Effect of fault zone and natural fracture on hydraulic fracture propagation in deep carbonate reservoirs

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Abstract. The Shunbei oil and gas field is located in the low uplift of Shuntuoguole, which is affected by the multistage tectonic movement of the basin. There are several strike-slip fault systems that have developed from north to south, and the geological characteristics of the reservoir are controlled by different combination of fault zones. A large cavernous fracture system is developed in the main fault zone. The stress inversion calculation and analysis methods are established for various types of faults. The three-dimensional stress field distribution in the study area was obtained through numerical simulation. The magnitude and direction of the stress field were analyzed at different depths and locations in different types of faults, including at the tip, in the middle, adjacent to the fault, and in the intersection to determine the magnitude and spatial distribution behavior of the stress field in the multi-fault area around the well. On the basis of the stress field simulation, the distribution of some natural fractures is preliminarily explained according to the statistical fracture distribution behavior, and a hydraulic fracturing process simulation is performed to reveal the distribution and influence range generated by hydraulic fracturing, which provides guidance for subsequent hydraulic fracturing scheme designs.

1. Introduction
Deep carbonate reservoirs contain abundant oil and gas resources. Sixty percent of the world’s proven oil and gas reserves are marine carbonate reservoirs, which have become an important field of oil and gas exploration and development. Shunbei Oilfield is located in the Tarim Basin, with an average depth of more than 7500 m. It is an ultra-deep fault-fracture carbonate reservoir controlled by main faults and formed by multistage karst transformation. How the existing fault zone disturbs the present in situ stress field and how the disturbed stress field and the natural fractures near the fault affect the extension direction and range of hydraulic fractures need to be further clarified to better stimulate the complex fault zone reservoir\textsuperscript{[1-4]}.
According to the seismic data of the fault zone and the spatial distribution characteristics of the geological faults, a three-dimensional distribution model of fractures in the study area is established. The strike of faults in the study area are mainly NNW and NEE. The eastern part of the Fig. 1 is the main part of the fault zone, which comprises eight small faults from south to north. The eastern region is the main fault zone, which comprises eight small faults from south to north (Fig. 1). The main part of the fault zone is a strike-slip extensional segment, and the eastern fault zone is compressed and uplifted locally, forming a flower-like structure. There are 11 small vertical faults in the southwest. First, the stress field in the fault zone is simulated throughout the whole region, and then the stress field is refined around a single well.

2. In situ stress characteristics with faults
Four approximately parallel NW-SE trending faults are developed near well X5. From left to right, the first and fourth faults extend more than 10 km to form the main Y-shaped fault body, the upper part of which is nearly vertical and the bottom of which is inclined. There are two small faults in the middle, extending 2–3 km, which are almost vertical. Taking into account the location of the well, part of the fault area was selected for calculation. The east–west direction of this model is 2.0 km, and the north–south direction is 2.4 km. After establishing the geological model, it is divided into 100 × 120 × 20 grids, in which the length and width of a single grid are both 20 m (Fig. 2). According to the fracture distribution behavior obtained from Formation Micro-Scanner Image (FMI), two groups of fracture spatial distributions were established.

Fig. 1. Fault distribution characteristics in the study area

According to the on field geological observations and seismic data, the faults in the vicinity of Well X5 are tensile normal faults in the Yingshan Formation with the vertical stress is the maximum stress,

Fig. 2. Fault assemblage and mesh model near well X5

According to the on field geological observations and seismic data, the faults in the vicinity of Well X5 are tensile normal faults in the Yingshan Formation with the vertical stress is the maximum stress,
vertical stress $> \text{maximum horizontal principal stress} > \text{minimum horizontal principal stress}$. On this basis, the stress field simulation calculation is carried out to reveal the influences of the faults on the distribution of the stress field\cite{5-8}.

![Fig. 3. Distribution characteristics of maximum principal stress near well X5.](image)

In the bedrock block, the main distribution range of the maximum horizontal principal stress is 160–185 MPa, with an average of 175 MPa (Fig. 3). The minimum stress in the center of the fault is 140 MPa, and the maximum stress on both sides is 200 MPa. The stress difference near the fault is up to 40 MPa. The direction of the maximum principal stress in the bedrock is NE52°. Near the fault, the direction of the principal stress deflects. On both sides of the main fault, the stress direction is perpendicular to the fault. At the end of the fault, the deflection direction of the principal stress is large, turning to NW350° in some areas, and the deflection angle is about 60°. According to the simulation results, the faults have a great influence on the stress field, and the influence range is two to three times the width of the fault.

![Fig. 4. Distribution characteristics of minimum principal stress near well X5](image)
The minimum principal stress in the bedrock is 130–160 MPa and the stress direction is NW328° (Fig. 4). The fault zone is a low stress area with a distribution range of 110–120 MPa. On both sides of the faults, at the end of the faults, and at the intersection of the faults, there are high stress concentration areas with a distribution range of 150–170 MPa. The minimum principal stress azimuth deflection is about 20–30°.

3. Design of rock support pattern distribution

Fig. 5 shows the initial fracture distributions around well X5. There are two groups of fractures developed in the area with directions of NE (red in Fig. 5) and NW (blue in Fig. 5), and the strike of the fractures is basically consistent with the fault strikes. The average length of the natural fractures is 80 m, and a single fracture extends 20–30 m vertically. The average fracture opening was set at 0.1 cm, the tangential stiffness was 1 MPa/mm, and the normal stiffness was 25 MPa/mm. Well X5 is located within an extensional fault zone in the Yingshan Formation, 300–400 m to the left of the main fault and about 80 m to the right of the feathered fault. The well is directly connected to the fracture.
On the basis of the stress field simulation, the hydraulic fracturing process is simulated [9-13]. During the simulation, the total fluid volume is 1600 m$^3$ and the fracturing fluid viscosity is 15 mPa·s. The pumping rate varies, as 6 m$^3$/min, 8 m$^3$/min, 10 m$^3$/min, and 12 m$^3$/min, and every 20 min the morphology of the generated hydraulic fractures is analyzed. Fig. 6 show the simulation calculation results with 6 m$^3$/min pumping rates. According to the simulation results, the generated fracture morphology parameters were statistically analyzed, and the results are shown in Table 1.

**Table 1.** Fracture parameters and stimulation volume generated by different pumping rates of the X5 well.

| Pump rate (m$^3$/min) | Hydraulic fracture length (m) | Hydraulic fracture height (m) | Hydraulic fracture strike ($^\circ$) | Communicating natural fractures (branches) | Communicating natural fracture length (m) | Natural fracture strike ($^\circ$) | Stimulation volume (m$^3$) |
|----------------------|-------------------------------|------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|---------------------------------|--------------------------|
| 6                    | 47.07                         | 35                           | 57.8                               | 6                                 | 271.3                             | 38.5                            | 598362                   |
| 8                    | 47.24                         | 37.5                         | 57.8                               | 6                                 | 175.7                             | 42.3                            | 618029                   |
| 10                   | 47.75                         | 37.5                         | 57.8                               | 6                                 | 175.7                             | 42.3                            | 647348                   |
| 12                   | 50.07                         | 37.5                         | 57.8                               | 6                                 | 175.7                             | 42.3                            | 715550                   |
As can be seen from the simulation results, the faults in the Well X5 area are tensile, and the stress differences near the faults are relatively small. Therefore, the fractures generated during hydraulic fracturing are different from the fracture propagation process with conventional uniform stress condition, which is specifically described as follows:

1) Well X5 is located in an area of high relative stress, and the horizontal stress difference is low the distance from the fault exceeds 50 m. The stress difference on the left side is even smaller. Therefore, during the hydraulic fracturing process, the natural fractures on the left side communicates with the main fracture first, and then the natural fractures farther away are opened to reach the artificial fracture’s end. As the injection volume continues to increase, the injection pressure exceeds the fracture pressure and the main fracture continues to expand to both sides and below, so that the lower fracture is opened.

2) The height of the main fracture generated is 76 m, and the length of the extended hydraulic fracture is between 47 m and 50 m. The stimulation volume between the main fracture and the reopened natural fractures ranges from 598,362 m$^3$ to 715,550 m$^3$. This shows that when natural fractures are fully connected, the stimulation volume increases.

4. Conclusion
(1) Overall, stress concentration increases near the compression faults. In the center part of the fault zone, rock breakage leads to the lowest stress value, then stress increases to the two sides, resulting in stress concentration, and then it slowly decreases and gradually transitions to normal stress. The influence range of the fault is about 0.5 times the width of the fault zone, and stress concentration easily occurs at both ends of the fault.
(2) Well X5 is connected to the natural fracture. During the fracturing process, a short main fracture parallel to the maximum horizontal principal stress is generated, and it continues to extend to communicate with the original natural fractures in the same layer. Finally, with the action of gravity, it connects to the natural fractures below.
(3) When the pumping rate increases, the total fluid quantity is kept constant and the hydraulic fracture expands faster; the extension communication range increases and the pumping time decreases, resulting in decreased fracture length.

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