Tectonic fracture prediction and its implication for hydrocarbon development with a case study in ultra-deep reservoirs of Kuqa Depression, Tarim Basin, NW China

Xu Ke, Zhang Hui, Wang Zhimin, Liu Xinyu, WANG Haiying
Petrochina Tarim Oilfield Company, Korla, Xinjiang Province, China

Abstract. Tectonic fractures can be important reserving space and the main contributor to permeability in ultra-deep reservoirs of Kuqa Depression. In this study, a workflow based on geomechanical method is presented. Firstly, a 3D heterogeneous mechanical field is constructed by core-logging-seismic data; then the finite element in-situ stress simulation is carried out, which is established using heterogeneous mechanical parameters instead of uniform parameters. Based on strain energy theory and energy conservation principle, the relationship between tectonic fracture parameters and in-situ stress field is established by a suitable rock fracture criterion for ultra-deep tight sandstone. Characteristics of tectonic fractures are predicted and revealed by the above stress field simulation and the established relationship between stress and tectonic fracture parameters. The results show that the maximum horizontal principal stress (S_H) orientation is generally N-S-trending in Bozi-1 gas reservoir. The present-day in-situ stress magnitudes are generally high with the minimum horizontal principal stress (S_h) is about 110~160MPa, and the stress difference is over 35MPa. The characteristics of present-day in-situ stress largely vary among different structural styles. The in-situ stress magnitude and burial depth generally indicates a linear relationship. The in-situ stress gradient is stratified with burial depth and is consistent with fold stress stratification. Controlled by the effect of fold bending and protection of salt layer, the development of tectonic fracture in pop-up structures is better with larger fracture aperture and higher permeability, and fracture strikes are generally consistent with the S_h orientation. Tectonic fractures in imbricated structures indicate great heterogeneity because of the development of faults and folds, and the rebuilding effect (permeability reduction) under the present-day in-situ stress field. Optimization of favourable zone for in-situ stress and tectonic fracture is of practical effects during well drilling and completion works.

1. Introduction
Tarim Basin is a large superimposed composite basin composed of Paleozoic marine craton basin and Mesozoic Cenozoic continental foreland basin. Kuqa depression is located in the northern margin of Kuqa depression, which starts from the southern margin of South Tianshan fold belt in the north, Tabei Uplift in the south, Yangxia depression in the East and Wushi depression in the West. It is mainly composed of Meso Cenozoic sediments, and is distributed in nee direction, with an area of about 3.7 km × 104km2. Kuqa depression is rich in natural gas resources, but the buried depth is large. The buried depth of Cretaceous sandstone reservoirs in Keshen-2 and Bozi-1 gas reservoirs is more than 6000m, and that of Keshen-9 and Bozi-8 gas reservoirs is even more than 8000m, which is a typical ultra-deep reservoir.
At this depth, the rocks bear huge overburden pressure, and the porosity of rock matrix is low, about 4% ~ 7%, but fractures are widely developed, which is an important reservoir space and seepage channel for this kind of ultra-deep fractured low porosity sandstone reservoir. Understanding and interpretation of where and when fractures would develop within a geological structure along with their orientation and intensity can be important to both exploration and production planning activities.

In this study, an innovative tectonic fracture prediction method is put forward, using the FEM based on the analysis of the structural evolutional characteristics, logging data calculation and imaging logging analysis. The development and distribution zones of tectonic fractures were predicted based on geomechanical method. The predicted results were verified using the fracture density distributions identified from boreholes and the capacity of gas wells. The results effectively support well placement, and make great contributions to well trajectory optimization and reservoir transformation. Bozi-1 gas reservoir is taking an example in this paper.

2. Geological background

Bozi-1 gas reservoir is located in Kelasu tectonic belt of Kuqa Depression. The Kuqa Depression is located at the northern margin of the Tarim Basin. Bozi-1 gas reservoir is an anticline with NE direction, which is clamped by two north dipping reverse faults, and its structural strike is basically consistent with that of the two boundary faults. A series of back thrusting structures (Fig. 1) are developed in the interior, which are clamped by two opposite faults, also called burst structures. Exploration practice shows that this structure is a high-quality structural type of oil and gas reservoir in Kuqa depression, and Bozi-1 gas reservoir is also one of the key blocks for current development.

From top to bottom, the strata drilled in Bozi block are Quaternary Xiyu formation (Q1x), Neogene Kuqa formation (N3k), Kangeun formation (N1-2k), Jidike formation (N1j), Paleogene suweiyi formation (E2-3s), kumgeliemu group (E1-2km), Cretaceous bashijiqike formation (K1bs), and Brazil reorganization (K1bx) (Fig. 1). Kumgelemu group is a set of gypsum salt strata with great thickness distribution difference, which has the characteristics of plastic flow, and its flow can control the development of sub salt fault thrust structure and the evolution of reservoir. The reservoir is the second and third lithologic members of the Cretaceous Bashijiqike formation, in which the second lithologic member is braided delta front subfacies; The third lithologic member is fan delta front subfacies. The reservoir lithology is mainly fine sandstone, followed by medium sandstone, coarse sandstone, siltstone and gravelly sandstone, which is an ultra-low porosity and low permeability reservoir. The test of pre-exploration wells in Bozi block shows that the methane content of natural gas is high, with an average of 88.6%, the heavy hydrocarbon (C2+) and nitrogen (N2) content is low, the CO2 content is small, and there is no H2S.
3. Method

3.1 1D geomechanical model

The most effective way to obtain the geomechanical parameters is generally based on core tests. However, due to the large burial depth and high stress concentration, it is difficult. In this study, the conventional logging data, micro resistivity imaging logging and six arm caliper logging are combined to calculate the rock mechanics parameters of single well, identify the current in-situ stress direction of different parts, and determine the current in-situ stress. In the process of drilling, with the removal of wellbore core, stress concentration will occur in the wellbore under the action of confining pressure, causing the development of drilling induced fractures. When the stress concentration exceeds the fracture strength of the rock around the wellbore, the wellbore collapse occurs. The direction of induced fracture often indicates the direction of maximum horizontal principal stress, while the direction of wellbore caving is generally perpendicular to the direction of maximum horizontal principal stress (Fig. 2). The orientation of induced fracture and borehole wall caving can be judged from the imaging logging (FMI), and the borehole wall caving appears as wide and dark bands alternating with each other on the imaging logging.

![Fig.2 Identification of the orientation of the maximum horizontal principal stress by the well bore trace](image)

According to the practical experience of Tarim Oilfield, the combined spring model assumes that there is no relative displacement between strata in the process of structural movement, and considers the influence of elastic modulus on the in-situ stress, which is greatly suitable for the Kuqa foreland thrust belt with strong compressions. The calculation model of combined spring is as follows:

\[
\begin{align*}
S_H &= \frac{\mu}{1-\mu} \left( S_v - \alpha P_p \right) + \frac{E \varepsilon_{Hv}}{1-\mu} + \frac{\mu E \varepsilon_{Ht}}{1-\mu^2} + \alpha P_p \\
S_h &= \frac{\mu}{1-\mu} \left( S_v - \alpha P_p \right) + \frac{E \varepsilon_{Hv}}{1-\mu} + \frac{\mu E \varepsilon_{Ht}}{1-\mu^2} + \alpha P_p 
\end{align*}
\]

(1)

where, \(S_H\) is the maximum horizontal principal stress, MPa; \(S_h\) is the minimum horizontal principal stress, MPa; \(S_v\) is the vertical principal stress, MPa; \(P_p\) is the pore pressure, MPa; \(\mu\) is Poisson's ratio, dimensionless; \(E\) is the modulus of elasticity, GPA; \(\alpha\) is the Biot coefficient, dimensionless; \(\varepsilon_{Hv}\) and \(\varepsilon_{Ht}\) are the maximum and minimum principal stress, respectively, dimensionless.

The mechanical properties of rock are the necessary parameters for the calculation of in-situ stress. The method of calculating the mechanical parameters of continuous rock with logging data is as follow:

\[
E_d = \frac{\rho_b}{\Delta t_s} \cdot \frac{3\Delta t_v^2 - 4\Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2}
\]

(2)
\[ \mu_d = \frac{\Delta t_s^2 - 2\Delta t_p^2}{2(\Delta t_e^2 - \Delta t_p^2)} \]  

where \( \rho_b \) is rock density, \( \text{kg/m}^3 \); \( \Delta t_p \) and \( \Delta t_s \) are P-wave time difference and S-wave time difference respectively, \( \mu/s/\text{ft} \).

Generally, the \( \xi_p \) and \( \xi_s \) are difficult to be directly determined. The value of \( S_H \) at specific locations are determined by hydraulic fracturing data, which is used as the basis of constraint and scale to indirectly determine the value. Generally, in the process of hydraulic fracturing, the shut-off pressure is the value of fracture closure pressure, which is equal to the \( S_b \), and the calculation method of the \( S_H \) is as follow:

\[
\begin{cases} 
S_b = P_c \\
S_H = 3S_b - P_r - P_p 
\end{cases}
\]  

where \( P_c \) is the shut-down pressure, \( \text{MPa} \); \( P_r \) is the fracture reopening pressure, \( \text{MPa} \).

Fig.3 1D Geomechanical histogram of Bozi-101-2
In addition, the characteristics of natural fractures in wellbore are picked up based on imaging logging. The 1D Geomechanical model is carried out for several wells in Bozi-1 gas reservoir based on the above methods, and the continuous changes of rock mechanical properties, in-situ stress, fracture characteristics and other parameters in the whole well section are clarified, taking the well Bozi-101-2 as an example.

As shown in Fig.3, it is a 1D geomechanical histogram of well Bozi-101-2. It can be seen that the Young's modulus of the target layer is about 25~45GPa, the average uniaxial compressive strength is about 150MPa, and the Poisson's ratio has a little change range, about 0.21~0.25. The three principal stresses obviously change with depth. The principals, $S_h$ and $S_v$ gradients are 2.2MPa/100m, 2.6~2.7MPa/100m, and 2.45MPa/100m, respectively. The $S_h$, $S_h$ and $S_v$ values are about 138MPa, 165MPa and 152MPa respectively, showing a dominant $S_h > S_v > S_h$, which is a strike-slip faulting stress regime.

3.2 3D finite element numerical simulation

Generally, the workflow for finite element numerical simulation method is as follow: Firstly, the geological body is discretized into finite elements. The elements are connected by nodes, and the corresponding rock mechanical parameters are given to these elements. The basic variables of the field function in the study area include displacement, stress and strain. According to the boundary stress conditions and node balance conditions, the solution of the equation group with node displacement as the unknown quantity and total stiffness matrix as the coefficient is obtained, and the displacement on each node is calculated, and then the stress and strain values in each element can be calculated.

The simulation of 3D heterogeneous stress field mainly includes the following five steps:

1. Establishing geological model based on the drilling data, logging data, seismic data and regional geological data.
2. Constructing the 3D heterogeneous rock mechanics field based on "core-logging-seismic" method.
3. Establishing 3D heterogeneous mechanical model by put the mechanical parameters into the finite elements.
4. Imposing constraints and loads, and debugging reasonable boundary conditions.
5. Checking the reliability of simulation results.

3.3 Geomechanical simulation of fracture distribution

In this paper, composite failure criterion inducing strain-energy release was used as an indicator for fracture development, and establish a relationship between fracture density and strain energy density.

When a rock mass is subjected to spatial principal stresses $\sigma_1$, $\sigma_2$ and $\sigma_3$, the strain-energy density at a given point can be expressed as:

$$\sigma = \frac{1}{2} (\sigma_1 \varepsilon_1 + \sigma_2 \varepsilon_2 + \sigma_3 \varepsilon_3)$$

where $\sigma$ is strain energy density (J/m$^3$); and $\varepsilon_1$, $\varepsilon_2$, $\varepsilon_3$ respectively are the strains corresponding to three principal stresses.

The Mohr-Coulomb Criterion suggests that a shear fracture only forms if the internal strength or cohesion of the rock ($C_0$) is exceeded, and depends on the magnitude of normal stress along a fracture plane. The relationships between fracture density, aperture and strain energy density, stress-strain are written as follows
\[
\begin{align*}
    w_r &= w - w_n = \frac{1}{2E} \left( \sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu(\sigma_1 + \sigma_2 + \sigma_3) - 0.85^2 \sigma_\rho^2 + 2\mu(\sigma_2 + \sigma_3)0.85\sigma_\rho \right) \\
    \sigma_\rho &= \frac{2C_0 \cos \phi + (1 + \sin \phi)\sigma_3}{1 - \sin \phi} \\
    E &= E_0 \sigma_\rho \\
    D_\eta &= \frac{w_r}{J} \\
    J &= J_0 + \Delta J = J_0 + \sigma_3 b \\
    D_{\eta f} &= \frac{2D_{\eta f} L_1 L_3 \sin \theta \cos \theta - L_2 \sin \theta - L_3 \cos \theta}{L_1^2 \sin^2 \theta + L_2^2 \cos^2 \theta} \\
    D_{\eta b} &= \| \varepsilon_3 \| - |\varepsilon_0| \\
    \varepsilon_0 &= \frac{1}{E} (\sigma_3 - \mu(0.85\sigma_\rho + \sigma_2))
\end{align*}
\]

where $\phi$ is the internal friction angle ($^\circ$); $\theta$ is the angle between normal to the newly formed fracture plane and the maximum principal stress ($^\circ$); $\sigma_\rho$ is the rupture stress under action of $\sigma_3$, different from the maximum principal stress; $\sigma_\eta$ is the tensile strength (MPa); $J_0$ is fracture surface energy with no confining pressure or under uniaxial compressive stress ($J/m^2$); $\Delta J$ is the additional surface energy caused by confining pressure $\sigma_3$ ($J/m^2$); $b$ is the fracture aperture, m; $D_{\eta f}$ is the fracture linear density ($1/m$); $\varepsilon_3$ is the tensile strain under current state of stress, dimensionless parameter; $\varepsilon_0$ is the maximum tensile strain, dimensionless parameter, corresponding to tensile strain when crack beginning to form; $E_0$ is the proportionality coefficient related to lithology; and $L_1$, $L_2$, $L_3$ are side length of the selecting representing element volume (REV).

4. Result and Discuss

4.1 Distribution of current in-situ stress and natural fracture

According to the 3D stress field simulation results of gas reservoir a (Fig.4), the numerical distribution trend of maximum horizontal principal stress is generally low in the north and high in the south, and the anticline high point is low, which is consistent with the distribution trend of measured data. The maximum horizontal principal stress is mainly between 175 MPa and 190 MPa. With the increase of burial depth, the maximum horizontal principal stress increases (Fig.4). The distribution trend of the minimum horizontal principal stress is similar to that of the maximum horizontal principal stress, which is generally low in the north and high in the south. The high point of the anticline is low, and the value is mainly between 135 and 150MPa. The stress value increases with the increase of burial depth. The horizontal stress difference is relatively high, the value is more than 30MPa, the distribution is relatively discrete, and the horizontal stress difference at the high point of the anticline is relatively low (Fig. 4). The distribution of the maximum horizontal principal stress in a gas reservoir is quite different and regular, and gradually deflects from NE to near EW from west to East. It should be noted that the maximum horizontal principal stress direction of A1-1 well and A104-1 well is vertical.

Bozi-1 gas reservoir is dominated by high angle fractures and vertical fractures, and the strike is concentrated in NW-SE ~ NE-SW, showing obvious heterogeneity. The fracture distribution depends on the characteristics of fault development and in-situ stress field. Bozi 101-Bozi 104 block has a high degree of fracture development (Fig.5).
4.2 Suggestions for efficient development

In view of the fact that in-situ stress and natural fracture play important roles in controlling ultra-deep reservoir quality and gas well productivity in Kuqa depression. In addition to the conventional physical factors, the current in-situ stress and natural fracture distribution should be fully considered in Bozi-1 block. Generally speaking, the low stress and more fracture area is the advantageous position, that is, the blue and green parts in Fig. 4 are preferred. However, due to the strong heterogeneity of in-situ stress, large buried depth and low quality of seismic data, the prediction results of bozi-1 gas reservoir have certain errors, and it is difficult to accurately "hit the target" in the drilling hole. It is possible to drill into the unfavorable part near the dominant area, that is, the red high stress zone. Therefore, it is suggested to use inclined wells to increase the probability of passing through the favorable area. As shown in Figure 4 and 5, highly deviated wells are easier to pass through the dominant zone than vertical wells, so as to reduce the possibility of failure. On the other hand, bozi-1 gas reservoir is characterized by strike slip stress mechanism. In this case, along the direction of the maximum horizontal principal stress or at a 45° angle with it° The range of included angle is the
most stable dominant azimuth range, while the vertical principal stress (SV) direction is the most unstable direction, that is, the vertical well is not a safe and stable well type.

5. Conclusion

(1) Bozi 1 gas reservoir is buried more than 6500m, and the current stress field is still generally strike slip type, with strong heterogeneity. The Kuqa Depression has been subjected to intense compression since the Late Himalayan. The maximum horizontal principal stress orientation in the Cretaceous reservoirs is generally N-S-trending. The present-day in-situ stress magnitudes are generally high with the minimum horizontal principal stress is about 110~160MPa, and the stress difference is over 35MPa.

(2) Bozi-1 gas reservoir is dominated by high angle fractures and vertical fractures, and the strike is concentrated in NW-SE ~ NE-SW, showing obvious heterogeneity. The fracture distribution depends on the characteristics of fault development and in-situ stress field. Bozi 101-Bozi 104 block has a high degree of fracture development.

(3) The well location deployment of Bozi-1 ultra-deep reservoir can not only consider the conventional physical factors, but also need to further consider the influence of current in-situ stress. The deployment of development wells also needs to fully consider the development status of adjacent wells. Highly deviated wells have the dual advantages of wide crossing of dominant areas and safe and stable well trajectory, which is an effective means to overcome the strong heterogeneity of reservoirs.

(4) The innovative significance of this workflow is that the tectonic fracture prediction accuracy has been increased by 20%. In addition, it has been successfully applied in the ultra-deep (>7000 m) reservoirs of Kuqa Depression, which is conductive to increase oil and gas production.

6. References

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