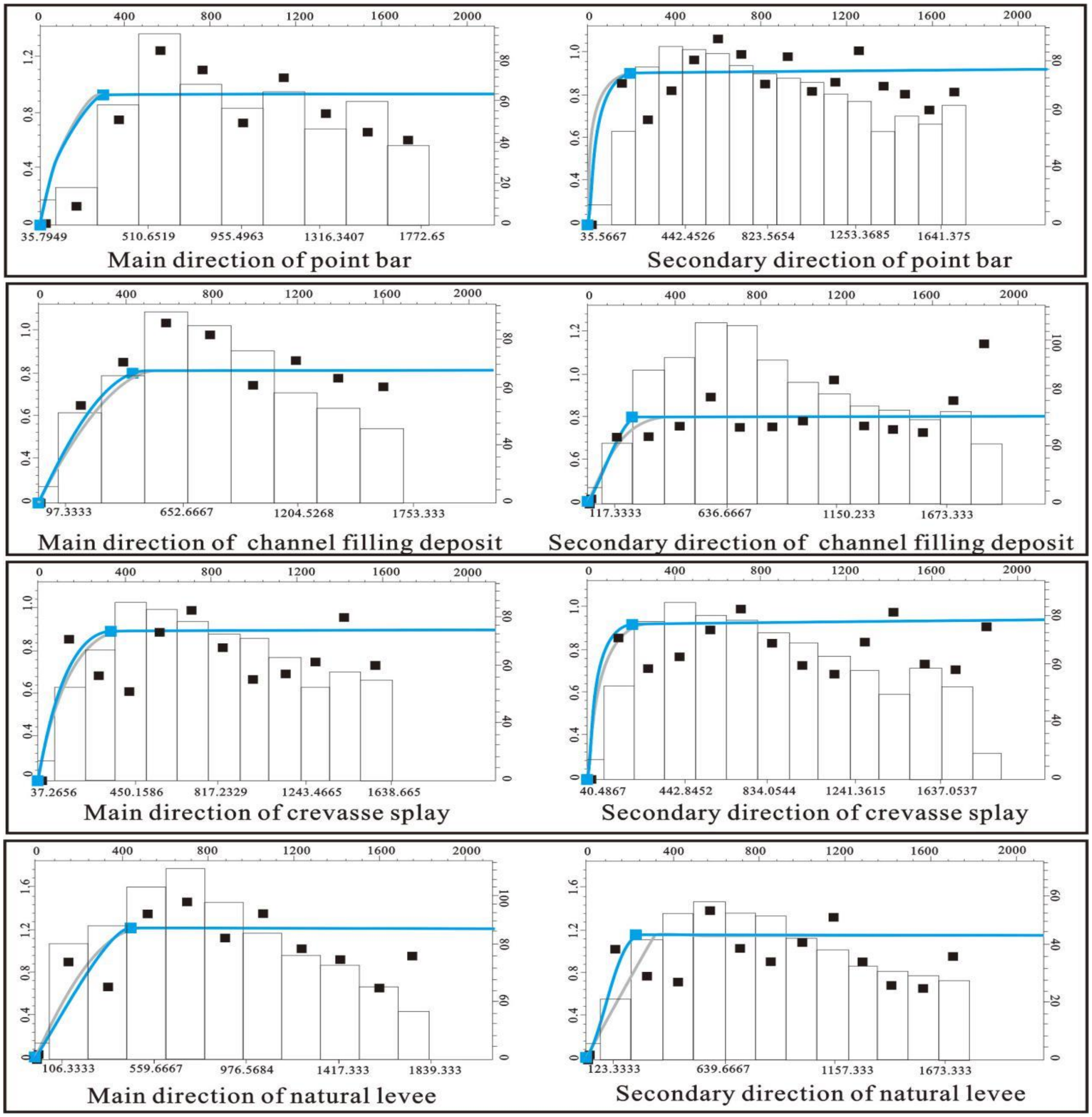


Figure 8: Experimental variogram fitting of Ed3Ⅲ-8 microfacies in the study area.

The parameter settings of each micro-phase change difference function in the simulation results are shown in Table 2. Figure **9a** shows that the modeling results of microfacies in the Ed3Ⅲ-8 sublayer. The distribution trend of river channel and mudstone can be clearly seen from the simulation results. The rivers are distributed in strips and wide strips, and most of them are in direct contact with mudstone, which is consistent with the actual geological conditions. The river channel is distributed in the southwest-northeast direction, which is well-matched with the two-dimensional sedimentary facies map (Figure **9b**).

Multi-point geostatistics can well reflect the relative positional relationship of river course and point sand bars. The simulation results are consistent with the conclusions of geological theory in the study area and have important reference significance for the prediction of the development of interwell reservoirs in the study area.

The sequential indication can simulate cumbersome and unknown geological conditions, but the boundary of the sedimentary facies simulated by this method is not smooth, and the geometry of the sedimentary microfacies cannot be clearly displayed, and the phenomenon of sporadic distribution of sedimentary microfacies appears.

Table 2: Parameter table of micro-phase change difference function of Ed3Ⅲ-8 sublayer in the study area. The range refers to the range in which the regionalized variables are spatially correlated, and a larger range means that the observed data in this direction are correlated in a larger range. The base station value reflects the total variability of regionalized variables in space. The larger the base station value, the greater the fluctuation degree of data

Sedimentary Microfacies Types	Variable range				
	Main Range	Secondary Range	Vertical Range	Base Station Value	Block Gold Constant
River channel filling deposit	433	224	1.3	0.8	0
Point bar	317	166	2	0.9	0
Crevasse splay	343	176	1.1	0.9	0
Natural levee	418	218	0.9	1.2	0

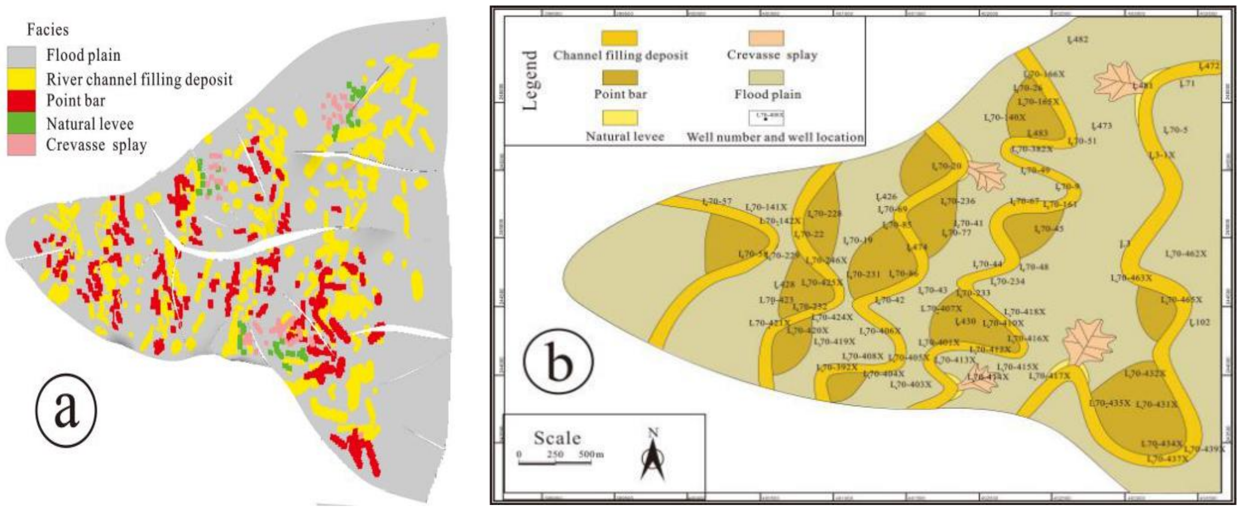


Figure 9: (a) Ed_3Ⅲ-8 sublayer indicates simulated sedimentary microfacies model; (**b**) Sedimentary microfacies plan of Ed_3Ⅲ-8 sublayer.

4.2.2. Constraints Based on Target Simulation Method

Target-based stochastic modeling of sedimentary microfacies is based on an accurate understanding of the shape, scale and combination of target bodies [35]. The target-based simulation method needs to set the geometric shape parameters (Table 3) of the target body in a meandering channel, which determines the rationality and accuracy of generating the target body. In addition, all kinds of geological knowledge should be transformed into constraints to participate in the simulation, including plane microfacies distribution, seismic attributes, cross-well connectivity knowledge and so on [36-37]. Under the constraints of these basic data and quantitative trends, the simulation of sedimentary microfacies can be carried out.

(1) It mainly includes the shape of the simulated target body (such as long strip on the plane of distributary channel and elliptic point dam), the scale (width, length and thickness), the direction of the target body (the direction of the main streamline of the channel) and various constraints (phase plan, seismic data, etc.). The acquisition of these data requires detailed and in-depth geological research and analysis of a large number of data samples (well point data, core data and seismic data) Quantitative geological knowledge base is the most important input data for target-based facies simulation, which determines whether the simulation results are consistent with objective geological reality and is the key to the success or failure of target-based facies simulation [38-39].

Table 3: Parameter setting of meandering river target in study area

River Channel Elements	Amplitude (m)	Wavelength (m)	Source Direction (°)	River Width (m)	River Depth (m)
River Channel Parameters	400-1200	500-1400	38-50	30-180	2-6

(2) Random simulation technology can get many possible realizations. To get the final accurate model, it is necessary to restrict it by various information to minimize the uncertainty. Constraints mainly include well data constraints, spatial probability of simulated microfacies and spatial distribution orientation of microfacies. Generally, the hard constraint data of the grid at the well point is obtained by gridding the well data. However, the spatial distribution probability of microfacies is difficult to obtain, so the sedimentary microfacies map can be transformed into the plane probability distribution of microfacies by subdivision and comparison, and the plane microfacies distribution map can also be used to establish the three-dimensional spatial probability distribution data of each target facies like the sand thickness map (Figure **10c**).

(3) The target facies is directional in spatial distribution due to the influence of sediment source direction and sedimentation, so the plane orientation of sedimentary microfacies can be used instead of the three-dimensional spatial orientation distribution, which accords with the actual geological understanding. Import the prepared microfacies map into the modeling work area and digitize it. On the previously established sedimentary microfacies map, a streamline reflecting the distribution direction of microfacies is drawn for each microfacies (Figure **10b**), the vector azimuth of the connecting line between two points on the streamline is calculated, the two-dimensional azimuth plane is made, and the microfacies distribution azimuth attribute model of each sedimentary unit is established by the method of grid attribute assignment (Figure **10a**), which can be used as the target orientation constraint of the target-based indicative point algorithm.

When the target volume-based method is used to simulate sedimentary microfacies, the non-reservoir microfacies-floodplain facies is set as the background facies, and the other four target facies are “inlaid” into the background facies according to a certain spatial allocation mode under the guidance of reservoir sedimentology. The realization of the spatial allocation relationship between different facies types needs the help of simulation logic relationship: when the point bar meets the floodplain microfacies in the background phase, it can be denuded and replaced; otherwise, the distribution pattern of the original background phase can be maintained. In this way, it can be ensured that the bar will not be distributed in other microfacies but only appear in the floodplain. On the basis of this logical relationship, the same set of modeling geological parameters is input, and the sedimentary microfacies model based on target simulation is obtained (Figure **10d**).

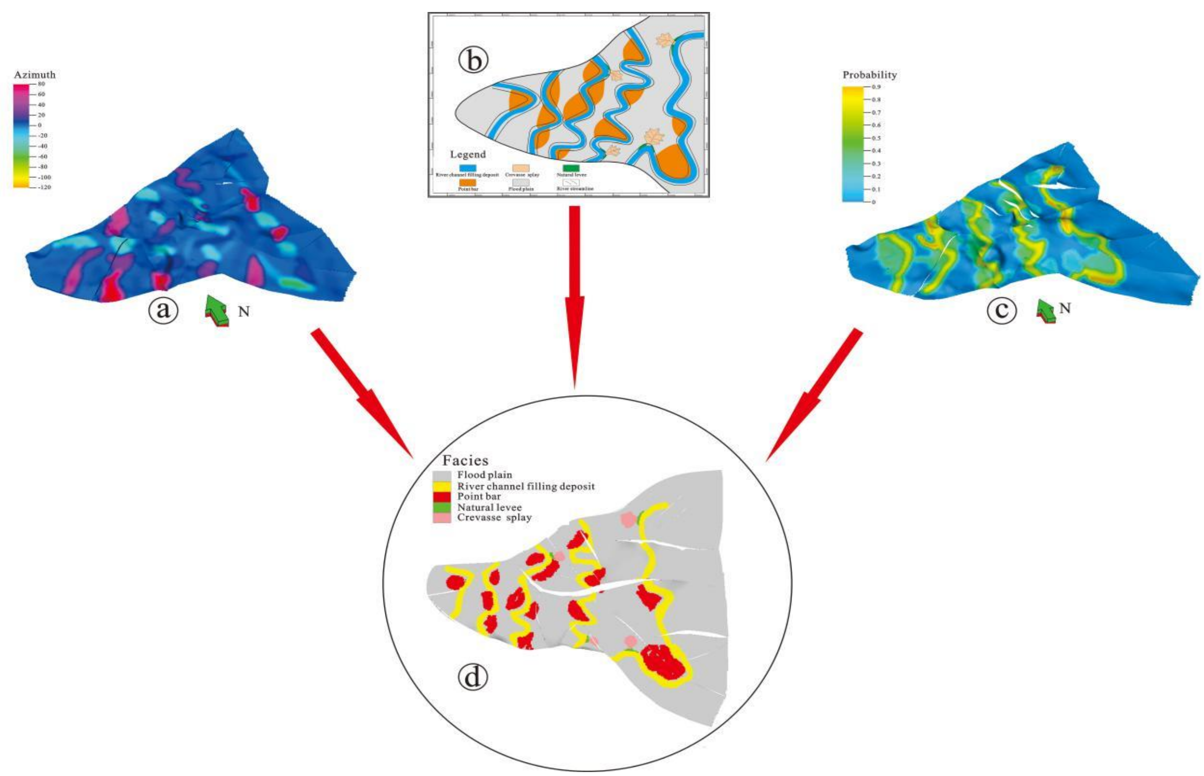


Figure 10: Flow chart of sedimentary microfacies model simulated by Ed3Ⅲ-8 sublayer based on target body: **(a)** Azimuth distribution model of sedimentary microfacies; **(b)** River streamline map; **(c)** Probability distribution model of sedimentary microfacies; **(d)** Simulation of sedimentary microfacies model of Ed3Ⅲ-8 sublayer based on the target body.

5. DISCUSSION

In the process of sedimentary facies modeling, the geological conditions of the work area, the selection of modeling methods, the size of the model grid, the coarsening method, and the training images used in multi-point geological statistics will have a great impact on the quality of the facies model. This kind of influence is inevitable. When it is within an acceptable range, we can think that the result of phase modeling is credible. Therefore, after the phase modeling is completed, we need to compare, analyze and judge the phase model in order to select the best phase model. This paper makes a comparison between two-dimensional and three-dimensional aspects.

Seen from the two-dimensional plane, the modeling results of the above three facies are consistent with the theoretical geological study of the study area, but there are obvious differences between them. Due to the uncertainty of the variogram, the simulation output model is uncertain, which can't simulate the geometric shape of the river channel and the relative relationship among the microfacies. The facies boundary is not smooth, and the microfacies are scattered, which can't explain the geological phenomenon (Figure **11a**). Goal-based simulation can show the geometric shape of the river channel and the phase sequence relationship with natural dikes when simulating the sedimentary system of the meandering river, but the point bar appears randomly in the river channel, which cannot well reflect the sedimentary phenomenon of "concave bank erosion and convex bank deposition" in the meandering river (Figure **11b**). From the simulation results, it can be seen that the sedimentary microfacies model generated by multi-point geostatistics simulation is relatively consistent with the actual geological body, which can better reflect the relative position relationship of the river channel, point bar and natural dike, and embody the characteristics of multi-channel and low-curvature meandering river sedimentary system (Figure **11c**).

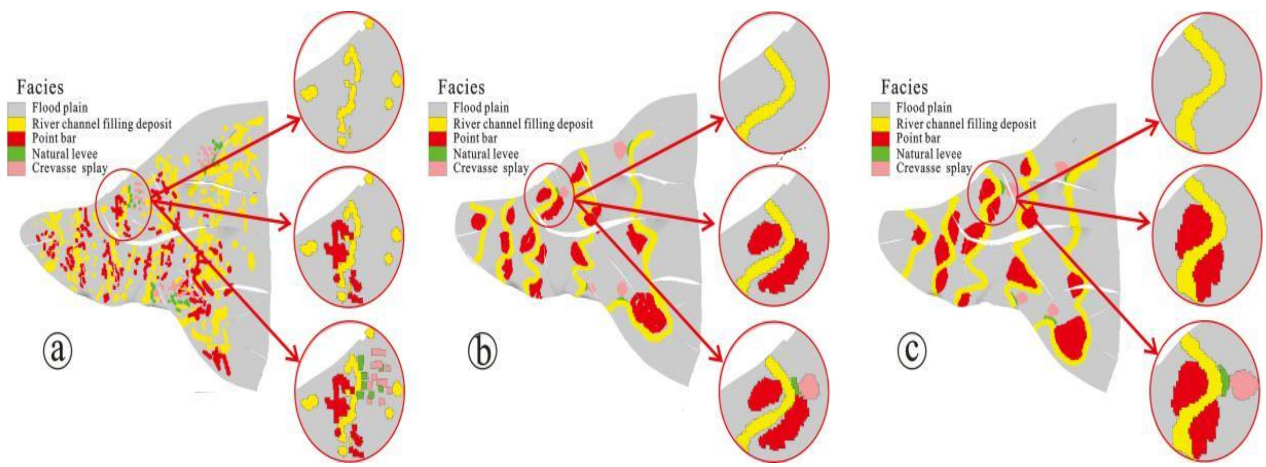


Figure 11: Three different methods to simulate sedimentary microfacies model on Ed3Ⅲ-8 sublayer in the study area: **(a)** Simulation of sedimentary facies model based on the sequential indication in Ed3Ⅲ-8 sublayer of the study area; **(b)** Sedimentary facies model of Ed3Ⅲ-8 sublayer in the study area based on target simulation; **(c)** Multi-point geostatistical sedimentary facies model of Ed3Ⅲ-8 sublayer in the study area.

From the perspective of three-dimensional, select one connecting well profile perpendicular to the direction of provenance and one connecting well profile perpendicular to the direction of provenance to compare and judge the quality of each phase model.

The well-connecting profile parallel to the provenance direction is the NE-SW well L70-40 well—L474 well—L70-86 well—L70-42 well—L70-406X well profile.

The well connection profile perpendicular to the provenance direction is the NW-SE well L70-158X well —L70-228 well —L70-19 well —L70-42 well —L70-401X well profile.

By using the facies model established based on the objective method, it can be seen from the vertical provenance section that the distribution of microfacies in each sublayer does not change much vertically, which cannot reflect the spatial change of each microfacies type. The sand body of the point bar in the study area is relatively developed, the thickness of the sand body is large, and the natural dike sand body is mostly isolated (Figure **12a**); Seen from the profile along the provenance direction, the point bar near the provenance direction is relatively developed, and the sedimentary sand bodies filled with river channels in different periods are distributed in pieces with good lateral connectivity (Figure **12b**).

Using the facies model established by the sequential indicator simulation method, it can be seen from the vertical provenance direction section that the distribution of point bar is irregular, the details of sand body distribution boundary are disordered, the sand bodies of the point bar gradually separate during the extension and development, showing a separate distribution state, and vertically overlap each other, and the river channel filling sedimentary sand bodies of different periods are separated by mudstone (Figure **13a**). Seen from the profile along the provenance direction, the point bar sand body is relatively developed near the provenance area, and the river channel filling deposits extend well in this direction and have good connectivity (Figure **13b**).

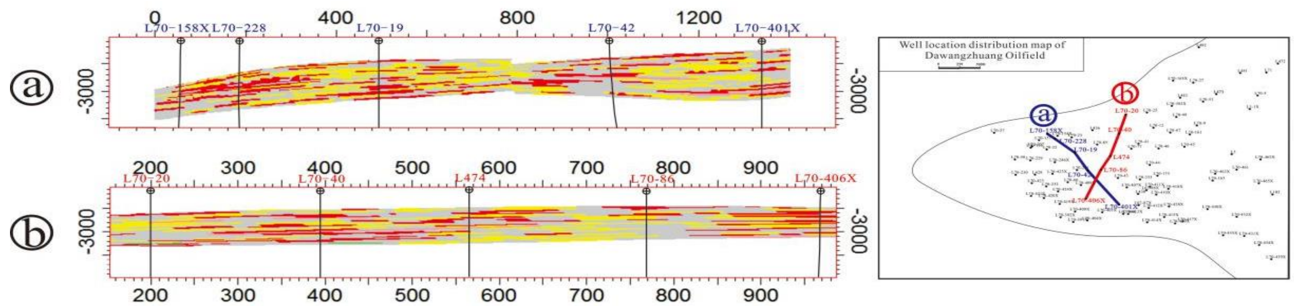


Figure 13: Profile of Ed3Ⅲ-8 small sequence penetration indication simulated sedimentary facies model in the study area: **(a)** Vertical provenance profile of Ed3Ⅲ-8 sublayer in the study area based on sequential indicator sedimentary facies model; **(b)** Profile along provenance direction based on sequential indicator sedimentary facies model of Ed3Ⅲ-8 sublayer in the study area.

Seen from the profile along the provenance direction, the distribution of microfacies sand bodies is consistent with the geological study of the work area, and the continuity of point bar sand bodies is very good at wells L474 and L70-86 along the provenance direction (Figure **14b**). Seen from the vertical provenance direction profile, the sand bodies of point bar are vertically superimposed and distributed, and there are thin mudstone barriers in different river channel filling sediments, which have good lateral connectivity and can well reflect the spatial changes of various microfacies types in the vertical direction (Figure **14a**).

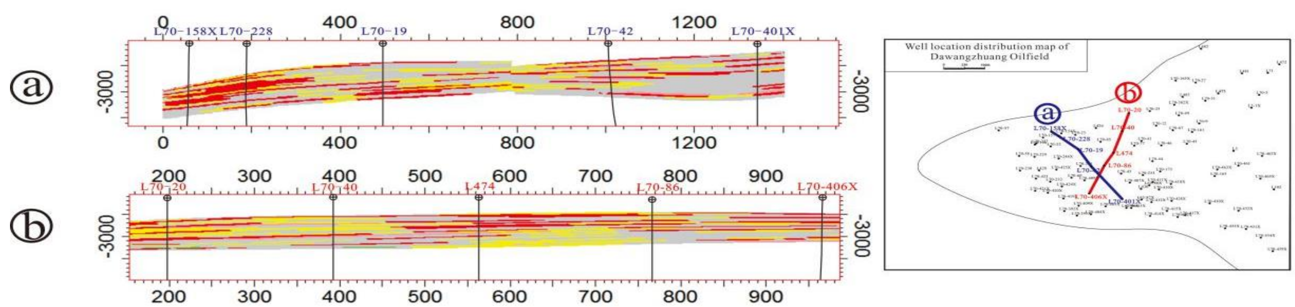


Figure 14: Profile of multi-point geostatistical sedimentary facies model of Ed3Ⅲ-8 sublayer in the study area: **(a)** Vertical provenance profile of multi-point geostatistical sedimentary facies model of Ed3Ⅲ-8 sublayer in the study area; **(b)** Multi-point geostatistical sedimentary facies model along with provenance profile of Ed3Ⅲ-8 sublayer in the study area.

Through the comparative analysis of facies modeling results, it can be concluded that the essence of modeling based on target facies is the spatial expression of sedimentary facies division results in geological research, which is faithful to the results of theoretical geological research in the study area, but cannot reflect the spatial changes of various microfacies types vertically; The realization of the spatial distribution of microfacies in the study area by sequential indicator facies model has a poor representation on the plane, which is quite different from the geological reality of the work area. Its simulation results are good in the vertical direction, which can reflect the distribution of microfacies sand bodies as a whole, but the simulation is random and the details of sand body distribution boundary are disordered. The multi-point geostatistical facies model can reflect the three-dimensional spatial distribution and contact relationship of microfacies sand bodies well, which is not only consistent with the actual situation of the work area but also consistent with the theoretical model of sedimentary evolution.

6. CONCLUSION

In multi-point geostatistics, three-dimensional training images can accurately reflect the plane distribution and spatial contact relationship of sand bodies in different stages and also overcome the problem that the above methods can not accurately reflect the distribution characteristics of vertical sand bodies. Three-dimensional training images can overcome the problems brought by two-dimensional training images, and the sand body of the point bar in the generated model shows certain continuity in the vertical and horizontal direction and longitudinal direction, with a high coincidence degree.

Sequential indicator simulation can't simulate the relative relationship among the microfacies of the meandering river well, and local distortion occurs, so sequential indicator simulation is not suitable for river facies modeling; The simulation method based on target body is time-consuming in calculating, and the location of point dam in river course is random, which cannot well reflect the deposition phenomenon of "concave bank erosion and convex bank deposition" in the meandering river, and is not suitable for river facies modeling.

With the development of the multi-point modeling method, multi-point geostatistical simulation can reproduce the complex geometry of meandering river sedimentary system with multi-channel and low curvature and can stably present the plane distribution and spatial superposition relationship of sedimentary microfacies, which provides an effective method for simulating the distribution of sedimentary microfacies in complex meandering river sedimentary environment, and has the advantage of fast calculation, and is suitable for fluvial facies modeling.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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