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3-D tectonic stress field simulation for serious heterogeneous reservoirs

Chuanhua Zhu, Weifeng Wang

China University of Petroleum, Qingdao 266580, China

Corresponding author is Chuanhua Zhu

Abstract
Turbidite reservoir with low permeability is an important reservoir type. Because of its complex structural feature and strong heterogeneity, there are some deficiencies in the three-dimensional tectonic stress field simulation. For instance, the geometry models and the structure of the reservoir do not fit well. Besides, the several mechanics parameters of the rock can't adequately reflect the reservoir heterogeneity. In this research, firstly the fine geological PETREL model is made in the way of faces-controlled modeling. It includes all the heterogeneity features of the turbidite reservoir, such as, fancies, lithology, and physical properties and so on. Then, the reverse engineering of cloud data is used to transfer the geological PETREL modeling into the mechanical ANSYS model. Thus the geological information is fully transfered into the ANSYS model. This greatly improve the accuracy of mechanical ANSYS model. Meanwhile, the rock mechanics parameters of the well is extended to the whole study area based on the three-dimensional velocity field PETREL model. This give the mechanical ANSYS model the properties of geology. What's more, the boundary conditions is determined referring to the stress of fractured well. In the end, the tectonic stress field simulation of the turbidite reservoirs with low permeability in FAN142 is carried out. According to the well measured stress, the accuracy of the simulation result is reliable and can find out the local abnormal tectonic stress caused by structural feature and heterogeneity of turbidite reservoir.
Keywords: THREE-DIMENSIONAL TECTONIC STRESS FIELD SIMULATION, TURBIDITE RESERVOIR, RESERVOIR WITH LOW PERMEABILITY, JOINT MODELING OF PETREL AND ANSYS, DONGYING DEPRESSION

1. Introduction

Low permeability reservoir can be regarded as an important reservoir type in Shengli Oilfield, the amount of the proven reserves of the low permeability in Shengli Oilfield can reach 10.10 million tons of oil, thus, the turbidite sand reservoirs with low permeability is an important part. However the turbidite sand has low permeability storage with thick layer, lithofacies, lithology, the changes of the physical properties are large, at the same time, the internal stress field distribution rule of storage layer is complex[1-3], which has seriously restricted the development of effective implementation of the advanced technology such as the «imitation of horizontal wells» and the reasonable deployment of developing well network. Studying on the low permeability reservoir structure stress field simulation method of turbid sand layer with high precision can have significant meaning for improving the development effect of low permeability reservoir, as well as the efficiency of oil field.

At present, because it is complicated to conduct 3D modeling and difficult to seek 3D rock parameters, the simulation calculation of tectonic stress field is basically carried out from the following two aspects: ①Simple two-dimensional simulation analysis[4-5]; ② In the case of 3D simulation analysis, the formation of a certain block is regarded as a homogeneous geological body to calculate the rock mechanical parameters of the reference well within the block, which are used to replace the rock mechanical parameters of the block to conduct three-dimensional simulation[6-8]. However, for the low permeability reservoir of turbid sand with complex structure and strong reservoir heterogeneity, the results calculated by using these simplified methods can not reflect the anomalies of local tectonic stress field resulting from the change in thickness of turbid sand body as well as the differences between mechanical properties of internal rock for the reservoir, while it is the key for the abnormal region to restrict the oilfield development effect of low permeability reservoir for further improvement.

2. General Situation and Technical Route of the Research Area

2.1. General Situation of the research area

Fan 142 is the key experimental development block of "Demonstration Base for Comprehensive Utilization of Low Permeability Reservoir in Shengli Oilfield", which has been developed by using the technology of "imitation of horizontal well" since 2010. The development technology of "imitation of horizontal well" needs to form an over 200 meters of long horizontal fracture through large-scale fracturing. The long fracture has high orientation requirements, and its extension direction is directly related to the development of the entire well network. However, the distribution of tectonic stress field controls the extension direction of fracturing fracture. Therefore, the detailed study of tectonic stress field directly affects the development of the research area.

Fan 142 block is located in Tang Fang Town, 15km far away from the east of Gao Qing County, whose area is 39km2, surrounded by BoXing, Zhenglizhuang, JinJia and Daluhu Oilfield. Structural location is located in the Northeast zone, namely, Jiyang, Boxing, sag of Dongying, the south slope of JinJia - Zhenglizhuang - Fanjia with nose typed structure zone. As for the objective layer sand three sub section layer, the upper part of slump turbidite sand body is the tectonic stress field simulation which can be regarded as the subject, the thickness of sand body often changes with complex structure; main body is composed of prosodic features with a thick layer, side position is sand and mud with thin interbeds in penetration and the penetration rate can reach 0.11×10-3μm2~6.01×10-3μm2, while the average of penetration rate is 1.5 x 10-3um2. Both in plane and vertical surface, it showed the feature of strong heterogeneity (Table 1).

Since 2003, Fan 142 block has entered the rolling exploration stage, with the complete coverage of the seismic data, at the same time, the logging data is complete, which has completed 8 core analysis wells, plus 27 fractured wells fracture monitoring data, which can not only provide basis for the accurate establishment of the early 3D geological model, but also can provide basis for the verification of the post simulation calculation results.

2.2. Technical route

This study focuses on the calculation of 3D rock mechanical parameters in research area by using the combination modeling technology of PETREL and ANSYS as well as the 3D interval velocity model.

Table 1. Heterogeneity parameters in the lower third sub-member of the Shahejie Formation, Fan 142

Research Area	Permeability /10-3μm2			Coefficient of Variation	Permeability Ratio	Heterogeneity Coefficient of Permeability	Average Coefficient
	Max.	Min.	Avg.				
Fan 142	4.95	0.042	0.42	2.01	117.857	11.79	0.085

According to: Luming Branch, Shengli Oilfield

Firstly, facies-controlled reservoir modeling was conducted by virtue of PETREL software, which completely contains the lithofacies, lithology, physical properties and other heterogeneity characteristics of turbidite sand body, in order to lay a foundation for carrying out the tectonic stress field simulation of turbidite sand body. Secondly, the PETREL tectonic model was converted into ANSYS geometric model through the 3D point-cloud reverse engineering, and the geologic information was completely converted into ANSYS model, which greatly improves the accuracy of ANSYS geometric model. Thirdly, based on the well-point rock mechanical parameters, the rock mechanical parameters were extended to the ANSYS 3D mechanical model of according to the PETREL 3D interval velocity field model, making the mechanical model have geological properties as well as providing protection for precise and accurate characterization of the stress state of various points within the geological body. Fourthly, the boundary condition was determined with reference to the stress state at the fracturing well point, and the numerical simulation calculation of 3D tectonic stress field was carried out. Furthermore, the simulation results were further verified and corrected repeatedly by virtue of the stress data at the well point, in order to obtain the results complying with the actual distribution of the reservoir tectonic stress field.

3. PETREL 3D Geological Modeling

Accurate tectonic model is the precondition of accurate simulation of tectonic stress field. The 3D interval velocity model is the data foundation for calculating the 3D rock mechanical parameters. The PETREL 3D geological modeling can get accurate tectonic model and 3D interval velocity model. In this study, first of all, the drilling data, logging information, seismic data and areal geological data were comprehensively used to establish the 3D tectonic model of the research area in PETREL. Then, based on the tectonic model, the sedimentary microfacies model was established combining with the division of single well sedimentary microfacies and plane sedimentary microfacies data. Finally, under the control of sedimentary microfacies, the interval velocity was calculated by using logging information, and the 3D interval velocity model was established [9-11].

3.1. Tectonic model

The 3D tectonic model is composed of level model and fault model. The level model is mainly established by two kinds of methods. One method is to fit the level by virtue of the tectonic maps obtained through directly using seismotectonics interpretation; the other method is to achieve interpolation level by virtue of the hierarchical data obtained through stratigraphic division and comparison. The levels obtained by the two methods can be adjusted by virtue of the hierarchical data of well point. The fault model is mainly established based on the plane and cross-section obtained by single well-point data and seismotectonics interpretation. In the process of constructing the model, the model should be rectified and adjusted according to the tectonic characteristics of the research area, thereby achieving the fitting of tectonic model with logging information, seismic data and geological rules.

The 3D tectonic model consists of four levels and 11 faults. As can be seen from the structural model, Fan 142 belongs to the north monoclinal structure with complex faults. The lower third sub-member has complex sand body structure and large thickness change, with a buried depth of 2460m~2890m, average thickness of strata of 285 m and sand body thickness of single well drilling of 5m~16m. Affected by near east-west direction compression, there are about 11 normal faults developed in near east-west direction, with the fault displacement of 10m~180m.

3.2. The Model of Layer Velocity

There is a good correlation between layer velocity and sedimentary facies distribution, based on the analysis of regional variable function, adopting phase control modeling method to realize the layer velocity modeling, which can make the model agree with the geological rules better.

Firstly, on the basis of analyzing regional tectonic and sedimentary characteristics, according to Fan 142 block's core, well logging and mud logging as well as analysis of test data, it can put Fan 142 block sand three sub section of sedimentary into micro phase division. After researching, it is believed that overall of Fan 142 block sand three sub section is in deep lake phases, which can be further divided into source sand body with sub phase, sliding collapse turbidity body subfacies and deep lake mud (ash) rock facies. The sub facies of the source sand body and the sliding and the collapse of the sub facies can be further divided into the main channel microfacies, the lateral margin of the channel and the micro facies of the sheet sand.

Then, according to the study of sedimentary microfacies of the acquired single well facies and plane facies sedimentary microfacies division results, adopting the deterministic modeling methods, establishing Fan 142 block sand three sub section sedimentary microfacies model. The source is located in the southwest of the studying area, in the southwest of the studying area, it belong to source sand body sub phase, which is formed by the source sand to the northeast slump with sliding collapse turbidity, the integrated sub phases is mainly located in the central and northwest of the studying area.

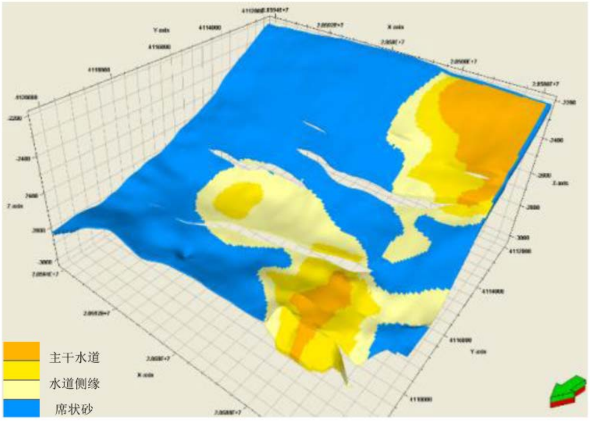

Figure 1. facies model of turbidite in the lower third sub-member of the Shahejie Formation, Fan142

Finally, on the basis of sedimentary microfacies model, it can use single well layer velocity data, adopting the facies controlled modeling method, so as to establish Fan 142 block 3D layer velocity model. The velocity of Fan 142 block sand three sub section is mainly distributed in 2700m/s-3500m/s, the average speed is about 3170m/s. Among them, the maximum speed of slump turbidites is about 3400m/s-3800m/s; the upper part of sand three sub section is composed by the lithology of mudstone, dolomite, oil shale with thin interbed and the layer velocity is much larger, which is mainly distributed in 3300m/s-3500m/s; besides the sliding collapse turbidity, the middle section of sand three sub section is mainly composed by oil shale, mudstone, tuffaceous dolomite, at the same time, the the layer velocity is smaller, which is mainly distributed in 2700m/s-3200m/s; while the lower lithologic feature of sand three sub section is mainly composed by thick mudstone and oil shale, interbedded with thin dolomite, at the same time, the interval velocity is larger, which is distributed in 3300m/s-3500m/s.

4. Rock mechanical parameters model of Fan 142

The heterogeneity of geological body is reflected in the mechanical model of ANSYS by different rock mechanical parameters. The rock mechanical parameters have quantitative conversion relationship with the interval velocity [12-20]. Based on the 3D interval velocity model, the distribution of 3D rock mechanical parameters for the research area can be gained combining with the conversion relationship between vertical and horizontal waves, dynamic and static Young's modulus as well as static and dynamic Poisson's ratio [12-19].

Due to certain differences in the conversion relationship between vertical and horizontal waves at different regions and intervals, the velocity conversion relationship between vertical and horizontal waves of Paleogene in Jiyang depression was selected according to the location, target interval and previous research results of the research area. In 2008, Ma Zhonggao fitted the velocity conversion relationship between vertical and horizontal waves of Paleogene in Jiyang depression for different lithology by using 344 samples with different intervals, lithology and sedimentary environment of the Paleogene in Jiyang depression, with correlation coefficients of over 0.95[20].

The formula for velocity conversion relationship between vertical and horizontal waves of Paleogene in Jiyang depression is as follows:

$$V_p = 1.8389V_s - 0.4574 \quad (1)$$

Where V_p is the velocity of vertical wave, in km/s; V_s is the velocity of horizontal wave, in km/s.

The formula for velocity conversion relationship between vertical and horizontal waves of Paleogene in Jiyang depression is as follows:

$$V_p = 1.6117V_s + 0.3503 \quad (2)$$

According to the elastic theory, the dynamic Poisson's ratio and elastic modulus of the rock are related to the velocity and density of vertical and horizontal waves, namely formula (3) and (4). Based on the velocity of vertical and horizontal waves calculated by formula (1) and (2), the dynamic Young's modulus and Poisson's ratio of the lower third sub-member of Fan142 can be calculated by formula (3) and (4) .

$$\mu_d = \frac{V_p{}^2 - 2V_s{}^2}{2(V_p{}^2 - V_s^2)} \quad (3)$$

$$E_d = 10^{-3}\rho V_s{}^2 \frac{3V_p{}^2 - 4V_s{}^2}{V_p{}^2 - V_s{}^2} \quad (4)$$

Where V_p–velocity of vertical wave, in m/s; V_s–velocity of horizontal wave, in m/s; ρ–rock density, in g/cm^3; μ_d–dynamic Poisson's ratio; E_d–dynamic elastic modulus, in MPa.

The conversion formula for the dynamic and static rock mechanical parameters can be obtained through regression calculation of the rock mechanical parameters based on the measured parameters of rock mechanics and conventional logging data by previous researchers:

$$\mu_s = 0.0522 + 0.5879\mu_d \quad (5)$$

$$E_s = 13684 + 0.1609E_d \quad (6)$$

Where μ_s represents the static Poisson's ratio; E_s represents the static Young's modulus.

Based on formula (5) and (6), the dynamic Young's modulus and Poisson's ratio for the lower third sub-member of the Shahejie Formation, Fan142 can be converted into the static Young's modulus and Poisson's ratio, and then the rock mechanical parameter model for the lower third sub-member of the Shahejie Formation, Fan142 can be obtained.

5. Simulation of ANSYS 3D Tectonic Stress Field

5.1. Establishment of mechanical model and determination of boundary conditions

It is the key to the accurate simulation of tectonic stress field to know how to fully convert PETREL 3D tectonic model to ANSYS mechanical model. The conversion ideas of the level model are as follows. Firstly, the point cloud data should be extracted from the level in PETREL tectonic model. Secondly, the point cloud data is fitted into ANSYS solid through the reverse engineering of 3D point cloud, in order to achieve the level conversion from PETREL tectonic model to ANSYS mechanical model. The fault model realizes direct modeling in ANSYS according to the plane shape, direction and position of fault as well as the section tendency and inclination data in PETREL 3D tectonic model; in addition, the fault thickness should be set according to the fault displacement, making the fault model in ANSYS more in line with the geology law.

Giving the complexity of the boundary conditions of the actual geological model, it is difficult to apply complex load boundary conditions for the exterior of the practical target interval model, and it is necessary to reduce the effect of the boundary conditions on the research area. Therefore, the cube with the 3D size larger than the target interval was established outside the model of the study area. ANSYS geometric model consists of three parts: 3 stratigraphic solids (the lower third sub-member is divided into three parts by the turbid sand body), 11 faults and the outer cube.

5.2. Discretization of Model and Rock Mechanics Parameter's Loading

In view of solid186 in ANSYS is a high order 3D solid structure unit with 20 nodes, which is a quadratic displacement mode, therefore, it can better simulate irregular grid model. So, both the rock area and fault section adopt solid186 unit. According to the requirements of the precision, considering the computational efficiency, the external cube discrete is the unit with larger size (less than 300m), as for the objective layer Fan142 block sand three sub section, it is the unit with small size (less than 30m), because the distribution rule of the fault section and two sets of stress field is complex [23], so it is necessary to refine the unit size of the fault section (less than 10 m), What's more, the model can be divided into 3,200,674 units, 4,385,999 nodes (Fig. 2).

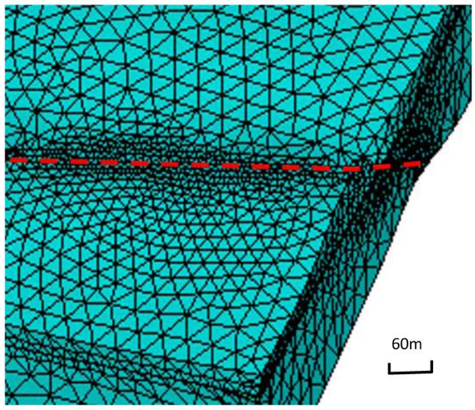

Figure 2. Discretization of the ANSYS model in the lower third sub-member of the Shahejie Formation, Fan142

After completing the discretization of the model, it can adopt the method by calculating the distance to scan (i.e. calculating the distance of mechanics parameters one by one according to the distance between a certain unit and its surrounding rock, selecting the minimum rock mechanical parameters of the distance, loading to the unit), loading 3D rock mechanical parameters to each element of the finite element analysis model in ANSYS (Fig. 3). The simulation results can calculate 19367 kinds of rock mechanics parameters, making the vertical and horizontal heterogeneity of the ANSYS model in the reservoir.

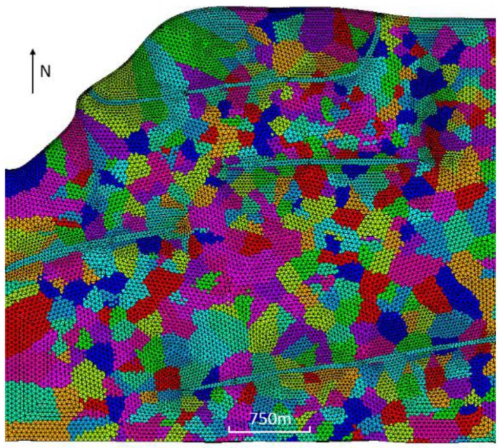

Figure 3. Distribution of turbidite rock mechanic parameters in the lower third sub-member of the Shahejie Formation, Fan142

5.3. Boundary conditions inversion and simulation results test

The internal stress distribution of turbid sand reservoir of Fan 142 is not uniform, and the stress size and direction have large change magnitude. According to the fracturing operating curves and crack monitoring reports of 22 fracturing operated wells of Fan 142, the size and direction of the maximum and minimum horizontal principal stress in the fractured section of the 22 wells can be obtained. The calculation results show that the minimum horizontal principal stress at the well point is 25.8MPa~33.8MPa, the maximum horizontal principal stress is 28.82MPa~42.71MPa, and the direction of the maximum horizontal principal stress is NE66.3°~NE92.9°. The present ground stress field of the lower third sub-member of Fan 142 should give priority to east-west extrusion, and should be constrained by the size and direction of the stress measured at the well point. After repeated trial calculation, the boundary conditions that the gradient pressure applied in the eastern border is Px=35~25MPa and the gradient extrusion load applied in the southern border is Py=45~25MPa are finally determined. The equivalent rock mass gravity load is applied according to the depth in vertical direction[24-26].

Based on the simulation calculation of finite elements, the present stress distribution characteristics of Fan 142 can be obtained, including the size and direction of maximum principal should force, intermediate principal stress, minimum principal stress and maximum shear stress, etc. The stress simulation results extracted at the well point of 11 wells are compared with the size and direction of the measured stress; the standard error of the maximum horizontal principal stress value, the minimum horizontal principal stress value and the direction of the maximum horizontal principal stress is 4.35% (Table 2), 3.26% and 5.6%, respectively.

Table 2. Comparative analysis of simulation results

Well No.	Depth/m	Measured Value/ MPa	Simulation Value/MPa	D-value/ MPa
F142-X330	-2821.07	34.46	34.61	-0.14
F142-X325	-2806.50	35.21	32.82	2.40
F142-X316	-2818.70	36.69	36.44	0.25
F142-X335	-2798.75	39.29	37.85	1.44
F142-X331	-2768.00	34.99	36.55	-1.55
F142-X304	-2817.70	31.50	34.04	-2.54
F142-X308	-2793.50	33.74	33.89	-0.15
F142-X311	-2812.50	36.15	35.03	1.13
F142-X303	-2825.00	36.63	36.96	-0.33
F142-X306	-2805.50	33.62	34.56	-0.93
F142-X330	-2821.70	34.46	34.61	-0.14

6. Result Analysis

The tectonic stress field simulation results of Fan 142 block showed that the first principal stress of Fan 142 block is vertical stress, the second principal stress is the maximum principal stress, while the third principal stress is the minimum horizontal principal stress. The maximum horizontal principal stress is gradually increased from southwest to northeast, the maximum value is 45MPa, while the minimum value is 25MPa. In the longitudinal direction, it showed the stress value is increased with the increase of depth, and the difference value of the bottom surface of the sub section is about 1MPa. In most regions of Fan 142 block, the area of which is mainly the proximal East-West horizontal squeeze, the direction of the maximum horizontal principal stress is from the southwest about NE60°to the northwest area NE75~NE85. However, part of the structural tectonic stress field is abnormal, which is influenced by the structure and mechanical parameters of rock. (Fig. 4).

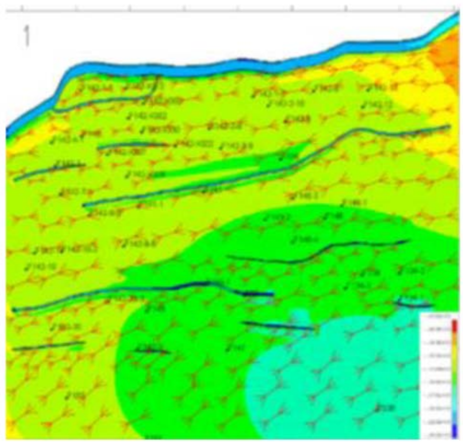

Figure 4. Distribution of maximum horizontal principal stress of the lower third sub-member of the Shahejie Formation, Fan142

The fault section and its surrounding stress value and direction is obviously affected by the fault section. The different parts of the section, scale, means of combination and trend of the fault can cause the stress field become abnormal. (Fig. 5).

The closer the distance to the fault end, the larger the size of the fault will be, the larger the difference between the fault direction and the direction of principal stress will be, and the greater the abnormal extent and scope of the stress field arsing around the fault will be. With the decrease of the distance to the fault, the maximum principal stress near the fault increases slowly at first and then decreases sharply; the stress on the fault is minimum (Fig. 6). The maximum principal stress direction of the fault is consistent to its direction; with the decrease of the distance to the fault, the maximum principal stress direction near the fault tends to the maximum principal stress direction of the fault (Fig. 7).

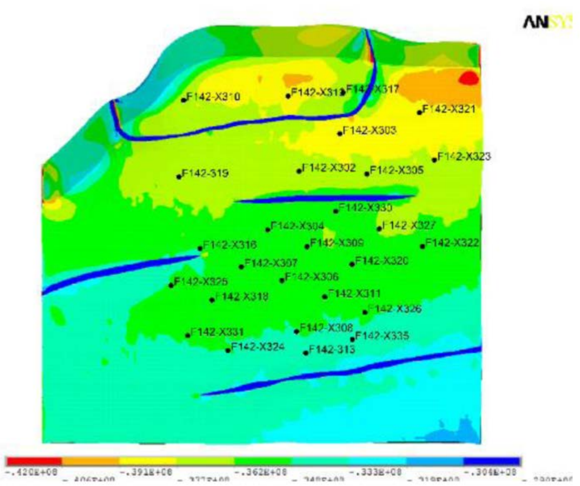

Figure 5. Distribution of maximum horizontal principal stress of the turbidite in the lower third sub-member of the Shahejie Formation, Fan142

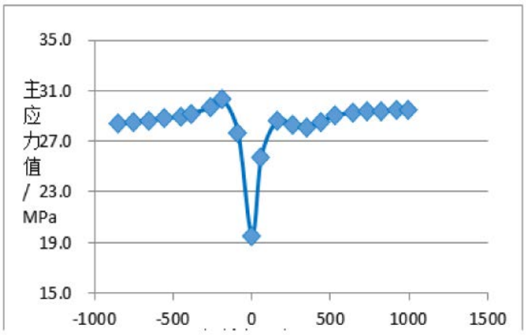

Figure 6. Distribution of maximum horizontal principal stress near the fault

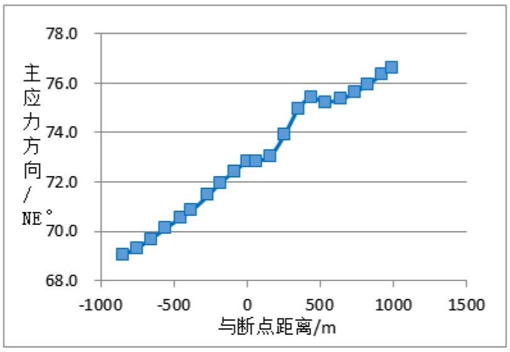

Figure 7. Distribution of the direction of maximum horizontal principal stress near the fault

The changes of the mechanical parameters of the muddy sand body are relatively large, and the boundary line of pressure gradient of the maximum principal stress value is also irregular. Under the background of regional horizontal maximum principal stress, there is high local stress, such as the area near Well F142-309 and Well F142-X302 (Fig. 5).

The 0 is the breakpoint; the negative direction is the footwall; the positive direction is the hanging wall.

The 0 is the breakpoint; the negative direction is the footwall; the positive direction is the hanging wall.

7. Conclusion

(1) The method that converts the PETREL tectonic model to the ANSYS geometric model through 3D point-cloud reverse engineering can accurately reflect the complex thickness change of the turbid sand reservoir.

(2) The method that calculates the 3D rock mechanical parameters according to the 3D interval velocity model and loads them into each unit of ANSYS finite element analysis model through using the distance scanning method can fully reflect the differences in the internal rock mechanical properties of the reservoir.

(3) The combined modeling technology of PETREL and ANSYS can fully integrate the advantages of PETREL geological modeling and ANSYS mechanical simulation, and contain all the lithofacies, lithology, physical properties and other heterogeneous features of the turbid sand body in the ANSYS mechanical model. The method provided in this paper can accurately simulate the present tectonic stress field, and show the abnormalities of local tectonic stress field caused by the effect of the tectonic form of turbid sand reservoir as well as its heterogeneity, which can provide a certain reference for the well pattern layout, hydraulic fracturing and optimized mining of oilfield development.

(4) The fault section and its surrounding stress value and direction is obviously affected by the fault section. The different parts of the section, scale, means of combination and trend of the fault can cause the stress field become abnormal; the rock mechanics parameters have significant influence on the abnormalities of local stress field.

(5) The tectonic stress field simulation results of Fan142 block sand three sub section showed that, as for the low permeability reservoir layer, which structure is complex, the changes of thickness is great, the reservoir heterogeneity turbidity is strong, the method provided in this paper can accurately simulate the current tectonic stress field, and show the structure features of the turbidite sand storage layer, as well as the abnormalities of local stress field caused by the uneven feature of the storage layer, which can provide a reference for the well pattern arrangement, hydraulic fracturing and the optimization of the mining of oil field development.

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