Investigation on Characteristics of Natural Fractures within Carbonate Formations and Mechanical Features of Related Tectonic Movement in a Block of Shunbei Oil Field

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Abstract. Investigation has been performed on natural fractures within carbonate formation in a block in Shunbei Oilfield. Classification has been done over natural fractures in the block. Patterns of distribution of natural fractures within the carbonate reservoir formation have been identified. Principal results include: 1) seismic data and sedimentation information along with history of tectonic movement have been used to analyze natural fractures. 2) It is found that natural fractures within T74-T76 carbonate reservoir formation are generated by tectonic movement of middle Caledonian I and II periods, and are mainly through fractures/faults with strike-slip characteristics. 3) 3D finite element model was built for this block with seismic data. Numerical calculations of 3D Continuum Damage Mechanics were performed. Results of numerical forward modeling has given out the 3D distribution of natural fractures which are represented by the localization band of damage variables under loading of tectonic movement of middle Caledonian period.

Keywords: Natural fracture; Middle Caledonian period; Tectonic movement; Shunbei Oil Field; Continuum Damage Mechanics; Carbonate reservoir.

1. Introduction
Shunbei oilfield is the main carbonate reservoir oilfield in the northern Tarim Basin. There are 13 fault zones in Shunbei Oilfield, and all kinds of natural fractures are well developed. Due to many geological and structural movements such as middle Caledonian, late Caledonian, Hercynian, Indosinian and Yanshanian[1,2,3,4,5], the distribution of natural fractures in various parts of the oilfield block is complex and it is difficult to predict accurately, which leads to high uncertainty risk factors in well layout, drilling and other engineering design links in Oilfield Development Engineering. In the actual drilling engineering, when the drilling meets the extremely broken stratum, the borehole wall collapses and mud leakage is serious, so the risk of drilling accident is very high. When the designed target layer is selected in the stratum with no natural fracture, the corresponding production is very low[1,2][6,7]. Therefore, it is of great significance and value for the development of carbonate reservoir in Shunbei oilfield to accurately understand and predict the distribution information of natural fractures. The task of this paper is to establish a three-dimensional geological model of the...
target block based on the seismic wave data of a target block in the north of Shunbei No.5 fault zone, and to study the distribution characteristics of natural fractures and the corresponding mechanical characteristics of structural movement in the target block, so as to provide the corresponding theoretical basis and accurate reference data for further well layout, drilling and other oilfield development engineering design.

The following section presents a three-dimensional fine geological model of a block in Shunbei Oilfield, and then a natural fracture analysis of each layer in the block. Then focus was put on the Ordovician carbonate target layer, and it gives out the characteristics of natural fracture system in the target layer. Finally, the mechanical mechanism of natural fracture formation in Ordovician carbonate formation is analyzed by using the finite element method as well as damage mechanics.

2. 3D Geological Model of a Block in Shunbei Oilfield

Fig. 1 is a three-dimensional geological model of a block in Shunbei Oilfield established in this paper based on seismic wave data and single well horizon information. There are 11 strata in the model, each layer is bounded by geological stratification interface, which are: Top-T30, T30-T33, T33-T46, T46-T50, T50-T56, T56-T60, T60-T63, T63-T70, T70-T74, T74-T76, T76-Base, totally 11 strata. T30 to T76 are the layers determined according to the end of stratum sedimentation. In this block, the Ordovician carbonate reservoir is located in T74-T76 formation, with a depth of about 7000-7600m. The dimensions of length, width and height of the block geological model in Fig. 1 are: 55km long, 26km wide and 9.98 km deep. The surface elevation is about 985m, and is nearly flat. The lowest layer, which sets as flat, is a layer added to introduce displacement constraint.

The figure on the right in Fig. 1 is the finite element mesh converted from the geological model. This finite element model is prepared for forward calculation and verification of damage mechanics of natural fractures. The lower right is the grid of T74-T76 Ordovician carbonate reservoir. The finite element model uses cubic linear elements with 127765 C3D8R three-dimensional eight nodes and 137088 nodes to discretize the target block model.

![3D Geological Model](image)

**Figure 1.** Three dimensional geological model (left) and corresponding finite element model (right) of a block in Shunbei Oilfield

3. Analysis of Natural Fracture in Each Layer in the Block

Ordovician carbonate target layer is T74-T76 formation below 7000 meters. In order to save costs, the seismic wave analysis work in the upper surface to within 3000 meters is omitted. Figure 2 is the natural fracture distribution plan of each layer from T74 to T76 based on seismic wave data interpretation. In Fig. 2, different colors represent layers with different depths of natural fractures. The natural fractures from T50 to T76 of Ordovician reservoir are divided into 5 groups according to the trend of natural fractures and the penetration degree of natural fractures in different strata:
1) The natural fractures in the upper T50\T56\T60 three layers form a system;
2) The natural fractures in the strata T60 to T63 are the second group;
3) In the third group, the natural fractures of T70 have some characteristics of upper and lower sides respectively. The rightmost fault has not yet formed north-south connection, which belongs to the area of orogenic transition;
4) The mudstone of T72 Sangtamu formation is a sealing layer with few natural fractures, which is the fourth group.
5) The natural fractures of T74-T76 stratum belong to the same natural fracture system, which is the fifth group. The natural fractures of this deep formation penetrate up and down, and the main large natural fractures / faults penetrate north and south.

![T74 natural fracture plane distribution](image1)

![T76 natural fracture plane distribution](image2)

**Figure 2.** Plane distribution of natural fractures in a block of Shunbei Oilfield obtained from seismic wave interpretation

In summary, the model contains 5 different natural fracture systems, each corresponding to a different orogeny. Most of the natural fractures are close to the vertical natural fractures, with a dip angle of 80-90 degrees. The T70 has more natural fractures / small faults on the right side of the block, which is obviously different from the natural fractures / through faults developed in the lower strata. Most of the natural fractures in T74 and below strata are connected from top to bottom, in north-south, and belong to the same natural fracture system.

4. Mechanical Mechanism Analysis of Natural Fracture Formation in Ordovician Carbonate Formation

Loads of the finite element model include: a) Gravity load, including the gravity load of T70-T80 and other strata; b) Surface force load at the top: 50MPa, simulate the possible overburden pressure, and play a role of stabilizing the convergence effect of calculation in numerical calculation.

This calculation uses the 'initial strain method' to simulate the squeezing load of the orogenic structure movement. The initial strain method is to apply an initial strain tensor $\varepsilon$ on each Gauss integral point of each element of the finite element model, so as to impose the strain load on each point in the formation. The advantage of this method is that it avoids the serious breakage near the loading point caused by the boundary loading method, and the distribution of damage field is reasonable. Its advantage is to avoid the phenomenon of severe crushing near the loading point generated by the boundary loading method, and the resulting damage field distribution is more reasonable.

The orogeny from the middle I to the middle II of Caledonian is derived from the compression of the basin margin in the northeast direction. The exact direction and angle of extrusion and the magnitude of extrusion displacement are not clearly recorded, so the method of phenomenon simulation is needed. According to the degree of coincidence between the distribution of natural fractures in the numerical results and the actual known distribution of natural fractures, the compression load parameters are determined by inversion. In this calculation, in order to determine the direction of the principal stress / strain in the orogenic extrusion, the series of five different values for the direction angle $\alpha$ of the local principal direction 2 of the strain of the initial strain method are given as: (a)$\alpha=30^\circ$; (b)$\alpha=15^\circ$; (c)$\alpha=0^\circ$; (d)$\alpha=-15^\circ$; (e)$\alpha=-30^\circ$.

The value of the initial strain applied in the local principal direction ($\alpha = 15^\circ$) is a series of different values between 0 and 0.5. The numerical results show that when the initial strain value is $\varepsilon_{22}=0.024$, which is 2.4%, the numerical solution of the damage mechanics of the natural fracture distribution is best consistent with the known natural fracture distribution. The initial strain component applied in
other directions is zero.

Figure 3. Plane view of damage field numerical solution cloud diagram when $\alpha=15^\circ$

Fig.3 shows the plane view of the numerical solution cloud of damage field distribution when the initial strain loading azimuth angle $\alpha=15^\circ$. The left figure here is the plane diagram of T74 formation damage variable distribution field. The maximum value of damage variable(SDEG) is 0.2566, that is, the degree of fragmentation is 25.66%. On the right is the damage variable distribution of T76 formation. It can be seen from Figure 6 that the damage variable value on T76 layer is slightly larger than that on T74 layer. The damage localization zone in Fig.3 represents the distribution of natural fractures in the stratum under the action of tectonic movement. The larger the value of the damage variable means the higher the degree of natural fracture.

By comparing the damage mechanics numerical solution of natural fracture distribution in Fig.3 with that of natural fracture distribution in T74 and T76 layers in Fig.2, it can be concluded that the numerical solution and seismic wave analysis solution are very close: the direction is the same, and the details are different.

Therefore, according to the natural fracture distribution results of the numerical solution, it can be concluded that the mechanical characteristics of the structural movement of the carbonate Ordovician T74-T76 formation are:
1) Tectonic movement is squeezing load;
2) The azimuth of the extrusion load is 15 degrees;
3) The strain corresponding to the magnitude of the extrusion load is 2.4%;

5. Conclusion

Natural fractures of carbonate reservoirs in a target block of Shunbei Oilfield was investigated by forward modeling, and the distribution law of natural fractures in the target block was presented. On this basis, combined with damage mechanics and finite element numerical simulation technology, the displacement direction and strain size of orogeny corresponding to natural fracture generation are determined, which provides theoretical basis for further oilfield development engineering design. The main results include: 1) According to the structural information of seismic wave strata, combined with the history of sedimentation and orogeny, the natural fractures of the existing strata are analyzed, including the natural fractures/faults of 7 layers from T50 to T76, which are classified into 5 groups of natural fracture systems. 2) the natural fractures in the Ordovician reservoirs from T74 to T76 belong to the same fracture system, corresponding to the tectonic movement of Caledonian I and Caledonian phase II, which are strike slip fractures/faults. 3) According to the geological structure of the block obtained from the seismic wave data, a three-dimensional finite element model of the block is established, and the three-dimensional damage mechanics finite element numerical analysis is carried out. The forward numerical calculation results of the natural fracture / fault distribution in the block under the action of the middle Caledonian orogeny are given. The numerical results show that the mechanical characteristics of orogeny are as follows: (1) The main direction angle of the formation is 15 degrees; (2) The degree of formation compression is equivalent to 2.4% of initial strain.

The numerical results indicate that: the damage mechanics model proposed here can simulate the three dimensional spatial distribution of natural fractures caused by tectonic movement, including the azimuth, width, degree of fracture, and extent of fracture. The forward modeling of damage mechanics is especially useful for the blocks which are difficult to identify by means of conventional seismic
wave when the natural fracture / fault discrepancy is small.

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