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Numerical study of multi-period palaeotectonic stress fields in Lower Cambrian shale reservoirs and the prediction of fractures distribution: A case study of the Niutitang Formation in Feng'gang No. 3 block, South China

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Abstract: Fractures not only control the distribution of oil and gas reservoirs, but also are key points in the research of oil and gas reservoir development programmes. The tectonic fractures in the Lower Cambrian shale reservoirs in the Feng'gang No. 3 block are effective reservoir spaces for hydrocarbon accumulation, and these fractures are controlled by palaeotectonic stress fields. Therefore, quantitatively predicting the development and distribution of tectonic fractures in the Lower Cambrian shale reservoir is important for the exploration and exploitation of shale gas in the Feng'gang No. 3 block. In the present study, a reasonable geological, mechanical and mathematical model of the study area was established based on the faults systems interpreted from seismic data, fracture characteristics from drilling data, uniaxial and triaxial compression tests and experiments on the acoustic emissions (AE) of rocks. Then, a three-dimensional (3-D) finite element method is applied to simulate the palaeotectonic stress field with the superposition of the Yanshan and Himalayan movements and used to predict the fracture distribution. The simulation results indicate that the maximum principal stress value within the study area ranged from 269.97 MPa to 281.18 MPa, the minimum principal stress ranged from 58.29 MPa to 79.64 MPa, and the shear stress value ranged from 91.05 MPa to 106.21 MPa. The palaeotectonic stress field is controlled by the fault zone locations. The fracture development zones are mainly controlled by the tectonic stress fields and are located around the faults, at the end of the fault zones, at the inflection point and at the intersection of the fault zones.

Keywords: Tectonic fractures; Niutitang Formation shale; numerical simulation; fracture distribution; palaeotectonic stress field

1. Introduction

As the production of oil and gas from conventional resources has decreased in recent years, shale gas has become a new interest for global oil and gas exploration and development. Shale gas is an unconventional natural gas resource; with its large reserves, higher virgin shale content, long production cycle and other advantages, it has attracted the attention of many countries. Shale gas is one of the most realistic alternative resources of conventional oil and gas and has an important strategic position (Pollastro, 2007; Jarvie et al., 2007; Ding et al., 2013; Melikoglu, 2014; Pireh et al., 2015). Currently, many countries have undertaken the exploration, development and production of shale gas. China's shale gas resources are thought to be plentiful. Various studies of sedimentary basins and shale formations in China have been conducted to identify potentially productive sites for shale gas exploration. Recently, the Anye-1 well in the area north of the Guizhou Province was shown to have a high shale gas content. This discovery was a major breakthrough for shale gas exploration, as it was the first time shale gas was found outside the Sichuan Basin in the complex geological structure area of South China (Guo et al., 2015; Teng, 2016).

Compared with other oil and gas reservoirs, shale reservoirs have extremely low permeabilities; therefore, fractures play an important role in the exploration and exploitation of shale reservoirs (Li et al., 2013; Rasouli and Sutherland, 2014; Wu et al., 2016). The degree of fracture development directly affects the accumulation and output of shale gas, improves the seepage ability of shale, and helps increase the total gas content of the shale. (Nelson, 2001; Curtis, 2002; Ghosh and Mitra, 2009; Lemonnier and Bourbiaux, 2010; Wang et al., 2015; Ding et al., 2015; Yang et al., 2016). Therefore, accurate and quantitative methods to predict fracture

distributions in shale reservoirs can significantly improve the efficiency of the exploration and exploitation of oil and gas resources. Tectonic fractures are the most significant type of fractures in shale, and these fractures are generally controlled by palaeotectonic stress fields (Lemonnier and Bourbiaux, 2010; Zeng et al., 2010; Meng and Xian, 2013; Ding et al., 2015). Numerical simulation of palaeotectonic stress fields is a valid method for predicting shale reservoir fracture distributions. In recent years, scholars have performed extensive research on such simulations using the finite element method (FEM), and the numerical computation results have been compared using the Griffith rupture criterion and the Mohr-Coulomb criterion (Jiu et al., 2013; Zeng et al., 2013; Ju et al., 2013; Ju and Sun, 2016; Guo et al., 2016). However, tectonic stress fields have simulated only a single stage of a tectonic stress field without considering the superimposed effect of multi-period tectonic stress fields. Reservoir fractures form in multi-period tectonic stress fields; therefore, a numerical simulation predicting the fracture distribution that considers different periods with tectonic stress field superposition can make the results more realistic. In addition, tectonic stress fields have been simulated in only a two-dimensional (2-D) plane, whereas a three-dimensional (3-D) tectonic stress field numerical simulation can avoid a structure model that is too simple, which is a problem in 2-D analyses. The boundary conditions can be applied more in line with the actual situation in order to better account for the interaction between the different layers (Camac and Hunt, 2009; Ding et al., 2012; Jiu et al., 2013; Zeng et al., 2013).

This study analysed the tectonic evolution in the Feng'gang No. 3 shale gas block of Guizhou Province, Southern China, and a 3-D multi-stage palaeotectonic stress field was simulated utilizing the FEM, based on the tectonic evolutionary characteristics, acoustic emission

experiments and rock mechanical tests. The distribution and development zones of tectonic fractures were quantitatively forecasted based on rock failure criteria. These fracture distribution predictions can provide an important methodology, and simulation results provide a significant reference value for the design of horizontal shale gas wells and a fracturing reform programme in Southern China (Tonglou and Zhang, 2014; Wang et al., 2016; Li et al., 2016).

2. Geological and structural setting

The research area of the Feng'gang No. 3 block is located in Meitan and Feng'gang, north of the Guizhou Province (Fig. 1), and covers an area of 1167 km². The study area in the division of the regional tectonic units belongs to the Yangtze Plate, North Guizhou Plateau uplift, Feng'gang NNE tectonic deformation zone. The folds and faults in this area are well developed and widely distributed. The main structural trend is NNE, NE and NS, and the geologic construction conditions are complicated. The tectonic movements of the Yanshan and Himalayan orogenies have a vital influence on the study area. The Yanshan movement, as the strongest tectonic movement, has established the present tectonic pattern, followed by the Himalayan movement. The structural features formed during the Yanshan movement were reformed by the Himalayan movement. The superposition of multiple tectonic movements caused the complex structural form of the Yangtze platform. According to the research results from tectonic evolution history and sedimentary system distribution characteristics in the study area, the northwest and southeast extrusion was the strongest compressive tectonic stress field under the Yanshan movement during the Mesozoic stage in Guizhou Province, China, and it originated from the interaction between the Pacific and the Asian plates.

The strong subduction of the Pacific plate to the Asian plate during the Yanshan movement

formed a series of NNE fold and fracture zones north of the Guizhou Province. The fracture properties are mainly based on the compression torsion, and the main formation period of the fault was in the Yanshan movement period. During the Yanshan movement period, the NW-SE extrusion stress acted strongly north of the Guizhou Province and formed the interphase anticline and syncline "slot - block" type tectonic framework. The Himalayan movement had a profound influence on the Guizhou geological structure and geological evolution. The period of tectonic deformation related to the earlier structure has obvious inheritance superposition relationships, prompting the Yanshan fold belt to enhance the deformation. During the Himalayan period, the directions of the axial portion of the fold and thrust faults were mostly NE and NNE, and the torsion fault was in mainly in the NEE direction. The mode of regional crustal stress was assumed to be approximately E-W in the direction of the extrusion.

The main strata developed in the research area are illustrated in Fig. 2. Niutitang shale in the Lower Cambrian is one of the most important shales for exploration and development. The shale thickness distribution is stable and varies from 80 to 110 m in the research area, which is mainly composed of siliceous shale and grey-to-black shale with high TOC contents that range from 3.54 wt% to 8.12 wt%, with an average TOC content of 7.24 wt%. The brittleness index is within the range of 19.14-51.87.

3. The significance of the principle of superposition in the analysis of geological structures

The structure of an oil and gas field is not a simple structure and is often a complex product of multi-stage tectonic movements. Two or more different directions or different ways of the tectonic stress field are experienced in the same area; this phenomenon is called structural

compounding superposition. Structural compounding is when two or more types of tectonic stresses occur in the same area in different period of time. The early formation of these structures has a limited role in the later structures; while late structural formation may use the early structures, the early structures may be transformed by the later constructs. For structural compounding, it is necessary to assume that the study of rock strata is uniformly continuous and isotropic.

According to the superposition principle of the elastic theory, geometric effects can be superimposed on the two strain fields or the displacement fields in the same area at the same time or successively (Timoshenko and Goodier, 1951). Structural compounding makes the mechanical properties of an oil and gas field complex in order to control the migration and accumulation of oil and gas. Tectonic superimposition not only directly controls the regional fractures distribution but also increases the fractures of the local structure system, improving the reservoir conditions (Yue and Du, 1987; Huang et al., 1996).

4. Method simulation and fracture distribution prediction for 3-D palaeotectonic stress fields

4.1. 3-D palaeotectonic stress field simulation

The tectonic stress field is a ground stress field generated by tectonic movement, and it is divided into the palaeotectonic and present tectonic stress fields over time. The palaeotectonic stress field is the tectonic stress field in the geological history period, and the present tectonic stress field is the tectonic stress field that is currently active. The palaeotectonic stress field is an important factor for controlling the development of tectonic fractures and for influencing the formation of fractured reservoirs. Simulation of palaeotectonic stress field inversion can predict

the favourable zone of fracture type, reservoir development and distribution. In this study, the finite element method and ABAQUS software were employed to simulate a 3-D tectonic stress field within the Feng'gang No. 3 block.

Numerical simulation of tectonic fractures prediction is not a single mathematical model or mechanical or geological problem but an integrated system of mutual penetration and mutual association. The entire process of numerical simulation includes the need to address the relationship between the following models: (1) the establishment of a geological structure model, (2) the establishment of a mechanical model, (3) the establishment of a mathematical model, (4) the determination of inversion criteria, and (5) the simulation of a palaeotectonic stress field.

4.1.1. Establishment of a geological structure model

The geological structure model is the foundation of the numerical simulation, and it directly determines both the mechanical model and the mathematical model. The geological structure model of the study area is proposed on the basis of a comprehensive study of geological law; tectonic evolution; and the distribution characteristics and genesis of the fractures, as well as seismic, well logging and drilling data. The target stratum, together with the basement and upper cover layers, was considered as a rock body of isolation for the simulation object. To eliminate the influence of the boundary effect on the calculation results, the geological isolation is generally larger than the actual research area. The study area surrounded the major structures and faults of the Feng'gang No. 3 block (Fig. 1a). The geological structure model of the study area was divided into the following unit types: the basement, the target strata, the cap rock, the overburden and the faults (Fig. 3). The Yanshan movement period was an important time period for fracture formation in the Early Paleozoic Cambrian shale reservoir. In addition, the fractures formed in the Yanshan

period were superimposed and were constructed in the Himalayan movement. Thus, we analysed the tectonic stress field of the Yanshan and the Himalayan periods.

4.1.2. Establishment of a mechanical model

A mechanical model is key to the implementation of the numerical simulation and should be established on the basis of a geological model. The mechanical model needs to identify the model with different material properties after establishing a geological structure model and must characterize the material properties of the geological model through the constitutive equation.

The establishment of a mechanical model includes the following procedures: (1) determining the loading methods and constraint type of the geological bodies and (2) determining the physical and mechanical parameters of the rock for the different layers and faults.

(1) Determining the loading methods and constraint type of the geological bodies

In general, from the macroscopic effect, the geological body was considered to be similar homogeneous blocks or slices of rock bodies. Consequently, the geological body was treated with an elastic model (Jiu et al., 2013). The constraint conditions of the model involved displacement constraint conditions and stress constraint conditions. The loads of the stress constraint conditions involved vertical gravity and horizontal tectonic forces. The vertical gravity of the geological body is considered in the model. The tectonic force on the boundary of the study area was assumed to have a definite value, and the horizontal tectonic forces are evenly distributed on the boundary of the model (Guo et al., 2016).

Although the determination of the palaeotectonic stress values is more difficult, rock acoustic emission experiments have provided an effective method to determine the tectonic stress value (Ding and Shao, 2001; Guo et al., 2016; Ju and Sun, 2016). The acoustic emission method

can be used to measure the maximum effective palaeostresses that have been experienced by the tested strata of the main tectonic movement periods. In particular, the test equipment included a United States Flex Test MTS815 GT servo rock mechanics test system and a United States Physical Acoustics production of PCI-2 PAC 12 channel sound emission testing instrument. The experimental samples were obtained from the FC-1 well. Nine standard 25 mm × 50 mm cylindrical samples were acquired by drilling in the core column. The drilling sample directions were along the X direction, Y direction, and XY 45° direction, and 3 samples were taken for every direction. The maximum palaeostress of the examined strata is shown in Fig. 4. The study focused on measuring the maximum principal stress σ_1 of Niutitang shale from the FC-1 well during the tectonic movements during the different periods (Table 1).

The most intense tectonic movement was the Yanshan movement during the Mesozoic era, which was also the main time for the formation of tectonic fractures, followed by the Himalayan movement during the Cenozoic era in the study area. Therefore, it is reasonable to believe that the maximum principal stress magnitude was 162.93 MPa during the Yanshan movement and 112.02 MPa during the Himalayan movement. During the Yanshan movement period, the research area was subjected to a NW-SE compressive stress field, and the displacement constraint conditions of the geological structure model were as follows: the Z axis was the depth, vertical downward was negative, and the X and Y axes were directed to the SE and NE, respectively. The displacement of the Z direction is constrained at the bottom of the model, and the horizontal direction can be moved. A maximum principal stress of 162.93 MPa was applied to the upper left and lower right boundaries. We believe that the maximum principal stress/minimum principal stress is 2.1 in the shallow crust, which is less than 4 km (Zeng et al., 2013; Ju and Sun, 2016; Guo et al., 2016).

Hence, the minimum principal stress calculated by the 77.59 MPa is loaded into the lower left and upper right boundaries. Furthermore, because the top region of model was a free surface, gravity was applied to the entire model (Fig. 5a).

The Himalayan movement had a profound impact on the geological structure and evolution in the study area. Himalayan tectonic deformation, related to the earlier structure, has an obvious inheritance superimposition relationship. The Himalayan movement enabled the Yanshan fold with an inheritance of deformation strengthening. During the Himalayan period, the study area as a whole experienced a compressional stress field in the east-west direction. The following displacement boundary conditions for the geological model were established in the tectonic stress field simulation of the Himalayan period: the Z axis was the depth; vertical downward was negative; the X-axis pointed to the east; and the Y-axis pointed to the north. Displacement in the Z direction is constrained at the bottom of the model, and the horizontal direction can be moved. The maximum principal stress of 112.02 MPa was loaded to the west and east directions, and the minimum principal stress calculated by the 53.34 MPa was loaded into the north and south boundaries. Moreover, because the top part of model was a free surface, gravity was applied to the entire model (Fig. 5b).

(2) Determining the physical and mechanical parameters of the rock for the different layers and faults

The mechanical properties of the rock directly affect the deformation behaviour of the rock, influencing the formation and development of cracks. Therefore, uniaxial and triaxial rock mechanical tests can be performed for the numerical simulation of the palaeostress field. The geological structure model of the research area mainly included the basement, the target strata, the

cap rock, the overburden and the faults. The average mechanical parameters of the rock in Feng'gang No. 3 block used in the simulation were determined by rock mechanical tests (Table 2).

According to the mechanicals measurement data of the rock from different lithologies in the study area (Table 2), the elastic modulus, Poisson's ratio, and the rock density, among others, were chosen as the main simulation parameters. The mechanical experiments on the rock were performed at Central South University. In this study, a total of 22 standard 25 mm × 50 mm cylindrical samples from the drill cores of the Niutitang Formation were used to determine the mechanical parameters of the rock. The elastic modulus and Poisson's ratio were obtained using uniaxial compressive experiments, the internal friction angle and the cohesion were obtained using triaxial compressive experiments, and the tensile strength was obtained using the Brazilian tensile test. The confining pressures employed in the triaxial compressive experiments were 10, 20, 30, 40, and 50 MPa.

In this research, considering the macro effect, the geological body in the different layers and the different structural aspects of the rock's physical and mechanical parameters can be considered a homogeneous relative fault zone. The fault zones were defined as soft zones. The elastic modulus of the fault zones is usually 50%-70% of the modulus of a corresponding normal sedimentary stratum (Table 3). Poisson's ratio of a fault zone is larger than Poisson's ratio of a corresponding normal sedimentary stratum, and the difference between these two ratios is generally between 0.02 and 0.1 (Jiu et al., 2013; Guo et al., 2016; Ju and Sun, 2016). The faults in the study area are numerous and complex but mainly comprise NE and NNE trending faults. Based on the scale of the study area and the influence of the strata, 7 faults were selected as the main simulation objects.

4.1.3. Establishment of a mathematical model

The mathematical model is a method to quantitatively predict fractures, and this model includes the numerical calculation method according to the mechanical model. The finite element method, chosen as the numerical calculation method in this study, is the most important method used to determine the element type, the element division and the concrete implementation plan, based on the geological model and the mechanical model for the finite element method. In general, the finer element is divided, and a more accurately computed result is obtained. To highlight the stress characteristics of the key parts and reduce the artificial error, a method of combining artificial control and automatic control was adopted for meshing. According to the C3D4 element, considering the capacity and complexity of the computer, the mathematical model included a total of 306,245 elements and 57,782 nodes (Fig. 6). The grid of the fault and the target layer was finely meshed, and the other places were roughly meshed.

The internal points along the space of the x , y , z coordinate axis directions showed displacement when the elements were subjected to the palaeotectonic stress. The displacement of each point along the three directions can be expressed as u , v , and w , and the displacements were all in relation to the coordinates of the point function. They can be defined as follows:

$$\begin{cases} u = u(x, y, z) \\ v = v(x, y, z) \\ w = w(x, y, z) \end{cases} \quad (1)$$

where u , v , and w are displacements on the x , y , and z axes.

Based on the elastic mechanics, there is a certain relationship between the displacement and the strain that can be expressed as follows:

$$\begin{cases} \varepsilon_x = \frac{\partial u}{\partial x}, \gamma_{xy} = \gamma_{yx} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \\ \varepsilon_y = \frac{\partial v}{\partial y}, \gamma_{yz} = \gamma_{zy} = \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \\ \varepsilon_z = \frac{\partial w}{\partial z}, \gamma_{zx} = \gamma_{xz} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \end{cases} \quad (2)$$

where $\varepsilon_x, \varepsilon_y, \varepsilon_z$ are the linear strain components, and $\gamma_{xy}, \gamma_{xz}, \gamma_{yz}$ are the shear strain components in the deformation of the element.

According to formula (2), the relationship between the strain and the nodal displacement matrix can be simplified as follows:

$$\varepsilon = B\delta \quad (3)$$

where δ is the displacement matrix of the nodes, and B is a geometric matrix.

From the elastic mechanics, stress and strain can be described in the following form:

$$\begin{cases} \varepsilon_x = \frac{1}{E}[\delta_x - \mu(\delta_y + \delta_z)], \gamma_{xy} = \gamma_{yx} = \frac{\tau_{xy}}{G} \\ \varepsilon_y = \frac{1}{E}[\delta_y - \mu(\delta_x + \delta_z)], \gamma_{yz} = \gamma_{zy} = \frac{\tau_{yz}}{G} \\ \varepsilon_z = \frac{1}{E}[\delta_z - \mu(\delta_x + \delta_y)], \gamma_{zx} = \gamma_{xz} = \frac{\tau_{xz}}{G} \end{cases} \quad (4)$$

Where $\delta_x, \delta_y, \delta_z$ are the normal stresses components; $\tau_{xy}, \tau_{xz}, \tau_{yz}$ are the shear stress components; E is the elastic modulus; μ is the Poisson's ratio; and G is the shear modulus.

By simplifying equation (4), stress and strain can be shown as follows:

$$[\delta] = [D][\varepsilon] \quad (5)$$

where $[D]$ is the elasticity matrix.

4.1.4. Determination of inversion criteria

As shown in Fig. 7a, the predicted maximum principal stress of the Yanshan stage at the site of the FC-1 well ranged from 167 MPa to 173 MPa, and the simulation result was close to the stress intensity (162.93 MPa) that was determined through the acoustic emission experiments. As shown in Fig. 7b, the simulated stress intensity of Himalayan period at the FC-1 well was between 114 and 121 MPa, which was highly consistent with the measured result (112.02 MPa) from the acoustic emission experiments conducted on the cores of the FC-1 well. According to previous study results (Meng et al., 2009), the inversion criteria can be designed as follows: the relative error between the numerical simulation and the experimental test value was less than 20%, supporting the reliability of the simulation results for stress intensity in the strata examined.

4.1.5. Simulation results of palaeotectonic stress field

ABAQUS software was utilized to simulate the palaeotectonic stress field during the Yanshan stage and the Himalayan stage in the Feng'gang No. 3 block in the northern Guizhou area. The distribution for the values of σ_1 , σ_2 and σ_3 were obtained from the simulation. σ_1 is the main factor for controlling tectonic deformation and the formation and distribution of faults. Decreasing the σ_3 values or increasing the σ_1 values is propitious to the formation of fractures. The factor τ plays an important role in the shear failure of rock.

4.2. Method for simulating and predicting tectonic fractures

The brittleness of rock is largely controlled by the mineral composition of the rock. The lower the clay mineral content in shale, the higher the content of quartz, feldspar, calcite and other brittle minerals and the higher the development of tectonic fractures in the shale reservoir (Zhang et al., 2016). The lithology of Cambrian Niutitang formation shale contains many brittle minerals, such as quartz, calcite, and dolomite, among others (Fig. 9). Therefore, it is easier to form tectonic

fractures that include mainly shear and tensional fractures (Rybacki et al., 2016). These fractures can be described by the Mohr–Coulomb criterion and Griffith criterion, respectively.

4.2.1. The Mohr–Coulomb criterion

The theoretical basis of the Mohr–Coulomb criterion is that the failure of rock is mainly the shear failure on a certain plane, and the shear failure depends on the normal stress σ and the shear stress τ along the plane (Fig. 10). The Mohr–Coulomb criterion for shear fractures can be described as

$$\tau = C + \sigma \tan \varphi \quad (6)$$

Where τ is the shear strength, φ is the internal friction angle, and C is the cohesion of the rock. Both C and φ can be determined by laboratory testing; σ is the normal stress.

4.2.2. 3D Griffith criterion

The Griffith criterion is a brittle tensional fracture criterion. Griffith considered that the failure of a brittle material is controlled by the existence of cracks in the interior of the material and that rock is a structure containing multiple cracks (Griffith, 1921). Due to the existence of microcracks in the rock, tensile stresses will be concentrated around the tips of the crack so that crack propagation occurs, damaging the formation of the tensile fracture. The three-dimensional Griffith criterion can be written as follows:

When $\sigma_1 + 3\sigma_3 \geq 0$ (the compressive stress is positive, and tensile stress is negative), it can be expressed as

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2 + 24(\sigma_1 + \sigma_2 + \sigma_3)\sigma_T = 0 \quad (7)$$

When $\sigma_1 + 3\sigma_3 < 0$, it can be expressed as

$$\sigma_3 + \sigma_T = 0 \quad (8)$$

Where σ_1 , σ_2 and σ_3 are the maximum, intermediate and minimum principal stresses, respectively, and σ_T is the effective tensile stress.

4.2.3. Determination of the degree of tectonic fracture development

After calculating the stress distribution of each element in the geological body, we can judge whether tectonic fractures occur in the rocks and the degree tectonic fracture development. As the stress state and physical properties of the rock are different in each part of the geological body, the fracture development of the rock is not identical.

Therefore, to quantitatively predict the degree of rock fracture development, the shear fracture rate S is introduced as follows (Ju and Sun, 2016):

$$S = MN / BM = r / DM \times \cos\varphi = (\sigma_1 - \sigma_3) / [(\sigma_1 + \sigma_3)\sin\varphi + 2C \cos\varphi] \quad (9)$$

where MN and BM are shown in Fig. 9. If $S \geq 1$, then a shear rupture will occur in an examined rock.

Similarly, the tensile fracture rate T is expressed as follows:

$$T = \sigma_T / \sigma_t \quad (10)$$

Where σ_T is the effective tensile stress, and σ_t is the tensile strength of the rock acquired by the Brazilian test. If $T \geq 1$, then a tension rupture will occur in the rock.

In the Feng'gang No 3 block, the shear and tensional fractures usually co-develop within shales. Considering that the shear and tensional fractures have a different developmental degrees, the indicator of comprehensive rupture rate I_c is introduced as follows:

$$I_c = mS + nT \quad (11)$$

where m and n are the proportions of the shear fractures and tensional fractures observed in the drill core, respectively. According to the statistics of the cracks in the drill cores of the FC-1

well, shear fractures account for 35%, and tensional fractures account for 65%. In Eq. (11), rocks begin to rupture when $I_c \geq 1$.

Through the numerical simulation results and the statistical analyses of tectonic fractures within the drill core, the degrees of fracture development in the shale reservoir were classified into three grades: developed zones ($I > 1.11$), relatively developed zones ($1.0 < I < 1.11$), and undeveloped zones ($I < 1.00$), therefore quantitatively evaluating the degree of development of tectonic fractures.

5. Results and discussion

5.1. Multi-period tectonic stress field simulation

As illustrated in Fig. 8a, the maximum principal stress in the Low Cambrian shale in the Feng'gang No. 3 block was commonly distributed between 250.36 and 281.18 MPa, which is indicative of compression. Due to the high degree of rock fragmentation at the fault zones, the stress concentration is easily caused. High stress levels were observed near the fault zones, at the end of the fault zones and at the fault intersection zones, especially as the maximum principal stress in these zones ranged between 269.97 MPa and 281.18 MPa.

As displayed in Fig. 8b, the minimum principal stress in the Low Cambrian shale in the study area was distributed between 58.29 MPa and 79.64 MPa. While the high stresses were distributed at the end of the fault zones, the low stresses were distributed between fault zones. The distribution of tectonic stress was controlled by the fault zones.

As demonstrated in Fig. 8c, the shear stress values in the study area are normally distributed between 91.05 MPa and 106.21 MPa. The shear stress distribution is primarily controlled by the location of the fault zones. The NE-SW, NNE-SSW, and N-S striking faults in the study area have markedly different influences on shear stress values, which indicates that the fault zones

significantly influence the distribution of the maximum principal stress, the minimum principal stress and the shear stress under the action of the compressive tectonic stress field.

5.2. Prediction of fracture distribution quantitatively

According to the three-dimensional stress field calculation results, fracture in the Lower Cambrian shale is achieved by using the abovementioned rupture criteria, and the results are expressed in the contour of the comprehensive rupture rate; the fracture distribution after the superposition of the Yanshan and the Himalayan movements was determined (Fig. 11).

The developed fracture zones ($I > 1.11$) primarily include: (1) the Hejiaba fault zone, the Suiyangshan fault zone, the Dangwan fault zone, the Taoping fault zone and the Feng'gang fault zone, and (2) the locations where the fault orientations change, as well as the intersecting areas of the fault.

The relatively developed fracture zones ($1.0 < I < 1.11$) are distributed in the following regions: the Yuquangou fault zone, west of the Suiyangshan fault zone, the Yonghe fault zone, west of the FC-1 well and east of the Feng'gang fault zone.

The distribution of the fracture development zones was mainly controlled by the fault zones, and the NE and NNE trending fault control effect was most remarkable. The fracture development zones were located at the end of the fault zones, at the inflection point and at the intersection of the fault zones.

6. Conclusions

(1) The simulation of the 3-D tectonic stress field in the Feng'gang No. 3 block area considers the entire sedimentary cover, which can reflect the difference between different layers and show the interactions between the layers. The ground stress and rock mechanics data can provide both

the mechanical model boundary conditions and the inputs. Therefore, a three-dimensional finite element analysis can obtain the palaeostress field distribution and predict fracture development zones in the shale reservoirs, which is of great significance to the exploration and development of oil and gas reservoirs.

(2) Because of the superposition of the two-phase stress fields in the Yanshan period (NW-SE) and the Himalayan period (S-E) compressed stress fields, the maximum principal stress in the Low Cambrian shale was commonly distributed between 250.36 and 281.18 MPa, the minimum principal stress was generally distributed between 58.29 MPa and 79.64 MPa, and the shear stress values in the study area was normally distributed between 91.05 MPa and 106.21 MPa in the Feng'gang No. 3 block.

(3) The developed fracture zones were mainly located in the fault zones, the regions in which the fault orientation changes and the areas in which the faults intersect. Using the comprehensive rupture rate as an indicator, the distribution of tectonic fractures in the Low Cambrian shale was quantitatively predicted and analysed. In addition to the lithology, the factors controlling the degree of the fracture development were mainly the palaeotectonic stress field during the crack formation period. The fracture development zones were located at the end of the fault zones, at the inflection point and at the intersection of the fault zones.

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Table 1 The result of tectonic stress measurements from the acoustic emissions for the shale samples from the FC-1 well.

Well ID	Depth(m)	Formation	Effective Tectonic Stress σ_1 During Various Periods (MPa)	Recorded Major Stages of Tectonic Movement
FC-1	2467.9-2468.2	Niutitang	4.89, 34.69, 44.81, 63.14 85.54, 112.02, 162.93	7

Table 2 Physical and mechanical parameters for the numerical simulation.

Strata	Elastic	Compressive	Density	Poisson's	Cohesion	Internal Friction	Tensile Strength
	Modulus	Strength	(g/cm ³)	Ratio	(MPa)	Angle	(MPa)
	(GPa)	(MPa)				(°)	
Overburden	38.40	145	2.65	0.27	33	21	13.12
Cap rock	54.75	131	2.53	0.26	27	32	11.16
Target strata	46.95	158	2.78	0.24	15	47	12.48
Basement	63.24	175	2.65	0.29	30	35	14.36

Table 3 Physical and mechanical parameters of faults.

Strata	Elastic	Density	Poisson's
	Modulus	(g/cm ³)	Ratio
	(GPa)		
Faults	30.15	2.41	0.31

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Systems	Series	Group	Lithology		Lithologic profile
Ordovician	Lower	(O ₁)	shale, Limestone		
Cambrian	Upper	Loushanguan (C ₃ ls)	Limestone		
	Middle	Gaotai (C ₂ g)	Dolomite		
	Lower	Qingxudong (C ₁ q)	Limestone		
		Jindingshan (C ₁ j)	SiltStone	Shale	
		Mingxinsi (C ₁ m)	Silty Shale	Shale, Silty Shale	
		Bianmachong (C ₁ b)		Limestone, Shale	
		Jiumenchong (C ₁ j)			
		Niutitang (C ₁ n)	Shale		
Sinian	Upper	Dengying (Z _b dn)	Dolomite	Shale	
		Doushantuo (Z _b d)	Shale		
	Lower	Nantuo (Z _a n)	Tillite		

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