

# 3D Geological Modeling under Extremely Complex Geological Conditions

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**Abstract**—3D modeling method is divided into geospatial modeling and 3D geological modeling. 3D geological modeling technique has become a favorable tool for people to observe and analyze the geological body enriched in mineral resources. Unlike geospatial modeling, 3D geological modeling must consider various geological conditions affecting spatial shape and petrophysical distribution of geological body for its complexity. This article analyzes the uncertainty, complexity and diversity of geological body, and lists complex geological conditions controlling spatial shape and petrophysical distributions of geological body. And then 3D geological modeling method under the control of complex geological conditions is proposed, and corresponding modeling workflow is set up. Finally, taking 3D geological modeling of petroleum exploration and development for example, 3D geological model of Shu II district in the Liaohe oil-field is built. Based on this model, some applications are realized, such as 3D visualization of structural model and petrophysical model, reserves calculation and drilling design, etc.

**Index Terms**—geological body, complex geological conditions, 3D geological modeling, modeling workflow

## I. INTRODUCTION

Based on computer graphics technology, the 3D visualization can give people an intuitive feel. With the aid of computer technology, communication technology, sensor and measurement technology, simulation technology etc, the virtual reality technology can create a virtual environment. The common influence of visual sense, auditory sense and tactile sense can make users feel in virtual environment as that they are experiencing in reality. The 3D visualization technology and virtual reality technology provide a favorable tool for people to

observe and analyze the world. The 3D modeling is the foundation of the 3D visualization technology and the virtual reality technology. In the 1970s, I.E. Sutherland at the massachusetts institute of technology's Lincoln laboratory issued a doctoral dissertation about a graphics system of man-machine communication. Since then, the 3D modeling theories and methods were continuously innovated. And 3D modeling softwares were also rapidly developed. Softwares supporting 3D modeling include AutoCAD, 3DS Marks, SolidWorks, SketchUp, MDT, Pro/Engineer, SkyLine, and so on Ref. [1]. The 3D modeling technology has been widely used in military, land and resources, urban construction, road traffic, architectural design, machine design, medical treatment and some other industries.

In traditional geological work, geological researches and results, such as well sections, geological profiles and plans, are showed by 2D maps. The essence is to project geological phenomena in 3D space, such as stratum, structure and landform, onto a plane, thus, it will cause the loss and distortion of spatial information Ref. [2, 3]. According to the different modeling objects, 3D modeling method is divided into geospatial modeling and 3D geological modeling Ref. [4]. In 1994, 3D geological modeling technology was firstly put up by Simon W Houlding from canada and introduced into the expression of geology research results Ref. [5]. By means of technologies of 3D geological modeling and 3D visualizing, geological body and geological environment can be understood and expressed directly in terms of 3D space Ref. [6]. So this technology is characterized by vividness, directness, precision, dynamic, abundance. The technology of 3D geological modeling will bring great changes in the methods of geological data acquiring, storing, processing and displaying Ref. [7].

In recent years, 3D modeling technology gets rapid development, and all kinds of modeling theories and methods are constantly put forward. In general, the modeling methods can be divided into two categories:

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modeling method based on facial model and modeling method based on volumetric model. These two kinds of modeling methods have their own advantages and disadvantages Ref. [8]. The key to establish a high precision 3D geological model is to design the reasonable modeling process and to choose the suitable modeling method with the aim at the characteristics of geological body. To fully exert respective advantage of modeling methods based on facial model and volumetric model, the paper submits a workable mixed geological modeling method. The 3D geological model built by this method can accurately depict planar geological bodies, and efficiently characterize solid models including sedimentary facies and petrophysical models. This method comprehensively considers the effects of structural condition, sedimentary environment and anisotropy on petrophysical distribution.

## II. RELATED WORK

To build high precision 3D geological model, we should not only have a clear understanding to the complicated geological body, but also grasp geological conditions that control petrophysical distribution. Meanwhile, all sorts of 3D modeling methods should be analyzed carefully and their merits and demerits should be known, and then appropriate modeling methods can be selected with the aim at every step of modeling workflow.

### A. Characteristics of 3D Geological Modeling

The complexity of geologic body makes 3D geological modeling largely different from geospatial modeling. Specific constraint elements and geological principles must be considered. The difficulties of 3D geological body modeling technology focus on how discrete geological data can be used to accurately rebuild complex geological structures Ref. [6].

For the different genesis and geological age, geological body has the features of uncertainty, complexity and diversity Ref. [7]. Hydrocarbon bearing geological body is located in underground 1000 to 3500 meters, so it can't be directly observed. Analysis and research on the geological body are carried out only through outcrop data, seismic data and drilling data. For the accuracy and limitation of these data, there are many uncertain factors in understanding geological body. Stratum is often affected by faults, and multi-period faults dislocate each other. Spatial topological relations between geological bodies are extremely complex. The generation of geological body is controlled by sedimentary environment. The advents of folds and faults make geological body diverse in geometric shapes. So establishing high precision geological body model must consider the following influences of three geological conditions Ref. [9, 10].

#### (1) Structural condition

In the forming process or after forming, geological bodies are often influenced by tectonic conditions such as faulting and folding, especially faulting will cause geological body dislocated in 3D space. Tectonic

conditions must be considered in building high precision model.

#### (2) Sedimentary environment

Geological bodies have various forms and physical properties, for their forming are controlled by sedimentary environment. Building 3D model of geological body should fully take the effects of sedimentary environment into consideration.

#### (3) Anisotropy in geological body

Geological body shows quite strong heterogeneity both in mineral content and physical properties such as density, porosity and permeability. During the process of building 3D model, appropriate mathematical model representing anisotropy of geological body in 3D space must be built to improve precision of the model.

Three geological conditions affect each other. Structural condition controls the form of sedimentation basin and affects the distribution form of sedimentary environment in sedimentation basin to some extent. The differences of sedimentary environment lead to strong macroscopic anisotropy in petrophysical distribution of geologic body. And within the same sedimentary environment, microscopic anisotropy is shown in petrophysical distribution. How to fully consider three geological conditions control of petrophysical distribution has become a hot study recently.

### B. Methods of 3D Geological Modeling

Present 3D geological modeling has gradually formed two modeling methods respectively based on facial model and volumetric model Ref. [8].

#### (1) Modeling Method Based on Facial Model

Modeling method based on facial model generates surface models by selecting a 3D space interpolation to interpolate 3D sampling points. Common 3D space interpolations in modeling methods based on facial model include inverse distance, minimum curvature, moving average and kriging. minimum curvature interpolation can effectively generate smooth surface model, and kriging interpolation can use mathematical model to reflect changing tendency of sample data in space. It is worth mentioning that the popular GIS platform, such as ArcGIS, MapInfo and SuperMap GIS, is an ideal 3D modeling platform not only offering 3D modeling method based on facial model but also supporting spatial topological relation building and spatial query.

This modeling method can carry texture mapping on generated surfaces, and nicely reflect external features and 3D spatial shape of geological body, but it can't reflect its internal petrophysical changes. Modeling method based on facial model is suitable for building geological surface and fault surface, and obtains a good 3D visualization effect. But this modeling method encounters insurmountable technological bottleneck in building petrophysical model.

#### (2) Modeling Method Based on Volumetric Model

Modeling method based on volumetric model uses 3D spatial grids to describe forms of geological body. Sample data of some physical property in geological body is interpolated to assign values to 3D spatial grids, thus 3D entity model reflecting this physical property is

generated. The modeling method can be further divided into determinable modeling and stochastic modeling. The understanding of geological body has been increasingly deepened, so there are uncertain factors existing in built determinable model. And stochastic modeling method can evaluate model's uncertainty. For the reasons, stochastic modeling is currently mainstream modeling method. Common 3D spatial interpolations adopted by modeling method based on volumetric model include inverse distance, moving average and kriging, sequential indicator, sequential gaussian simulation and neural net. There are many softwares support modeling method based on volumetric model, such as SolidWorks, SolidEdge, RMS, Petrel, and so on.

The modeling method can nicely reflect internal changes of geological body. Because built model is heaped up by 3D grids, the description of external features and spatial forms of geological body is relatively weakly under the control of grid splitting precision. Modeling method based on volumetric model is used to build 3D petrophysical models like porosity, permeability and oil saturation.

To fully exert respective advantage of modeling methods based on facial model and volumetric model, the article submits a workable mixed geological modeling method. The 3D geological model built by this method can accurately depict planar geological bodies, and efficiently characterize solid models including sedimentary facies and petrophysical models. This method comprehensively considers the effects of structural condition, sedimentary environment and anisotropy on petrophysical distribution.

### III. MODELING WORKFLOW

This paper presents one fundamental workflow to build 3D geological model. Basic modeling workflow is shown in Fig. 1.

Firstly, the modeling method based on facial model is used to build a structural model which can accurately depict planar geological bodies, such as geological surface and fault surface. Under the control of structure model, spatial grids are split and 3D grid model is generated to describe geological body. The model can characterize structure factor's effect on geological body.

Secondary, based on the sample data of sedimentary facies, it uses sequential indicator which is a modeling method based on volumetric model to carry out spatial interpolation. This method is a spatial interpolation aiming at discrete variables, and assigns value to every grid in 3D grid model, to build 3D solid model of sedimentary facies. The model describes spatial distribution of sedimentary facies, and reflects the influence of sedimentary environment on geological body.

Thirdly, based on the petrophysical sample data of geological body and under the control of structure model and sedimentary facies model, data conversion and analysis are performed aiming at sedimentary facies in every stratigraphic unit, and variograms are built to describe the anisotropy of geological sample data in 3D space.

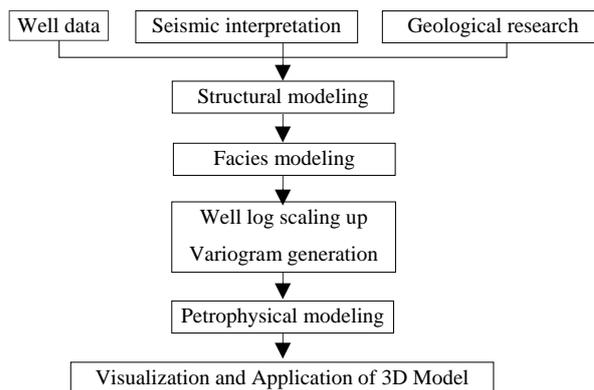


Figure 1. Workflow of 3D geological modeling

Finally, based on the petrophysical sample data, the sequential Gaussian simulation, another modeling method based on volumetric model, is used to carry on spatial interpolation. It is spatial interpolation method aiming at continuous variables to assign value to every grid in 3D grid model and generate petrophysical model of geological body. The interpolating process of sequential Gaussian simulation is controlled by the space range of structural model and sedimentary facies model, and is lead by the variogram reflecting the anisotropy of geological body Ref. [11].

In comparison with common spatial interpolation algorithms, such as inverse distance, moving average and kriging, sequential Gaussian simulation method considers fully the effects of structural condition, sedimentary environment and anisotropy on spatial distribution of petrophysical models. So the accuracy of petrophysical model is greatly increased.

### IV. EXAMPLE

Taking Shu-II district in the Liaohe oil-field for example, this paper carries out 3D geological modeling aimed at Dalinghe reservoir. The Shu-II district lies in Liaohe fault-depression. Developed target zone is Dalinghe reservoir in the third member of Shahejie stratum. Under the control of extremely complex geological conditions, reservoir characteristics are very complex. Building fine 3D geological model is of great importance for oil-field reasonable development, development well patter arrangement, reserves potential tapping.

#### A. Basic Data for Modeling

Collected data information in this project is shown as following. Fig. 2 shows the loading effect of basic data.

##### (1) Well drilling data

These include well location, well path, oil-water contact, well log and geological research data.

Well location: It mainly includes well name, X coordinate and Y coordinate of wellhead which are used to locate wellhead.

Well path: It mainly includes measure depth, azimuth, inclination and magnetic variation which are used to build 3D model of drilling well trajectory. Table I shows well path data format.

Geological research data: These results include well top, sedimentation model, map of sedimentary facies, analysis information of petrophysical property, etc. Table II shows well top data format.

(2) Seismic interpretation data

These results include seismic surfaces and fault sticks. Seismic surfaces are used as trend constraint to build geological surface. Fault sticks are used to build fault surfaces.

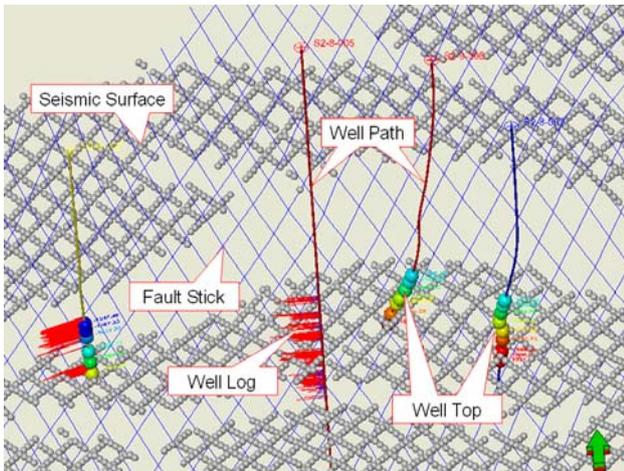


Figure 2. Loading effect of basic data for modeling

TABLE I. WELL DEVIATION DATA

WELL	Magnetic	MD	INCL	AZIM
S2-05-08	-7.72	1200	12.72	207.18
S2-05-08	-7.72	1225	12.5	209.67
S2-05-08	-7.72	1250	12.25	206.82
S2-05-08	-7.72	1275	11.98	209.05
S2-05-08	-7.72	1300	12.42	209.28
S2-05-08	-7.72	1325	12.97	213.42
S2-05-08	-7.72	1350	12.95	215.27
S2-05-08	-7.72	1375	13.88	218.78
S2-05-08	-7.72	1400	14.17	221.73

TABLE II. WELL TOP DATA

WELL	MD	TYPE	SURFACE
S2-5-11	2047.18	Horizon	dlh-top
S2-5-11	2089.22	Horizon	dlh-1-1
S2-5-11	2133.46	Horizon	dlh-1-2
S2-5-11	2194.41	Horizon	dlh-2-1
S2-5-11	2240.08	Horizon	dlh-2-2
S2-5-11	2282.92	Horizon	dlh-3-1
S2-5-11	2320.42	Horizon	dlh-3-2
S2-5-11	2353.07	Horizon	lh-1-1
S2-5-11	2384.58	Horizon	lh-1-2

B. Structural Modeling

Modeling method based on facial model is used to build structural model, which includes geological surfaces and fault surfaces, and generates 3D basic grids of geological body. Fig. 3 shows structural modeling workflows. And Fig. 4 displays structural model of geological body.

(1) Building geological surfaces

On the basis of seismic surfaces and geological layers, 3D model of four geological horizons, named Top, Y1bottom, Y2bottom and Bottom, is built by selecting Minimum Curvature interpolation.

(2) Building fault surface

On the basis of fault data from seismic interpretation and fault-point data from geological analysis, 3D model of faults is built by selecting Minimum Curvature interpolation.

(3) 3D gridding

On the basis of 3D models of geological surfaces and fault surfaces, 3D grids of geological body in the target zone are built. This model can reflect 3D entity forms of geological body.

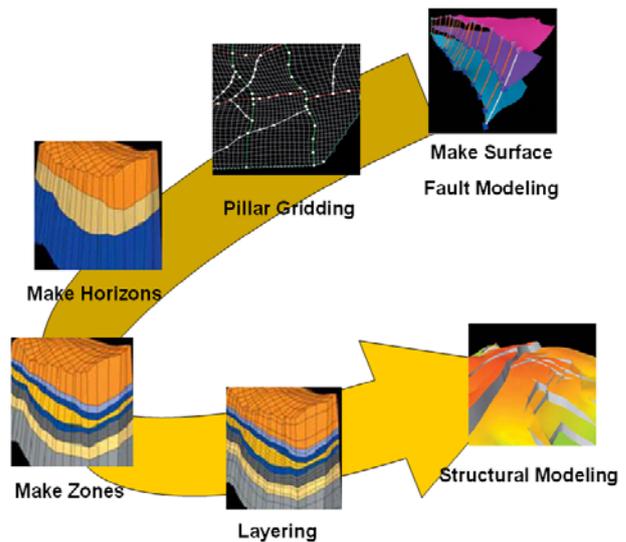


Figure 3. Structural modeling workflows(After Wu S.H., 1999)

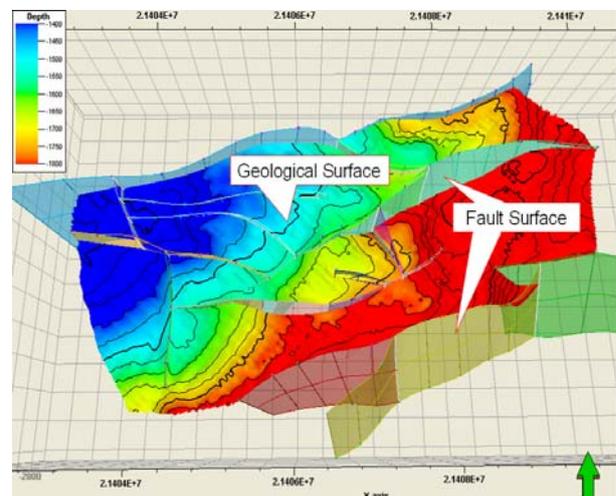


Figure 4. Structural model of geological body

C. Facies Modeling

Modeling method based on volumetric model is used to build facies model. Firstly, scaling up sedimentary facies data is assigned to 3D spatial grids crossed by well trajectories. Then assigned grids are analyzed. Sedimentary facies sampling data is a kind of discrete data. Common data analysis includes proportion, thickness and probability. Based on the data analysis, variogram representing sedimentary facies anisotropy is established. Finally, sequential indicator, one spatial interpolation method, is used to build 3D model of sedimentary facies. Fig. 5 shows the 3D model of sedimentary facies.

D. Petrophysical Modeling

Petrophysical modeling takes place in following three steps.

(1) Data analysis

3D grids crossed by well trajectories are assigned by scaling up logging curves. These assigned grids are petrophysical sample data of geological body. They are transformed and analyzed, such as Output Truncation, Input Truncation, Logarithmic transformation, Scale Shift and Normal Score Transformation, etc.

(2) Variogram generation

A typical variogram is a plot of variability in terms of semi-variance against separation distance. It is generated by finding pairs of data with similar separation distances and then calculating the degree of dissimilarity between these pairs. Fig. 6 is a diagram of typical variogram. Aiming at assigned 3D-grid sample points, variogram is built to reflect anisotropy of sample data by geostatistics method. Variogram is used to restrain interpolating of 3D spatial interpolation. Variograms in X, Y and Z direction aiming at sedimentary facies of every stratigraphic unit are built.

(3) 3D petrophysical modeling

3D petrophysical model is built by the modeling method based on volumetric model. On the basis of data analysis and variogram, the 3D spatial interpolation of sequential Gaussian simulation is selected to generate petrophysical model such as porosity, permeability, oil saturation, etc.

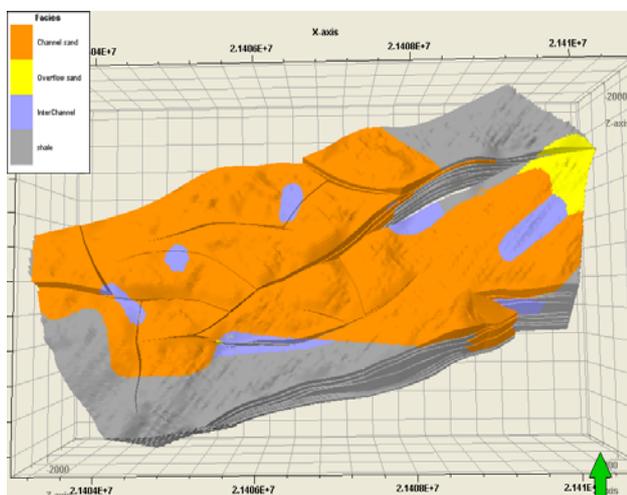


Figure 5. 3D model of sedimentary facies

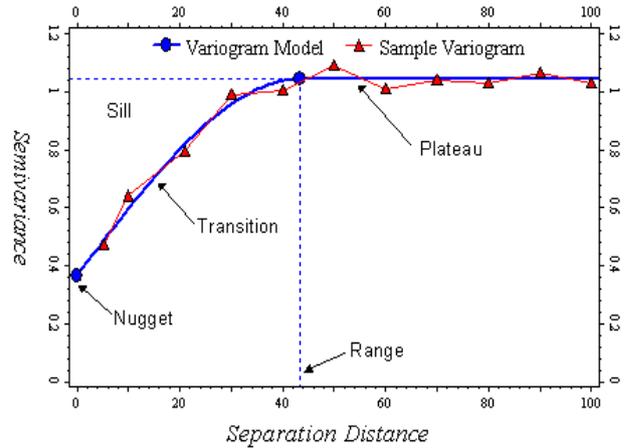


Figure 6. Diagram of variogram

E. Quality Inspection

Quality inspection must be performed to guarantee the veracity of 3D model. There are many methods for quality inspecting, e.g. 3D visualization, statistical information and histogram of model et al. Fig. 7 shows the distribution characteristics of the original data, discrete model and final model, which are used to analyze the accuracy of the model. Based on the petrophysical model, well logs can be generated inversely. The reversing generated well logs and original well logs were compared to test the model's accuracy in Fig. 8.

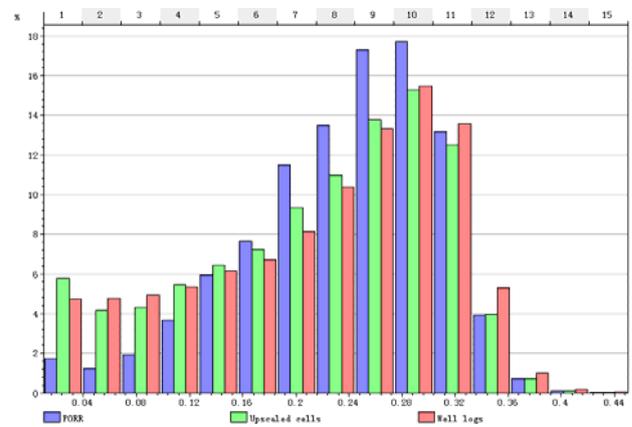


Figure 7. Column diagram of porosity in Dalinghe reservoir

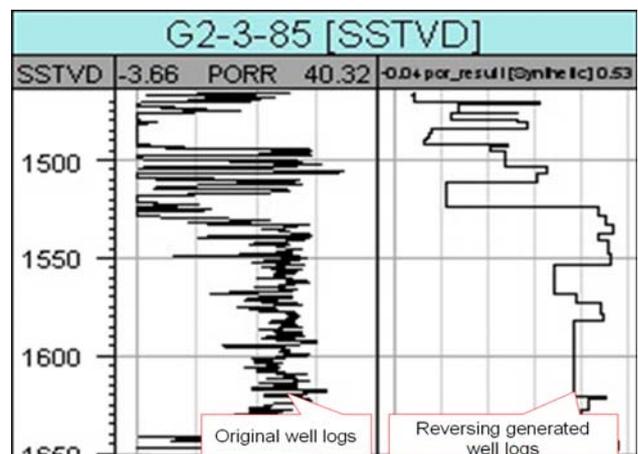


Figure 8. The contrast of original logs and generated logs of well

## V. APPLICATIONS OF MODEL

### A. Visualization of 3D Structural Model

By the visualization of 3D structural model, structure shape of geological body can be observed intuitively, and drilled formations and faults can be accurately mastered. These are shown in Fig. 9.

### B. Visualization of Petrophysical Model

For geological body is originally buried under the ground, the distributions of petrophysical parameters can not be directly perceived. By 3D visualization of petrophysical model, distribution information of petrophysical parameters in 3D space can be accurately obtained. Fig. 10 shows the 3D visualization of petrophysical model by geological section. And Fig. 11 shows the 3D visualization of petrophysical model by fence diagram.

### C. Reserves Calculation

Traditional reserves calculation method uses average effective thickness, average effective porosity and average water saturation to estimate reserves, so the effect of reservoir heterogeneity on reserves calculation is masked. Based on 3D geological body model and 3D petrophysical model, 3D volume method calculates oil-gas reserves according to grids, and will greatly improve reserves calculating precision.

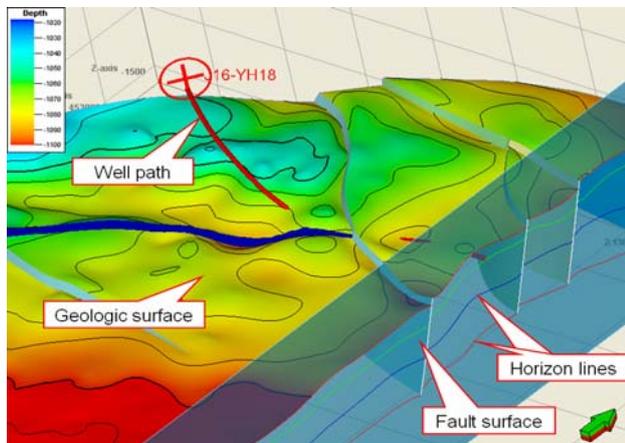


Figure 9. Structural model visualization

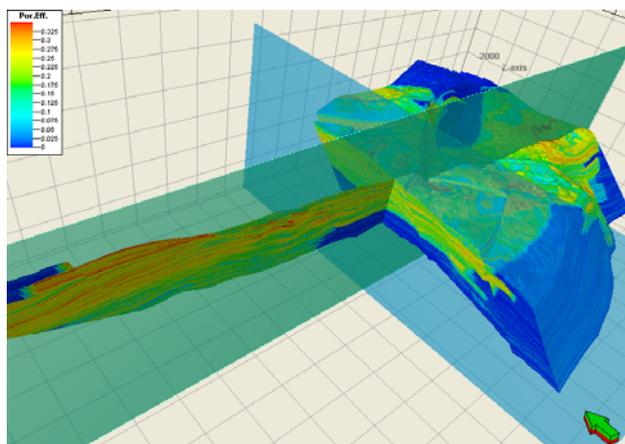


Figure 10. Visualization of geological section

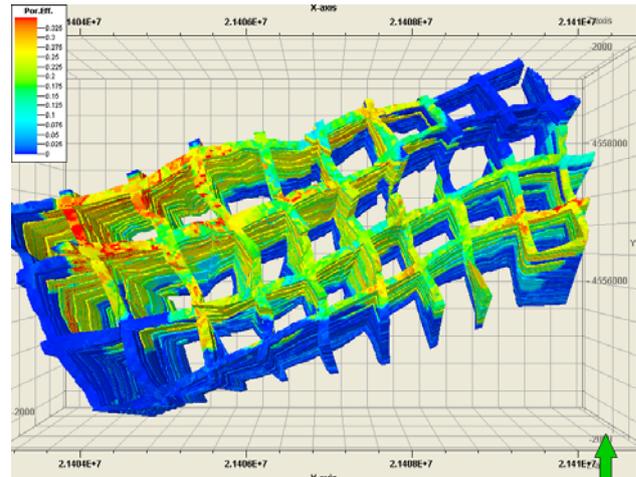


Figure 11. Fence diagram of geologic body

### D. Drilling Design

In petroleum exploration and development, drilling is a high capital investment. So drilling failing will cause tremendous economic loss to the petroleum company. In order to reduce drilling risk, it is generally necessary to carry out drilling design. Based on various data and 2D maps, traditional drilling design analyzes formation and petrophysical parameters possibly drilled to estimate well drilling risk. This method is neither accurate nor intuitional. But drilling design based on 3D geological body model is carried out in 3D visualization window. It is visual to analyze drilled formation, petrophysical parameters and oil-bearing property. The method reduces drilling risk, increases success ration and becomes an important means of helping making decision for oil-gas exploration and development.

## VI. CONCLUSION

Hydrocarbon bearing geological body is the main study object of petroleum exploration and development. Building high-precision 3D geological model can offer basic information platform for oil-gas exploration and development and realize 3D visualization of geological body, so it is very important to improve efficiency and reduce risk of oil-gas exploration and development. On the basis of 3D geological modeling method studying, this article builds 3D geological model of Dalinghe reservoir, Shu-II district, Liaohe oil-field, which includes 3D models of geological structure, sedimentary facies and petrophysical models. With the continuous development of 3D geological modeling technology, 3D geological modeling will certainly become one of core works of petroleum exploration and development, and supply strong guarantee for the scientific and reasonable development of oil and gas.

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