Hindawi
Geofluids
Volume 2021, Article ID 5581549, 12 pages
https://doi.org/10.1155/2021/5581549

Research Article

Wellbore Fracture Mode and Fracture Pressure Drilled in Depleted Reservoir

Kai Zhao,[1,2,3] **Junliang Yuan**,[4] **Ming Liu**,[5] **Chuanliang Yan**,[6] **Liangbin Dou**,[1] **Gang Bi**,[1] **Runsen Li**,[1] **and Wei Gao**[1]

[1]*College of Petroleum Engineering, Xi'an Shiyou University, Xi'an, China*
[2]*Key Laboratory of Deep Geodrilling Technology, Ministry of Natural Resources, Beijing, China*
[3]*Xi'an Key Laboratory of Tight Oil (Shale Oil) Development (Xi'an Shiyou University), Xi'an, China*
[4]*CNOOC Research Institute Co., Ltd., Beijing, China*
[5]*CNPC Oilfield Technical Service Limited, Oil Mansion, No. 9 Dongzhimen North St., Dongcheng Dist., Beijing, China*
[6]*School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, China*

Correspondence should be addressed to Kai Zhao; zkaiup@126.com and Junliang Yuan; yuan6688699@163.com

Received 21 January 2021; Accepted 17 May 2021; Published 8 June 2021

Academic Editor: Keni Zhang

Drilling fluid loss in depleted reservoir has been an import issue faced by further tapping the potential of old oil fields. Accurate evaluation of the fracture pressure is the foundation to avoid mud loss. Traditional views suggest that tensile failure is the only fracture mode and the fracture pressure should be determined by a tensile failure criterion, which are not suitable for wells drilled in the depleted reservoir. In this paper, the analysis focuses on the fracture mode and fracture pressure in depleted reservoir, and case studies show that three fracture modes may first occur, and the fracture mode will be changed with reservoir depletion which highly depends on reservoir depletion degree, well azimuth and deviation angle, and the in situ stress state; different failure criteria at different stages of reservoir depletion should be selected to accurately evaluate the fracture pressure. For the vertical well, fracture pressure is no longer a single linear reduction with reservoir depletion; instead, a three-step and two-step reduction may appear, and for the directional well, the fracture pressure is not always decreased; the other patterns such as increase and first increase then decrease may also appear for the wells drilled in reverse and strike fault stress regimes.

1. Introduction

At present, more than 70% hydrocarbon resources are obtained from secondary and tertiary recovery [1]. Further tapping the potential of old oil fields is one of the main directions to improve oil recovery rate in the future. But due to the long-term hydrocarbon production, reservoir pressure often decreases which extends with time from wellbore vicinity to the far field of the reservoir over the lifetime of the oil field unless sufficient pressure support is supplemented. The in situ stress also changes due to reservoir compaction deformation along with pressure depletion [2]. Therefore, the fracture mode and fracture pressure are both changed when wellbore is drilled through highly depleted reservoirs to make new horizontal wells as producers or injectors, or develop new untapped reservoirs in deeper horizons. Field evidences have indicated that the fracture pressure was decreased with reservoir depletion and more drilling fluid losses occurred which have serious impact on drilling safety and costs [3–10].

Extensive related studies have been conducted in order to avoid drilling fluid loss in depleted reservoir, but most of the previous research focused on the fracture pressure [11–14] and only few on fracture mode in depleted reservoir, which result in the wrong fracture pressure calculation model selection and inaccurate fracture pressure calculation results. For example, the previous research have concluded that when the drilling fluid pressure inside the wellbore is high enough, tensile fracture first occurs at the wellbore along the direction of minimum principal stress, and fracture pressure should be determined by a tensile failure criterion [15].

On the basis of those facts, we can reach the conclusion that the fracture pressure of vertical well decreases linearly with reservoir depletion.

In fact, with reservoir depletion, the original tensile failure mode may be transformed into shear failure mode, and shear fracture may first occur at the wellbore when the drilling fluid pressure inside the wellbore is high enough. In this case, fracture pressure should not be determined by a tensile failure criterion, and the reduction of fracture pressure of vertical well will present a more complex law. Furthermore, the problem becomes more complicated in directional wells due to changes in well inclination and azimuth. Aiming at this problem, the analytical method for wellbore fracture mode and fracture pressure in depleted reservoir is established in this paper, and the fracture mode and fracture pressure in different reservoir and wellbore conditions are analyzed in depth.

2. Changes of In Situ Stresses with Reservoir Depletion

For a developed reservoir, the long-term recovery of oil and gas resources will lead to the decrease of pore pressure, unless the energy is fully replenished by water injection or the other operations. The reservoir with an overall reduction in pore pressure is defined as depleted reservoir. Using reservoir numerical simulation method, by setting the number and location of producing and injection wells, reservoir characteristic parameters (permeability, porosity, and saturation), production parameters (production rate, injection rate, and production time), etc. can simulate and determine the pressure depletion degree at different stages.

Reservoir depletion will induce its compaction deformation. As a result, the magnitudes of in situ stresses will be changed [2]. The change of in situ stresses depends on a number of factors, such as pore pressure depletion, reservoir properties, and boundary conditions. But fortunately, a simple linear relationship usually exists between the change of horizontal stress and the reservoir depletion for all different scenarios, which can be expressed as follows:

$$\Delta\sigma_H = \Delta\sigma_h = A\Delta P_p, \tag{1}$$

where $\Delta\sigma_H$ and $\Delta\sigma_h$ are the changes of the horizontal maximum and minimum stress due to reservoir depletion, respectively; ΔP_p is the pore pressure depletion; A is a correlation coefficient which is related to rock mechanical properties and reservoir boundary conditions.

When the hydrocarbon reservoir is considered to be horizontal and infinite in lateral extent, while its thickness is finite, the correlation coefficient A can be written as follows:

$$A = \delta\frac{1-2\nu}{1-\nu}, \tag{2}$$

where ν is the Poisson ratio and δ is the Biot coefficient.

Under the same conditions, the vertical principal stress component does not change with reservoir depletion, i.e.,

$$\Delta\sigma_v = 0. \tag{3}$$

3. Fracture Mode and Fracture Pressure of Vertical Well in Depleted Reservoir

When the drilling fluid pressure inside the wellbore is high enough to fracture the rock surrounding the borehole, the critical pressure is defined as fracture pressure. To calculate the fracture pressure, the first is to get the effective stress state around vertical wellbore wall under the effect of in situ stress and drilling fluid pressure inside the borehole, which has been presented by many published literatures as follows [16, 17]:

$$\begin{cases} \sigma_r' = P_W - \delta P_P, \\ \sigma_\theta' = -P_W + (1-2\cos 2\theta)\sigma_H + (1+2\cos 2\theta)\sigma_h - \delta P_P, \\ \sigma_z' = \sigma_v - \nu[2(\sigma_H - \sigma_h)\cos 2\theta] - \delta P_P, \end{cases} \tag{4}$$

where σ_r', σ_θ', and σ_z' are the effective radical, tangential, and axial stresses in the borehole coordinate system, respectively; P_W is the drilling fluid pressure inside the borehole; θ is the angle from the direction of σ_H to the radius vector of the borehole.

When reservoir pressure is depleted by ΔP_p, the effective stress state around vertical wellbore can be derived by substituting Equation (1) into Equation (4):

$$\begin{cases} \sigma_r' = P_W - \delta P_P + \delta\Delta P_p, \\ \sigma_\theta' = -P_W + (1-2\cos 2\theta)\sigma_H + (1+2\cos 2\theta)\sigma_h - \delta P_P + (\delta - 2A)\Delta P_p, \\ \sigma_z' = \sigma_v - \nu[2(\sigma_H - \sigma_h)\cos 2\theta] - \delta P_P + \delta\Delta P_p. \end{cases} \tag{5}$$

The previous research have concluded that when the drilling fluid pressure inside the wellbore is high enough, tensile fracture first occurs at the wellbore along the direction of minimum principal stress, and fracture pressure should be determined by a tensile failure criterion [15].

But a new phenomenon has also been observed after reservoir depletion. The change of the effective stress state around vertical wellbore with reservoir depletion is calculated according to the above equation, and the results (Figure 1) show that tensile fracture occurred first at the location of $\theta = 0°$ when the drilling fluid pressure is high enough, but when the reservoir pressure is depleted (from 20 MPa to 10 MPa), the minimum effective tangential stress is changed very little, and the maximum stress differences of $(\sigma_r' - \sigma_\theta')$ and $(\sigma_z' - \sigma_\theta')$ at the location of $\theta = 0°$ are both getting wider and wider; hence, shear fracture may first occur with reservoir depletion according Mohr-Coulomb criterion. As a result, the wellbore fracture mode in the depleted reservoir can be divided into three types which depend on the reservoir

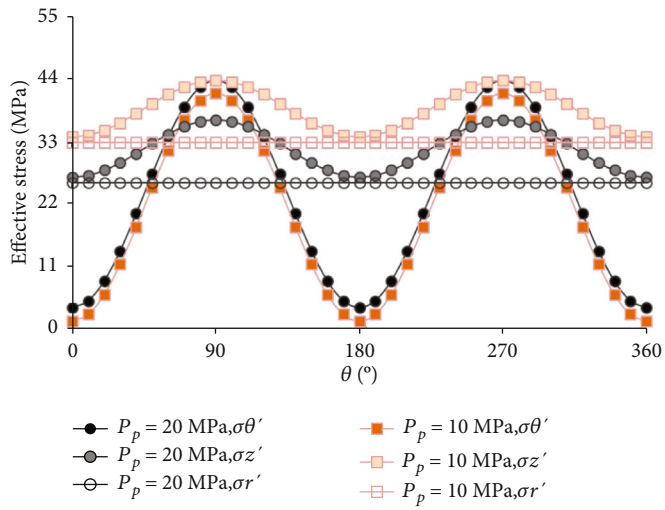


Figure 1: Change of the effective stress state around vertical wellbore with reservoir depletion. The initial reservoir pressure is 20 MPa, and the current pressure after reservoir depletion is 10 MPa.

depletion and so on: (1) Mode 1: tensile fracture, (2) Mode 2: shear fracture and $(\sigma_z' - \sigma_\theta') > (\sigma_r' - \sigma_\theta')$, and (3) Mode 3: shear fracture and $(\sigma_r' - \sigma_\theta') > (\sigma_z' - \sigma_\theta')$.

According to the above analysis, fracture always first occurred at the location of $\theta = 0°$ for any of the three modes due to its minimum effective tangential stress and the maximum stress differences around the borehole. So, if we want to get the fracture pressure, the effective stress state at the location of $\theta = 0°$ should be first derived based on Equation (5):

$$\begin{cases} \sigma_r' = P_W - \delta P_P + \delta \Delta P_p, \\ \sigma_\theta' = -P_W - \sigma_H + 3\sigma_h - \delta P_P + (\delta - 2A)\Delta P_p, \\ \sigma_z' = \sigma_v - 2\nu(\sigma_H - \sigma_h) - \delta P_P + \delta \Delta P_p. \end{cases} \quad (6)$$

For Mode 1, fracture pressure should be determined by a tensile failure criterion:

$$\sigma_\theta' = -P_W - \sigma_H + 3\sigma_h - \delta P_P + (\delta - 2A)\Delta P_p \le -S_t, \quad (7)$$

where S_t is the tensile strength.

Then, we can get the fracture pressure in this mode:

$$P_{f1} = -\sigma_H + 3\sigma_h - \delta P_P + (\delta - 2A)\Delta P_p + S_t. \quad (8)$$

For Mode 2, fracture pressure should be determined by Mohr-Coulomb shear failure criterion when $(\sigma_z' - \sigma_\theta') > (\sigma_r' - \sigma_\theta')$:

$$\sigma_z' \ge \sigma_\theta' \tan^2\left(45° + \frac{\phi}{2}\right) + 2C \tan\left(45° + \frac{\phi}{2}\right), \quad (9)$$

where C is the cohesive force; ϕ is the internal friction angle.

Then, we can get the fracture pressure in this mode by taking Equation (6) into Equation (9):

$$P_{f2} = -\sigma_H + 3\sigma_h - \delta P_P + (\delta - 2A)\Delta P_p + \frac{2CK - \left[\sigma_v - 2\nu(\sigma_H - \sigma_h) - \delta P_P + \delta \Delta P_p\right]}{K^2}, \quad (10)$$

where $K = \tan(45° + (\phi/2))$.

For Mode 3, fracture pressure should be determined by Mohr-Coulomb shear failure criterion when $(\sigma_r' - \sigma_\theta') > (\sigma_z' - \sigma_\theta')$:

$$\sigma_r' \ge \sigma_\theta' \tan^2\left(45° + \frac{\phi}{2}\right) + 2C \tan\left(45° + \frac{\phi}{2}\right). \quad (11)$$

Then, we can get the fracture pressure in this mode by taking Equation (6) into Equation (11):

$$P_{f3} = \frac{\left[-\sigma_H + 3\sigma_h - \delta P_P + (\delta - 2A)\Delta P_p\right]K^2 + 2CK + \delta P_P - \delta \Delta P_p}{1 + K^2}. \quad (12)$$

Through the comparison of the fracture pressures in the three modes, the fracture pressure of the vertical well in depleted reservoir can be determined as follows:

$$P_f = \min\left(P_{f1}, P_{f2}, P_{f3}\right). \quad (13)$$

The fracture mode and corresponding conditions can be determined by the following principles:

(1) If $P_f = P_{f1}$, tensile fracture first occurs and the fracture mode is Mode 1, and the occurrence conditions is $S_t < 2CK - [\sigma_v - 2\nu(\sigma_H - \sigma_h) - \delta P_P + \delta \Delta P_p]/K^2$ and $S_t < 2CK + \delta P_P - \delta \Delta P_p - [-\sigma_H + 3\sigma_h - \delta P_P + (\delta - 2A)\Delta P_p]/(1 + K^2)$

(2) If $P_f = P_{f2}$, shear fracture first occurs and the fracture mode is Mode 2, and the occurrence conditions is $2CK - [\sigma_v - 2\nu(\sigma_H - \sigma_h) - \delta P_P + \delta\Delta P_p]/K^2 < S_t$ and $2CK - [\sigma_v - 2\nu(\sigma_H - \sigma_h) - \delta P_P + \delta\Delta P_p]/K^2 < 2CK + \delta P_P - \delta\Delta P_p - [-\sigma_H + 3\sigma_h - \delta P_P + (\delta - 2A)\Delta P_p]/(1 + K^2)$

(3) If $P_f = P_{f3}$, shear fracture first occurs and the fracture mode is Mode 3, and the occurrence conditions is $2CK + \delta P_P - \delta\Delta P_p - [-\sigma_H + 3\sigma_h - \delta P_P + (\delta - 2A)\Delta P_p]/(1 + K^2) < S_t$ and $2CK + \delta P_P - \delta\Delta P_p - [-\sigma_H + 3\sigma_h - \delta P_P + (\delta - 2A)\Delta P_p]/(1 + K^2) < 2CK - [\sigma_v - 2\nu(\sigma_H - \sigma_h) - \delta P_P + \delta\Delta P_p]/K^2$

4. Fracture Mode and Fracture Pressure of Directional Well in Depleted Reservoir

In order to further tap the potential of old oil fields, more directional wells including horizontal wells are drilled. But due to unequal change of the vertical and horizontal principal stress, fracture mode and fracture pressure of directional well in depleted reservoir are more complicated. For example, the fracture pressure in Mode 1 of the horizontal wells drilled in the direction of maximum horizontal in situ stress should be described in two types, and the influences on the fracture pressure of reservoir depletion for the two types are both different from the vertical well:

(1) In normal and strike fault stress regime, the in situ stress state is $\sigma_v > \sigma_H > \sigma_h$ and $\sigma_H > \sigma_v > \sigma_h$, respectively [18]. Hence, the fracture pressure is as follows, and the influence coefficient of reservoir depletion is$(\delta - 3A)$

$$P_{f1} = -\sigma_v + 3\sigma_h - \delta P_P + (\delta - 3A)\Delta P_p + S_t. \quad (14)$$

(2) In reverse fault stress regime, the in situ stress state in reverse fault regimes is $\sigma_H > \sigma_h > \sigma_v$. Hence, the fracture pressure is as follows, and the influence coefficient of reservoir depletion is $(\delta - A)$

$$P_{f1} = -\sigma_h + 3\sigma_v - \delta P_P + (\delta - A)\Delta P_p + S_t. \quad (15)$$

For an arbitrarily deviated well, the stress components of in situ ground stresses in borehole coordinate system can be derived by coordinate system transformation [17]:

$$\begin{cases} \sigma_{xx} = \sigma_H \cos^2\alpha \cos^2\gamma + \sigma_h \cos^2\alpha \sin^2\gamma + \sigma_v \sin^2\alpha, \\ \sigma_{yy} = \sigma_H \sin^2\gamma + \sigma_h \cos^2\gamma, \\ \sigma_{zz} = \sigma_H \sin^2\alpha \cos^2\gamma + \sigma_h \sin^2\alpha \sin^2\gamma + \sigma_v \cos^2\alpha, \\ \sigma_{xy} = -\sigma_H \cos\alpha \cos\gamma \sin\gamma + \sigma_h \cos\alpha \cos\gamma \sin\gamma, \\ \sigma_{xz} = \sigma_H \cos\alpha \sin\alpha \cos^2\gamma + \sigma_h \cos\alpha \sin\alpha \sin^2\gamma - \sigma_v \cos\alpha \sin\alpha, \\ \sigma_{yz} = -\sigma_H \sin\alpha \cos\gamma \sin\gamma + \sigma_h \sin\alpha \cos\gamma \sin\gamma, \end{cases} \quad (16)$$

where α is the well deviation angle and γ is the well azimuth angle relative to the maximum horizontal principal stress orientation.

After reservoir depletion, the stress components will be changed due to in situ stress change which can be derived by substituting Equation (1) into Equation (16):

$$\begin{cases} \sigma_{xx} = \sigma_H \cos^2\alpha \cos^2\gamma + \sigma_h \cos^2\alpha \sin^2\gamma + \sigma_v \sin^2\alpha - \cos^2\alpha A\Delta P_p, \\ \sigma_{yy} = \sigma_H \sin^2\gamma + \sigma_h \cos^2\gamma - A\Delta P_p, \\ \sigma_{zz} = \sigma_H \sin^2\alpha \cos^2\gamma + \sigma_h \sin^2\alpha \sin^2\gamma + \sigma_v \cos^2\alpha - \sin^2\alpha A\Delta P_p, \\ \sigma_{xy} = -\sigma_H \cos\alpha \cos\gamma \sin\gamma + \sigma_h \cos\alpha \cos\gamma \sin\gamma, \\ \sigma_{xz} = \sigma_H \cos\alpha \sin\alpha \cos^2\gamma + \sigma_h \cos\alpha \sin\alpha \sin^2\gamma - \sigma_v \cos\alpha \sin\alpha - \cos\alpha \sin\alpha A\Delta P_p, \\ \sigma_{yz} = -\sigma_H \sin\alpha \cos\gamma \sin\gamma + \sigma_h \sin\alpha \cos\gamma \sin\gamma. \end{cases} \quad (17)$$

Assuming the plane strain is normal to the borehole axis, concentrated stress component solutions surrounding an arbitrarily deviated well wall in terms of cylindrical polar coordinates can be written as follows:

$$\begin{cases} \sigma_r = P_W, \\ \sigma_\theta = -P_W + (\sigma_{xx} + \sigma_{yy}) - 2(\sigma_{xx} - \sigma_{yy}) \cos 2\theta - 4\sigma_{xy} \sin 2\theta, \\ \sigma_z = \sigma_{zz} - \mu[2(\sigma_{xx} - \sigma_{yy}) \cos 2\theta + 4\sigma_{xy} \sin 2\theta], \\ \tau_{r\theta} = 0, \\ \tau_{\theta z} = 2\sigma_{yz} \cos\theta - 2\sigma_{xz} \sin\theta, \\ \tau_{rz} = 0. \end{cases} \quad (18)$$

Because$\tau_{r\theta} = \tau_{rz} = 0$, σ_r is one of the three principal stresses, and the other two principal stresses can be derived as follows:

$$\begin{cases} \sigma_{\max} = \dfrac{(\sigma_\theta + \sigma_z)}{2} + \sqrt{\left(\dfrac{\sigma_\theta - \sigma_z}{2}\right)^2 + \tau_{\theta z}{}^2}, \\ \sigma_{\min} = \dfrac{(\sigma_\theta + \sigma_z)}{2} - \sqrt{\left(\dfrac{\sigma_\theta - \sigma_z}{2}\right)^2 + \tau_{\theta z}{}^2}. \end{cases} \quad (19)$$

Based on the analysis of vertical well, failure criterion in different fracture modes should be described as the following principles:

(1) For Mode 1, fracture pressure should be determined by a tensile failure criterion

$$\sigma_{\min} - \delta P_P \le -S_t. \quad (20)$$

(2) For Mode 2, fracture pressure should be determined by Mohr-Coulomb shear failure criterion

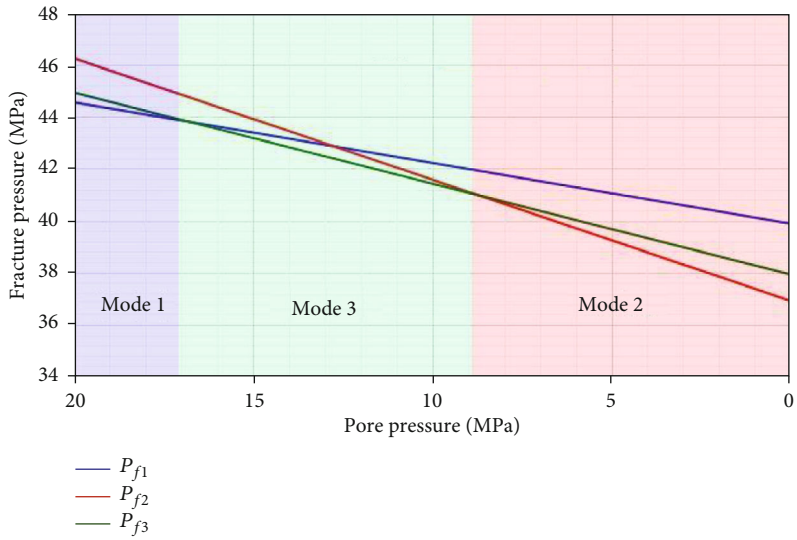


Figure 2: Change of fracture mode and fracture pressure with reservoir depletion of vertical wellbore drilled in normal fault stress regime.

$$\sigma_{\max} - \delta P_P \geq (\sigma_{\min} - \delta P_P) \tan^2\left(45^\circ + \frac{\phi}{2}\right) + 2C \tan\left(45^\circ + \frac{\phi}{2}\right). \tag{21}$$

(3) For Mode 3, fracture pressure should also be determined by Mohr-Coulomb shear failure criterion

$$\sigma_r - \delta P_P \geq (\sigma_{\min} - \delta P_P) \tan^2\left(45^\circ + \frac{\phi}{2}\right) + 2C \tan\left(45^\circ + \frac{\phi}{2}\right). \tag{22}$$

The fracture pressure in the three fracture modes can be solved by substituting Equation (18) and Equation (19) into Equation (20) to Equation (22), respectively. But because there is no analytical solution to the fracture pressure of directional wells in depleted reservoir, the fracture pressures (P_{f1}, P_{f2}, and P_{f3}) in the three fracture modes should be solved numerically by iteration. The final fracture pressure and fracture mode can be determined by using Equation (13), and fracture mode discrimination principles are the same with that of the vertical well.

5. Case Study and Discussion

Using the theory described above, case studies are performed in this section to illustrate the evolution of fracture mode and fracture pressure with reservoir depletion. The following parameters are chosen for the base case:

(i) Reservoir mechanical parameters: Poisson's ratio = 0.25, Biot's coefficient = 0.7, tensile strength = 1 MPa, cohesive force = 10 MPa, and internal friction angle = 30°.

(ii) Initial pore pressure = 20 MPa

(iii) The direction of maximum horizontal in situ stress = N120°E

(iv) Three types of initial in situ stress states are considered:

(a) Normal fault stress regime: $\sigma_v = 46$ MPa $> \sigma_H = 44$ MPa $> \sigma_h = 34$ MPa

(b) Reverse fault stress regime: $\sigma_H = 58$ MPa $> \sigma_h = 56$ MPa $> \sigma_v = 46$ MPa

(c) Strike fault stress regime: $\sigma_H = 48$ MPa $> \sigma_v = 46$ MPa $> \sigma_h = 36$ MPa

5.1. Vertical Well. For the vertical well drilled in different fault stress regimes, the changes of fracture mode and fracture pressure with reservoir depletion are illustrated in Figures 2–4, respectively. In the figures, the blue line represents the fracture pressure in Mode 1, the red line represents the fracture pressure in Mode 2, and the green line represents the fracture pressure in Mode 3, and the final fracture pressure should be the minimum of the three. Furthermore, the pale blue areas represent Mode 1 first occurs when the well is fractured, the pale red areas represent Mode 2 first occurs, and the pale green areas represent Mode 3 first occurs.

The results show several differences from conventional views:

(1) Tension failure is not the only fracture mode; two types of shear fracture modes also occur; for example, in reverse fault stress regime (Figure 3), Mode 3 always first occurs when the vertical well is fractured with reservoir depletion, and the fracture pressure should always be determined by the Mohr-Coulomb shear failure criterion, and the tensile failure criterion

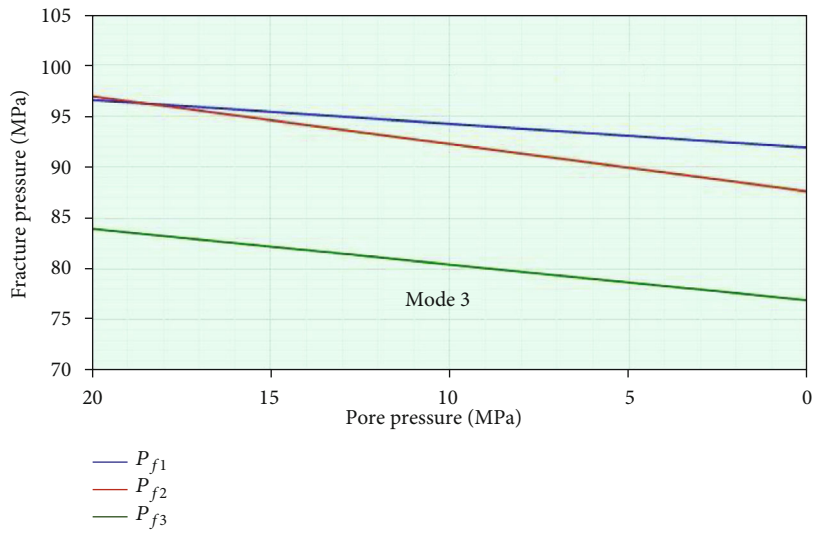


Figure 3: Change of fracture mode and fracture pressure with reservoir depletion of vertical wellbore drilled in reverse fault stress regime.

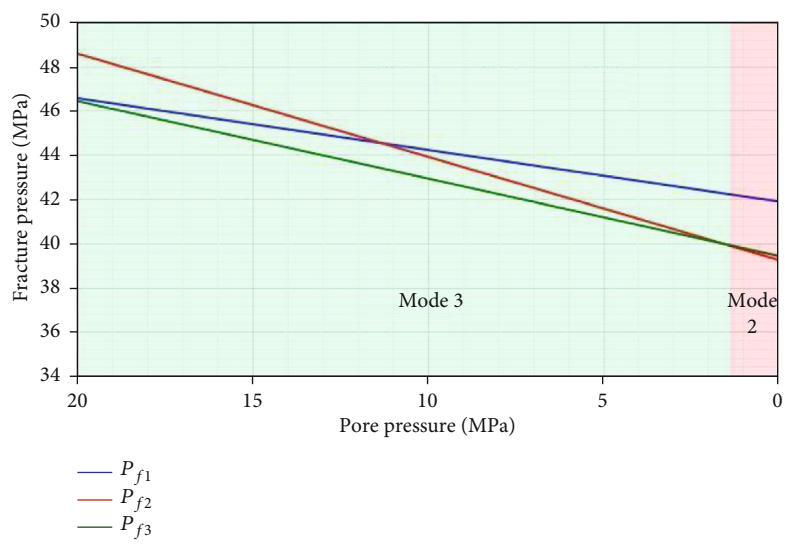


Figure 4: Change of fracture mode and fracture pressure with reservoir depletion of vertical wellbore drilled in strike fault stress regime.

used in previous calculations may make a great overestimate (about 13 MPa) for the fracture pressure

(2) Fracture mode will be changed with reservoir depletion, so different failure criteria at different stages of reservoir depletion should be selected; for example, in normal fault stress regime (Figure 2), Mode 1 first occurs in initial stage of reservoir depletion (16 MPa $\leq P_P \leq$ 20 MPa), but Mode 3 first occurs in the medium-term stage ($8 \leq P_P \leq 16$ MPa), and in the later period ($0 \leq P_P \leq 8$ MPa), Mode 2 first occurs

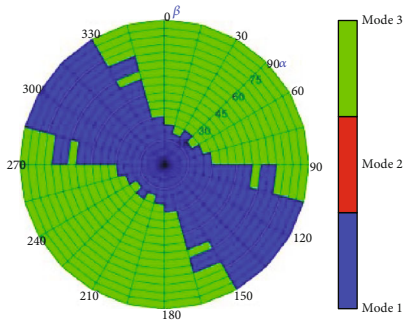
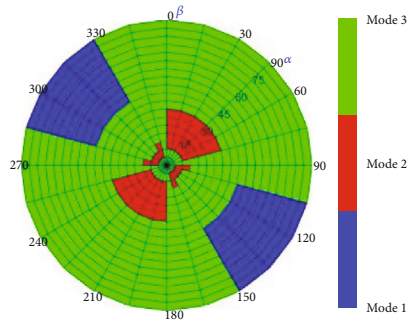
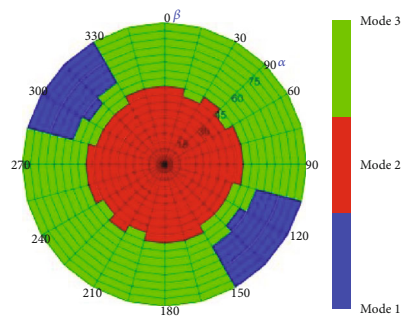
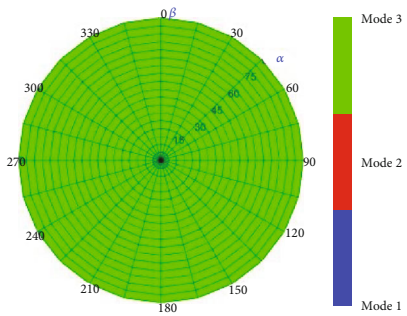
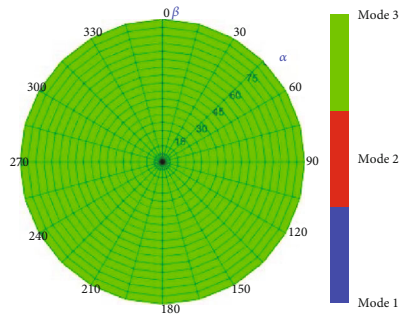
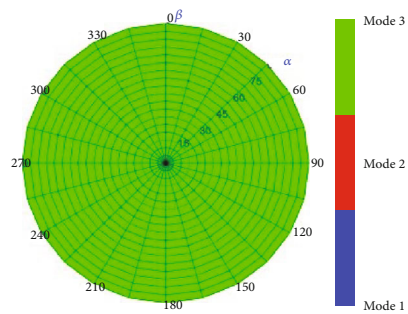
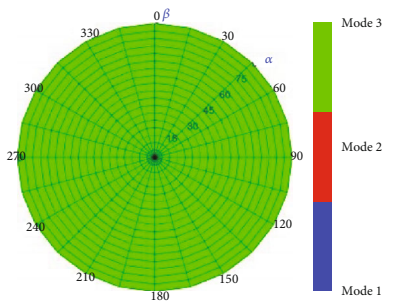
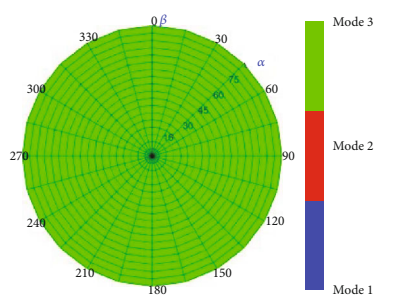
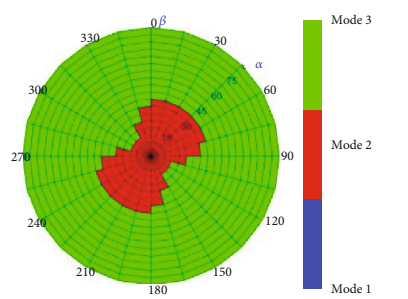
(3) Fracture pressure is no longer a single linear reduction with reservoir depletion; instead, three-step and two-step reduction may appear as shown in normal and strike fault stress regimes, respectively (Figures 2 and 4)

5.2. Directional Well. The changes of fracture mode with reservoir depletion of directional wellbore drilled in different fault stress regimes are illustrated in Table 1. In the table, the polar angle of the pies represents the well azimuth angle β, ranging from 0 to 360°, and the polar radius represents the well deviation angle α, ranging from 0 to 90°. Moreover, the blue areas represent Mode 1 first occurs when the well is fractured, the red areas represent Mode 2 first occurs, and the green areas represent Mode 3 first occurs.

The results show that fracture mode highly depends on reservoir depletion degree, well azimuth and deviation angle, and the in situ stress state; the specific relationships are as follows:

(1) In initial stage of reservoir depletion ($\Delta P_p = 0$ MPa), Mode 3 is the only fracture mode for the arbitrary

Table 1: Change of fracture mode with reservoir depletion of directional wellbore drilled in different fault stress regimes.

Fault type	Fracture mode ($\Delta P_p = 0$ MPa)	Fracture mode ($\Delta P_p = 10$ MPa)	Fracture mode ($\Delta P_p = 20$ MPa)
Normal fault			
Reverse fault			
Strike fault			

directional well drilled in the reverse and strike fault stress regimes, but for the normal fault stress regime, Mode 1 also appears in the wells drilled towards the direction of maximum horizontal in situ stress

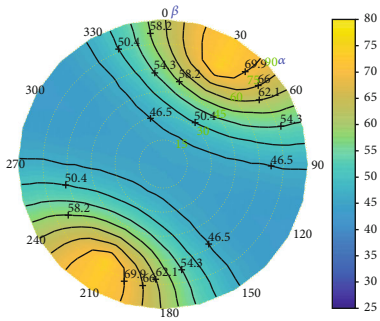
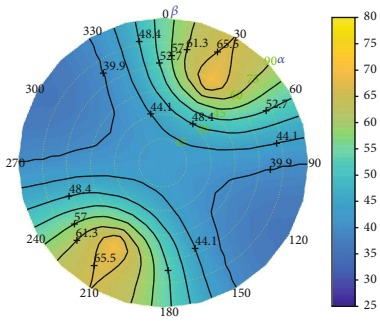
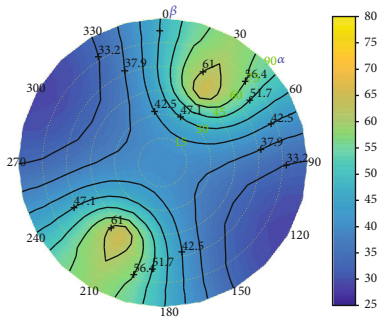
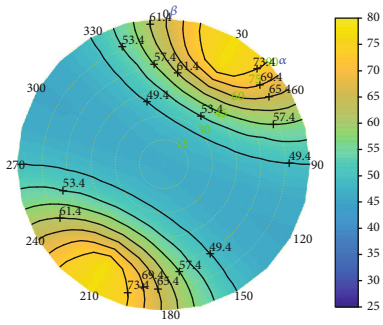
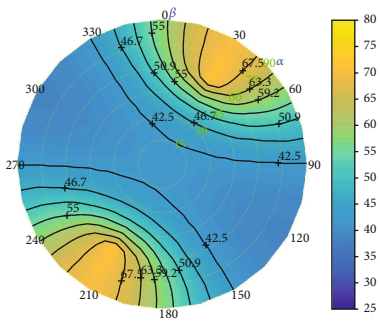
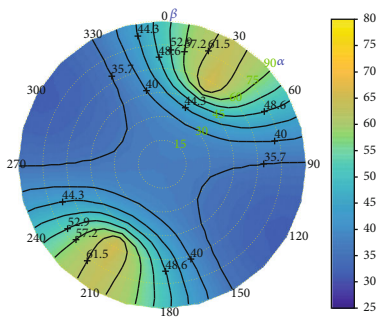
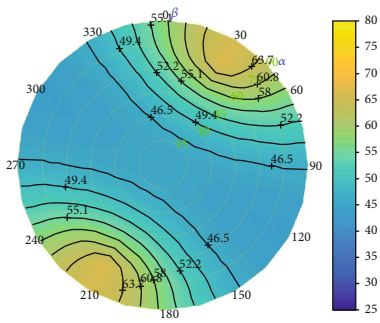
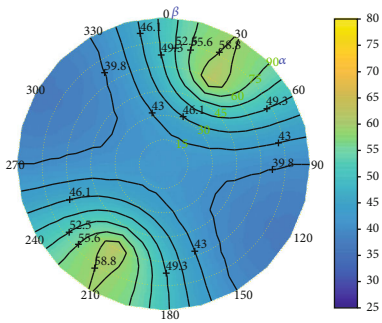
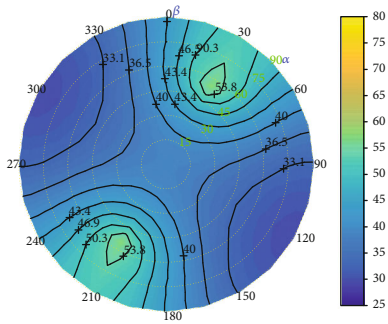
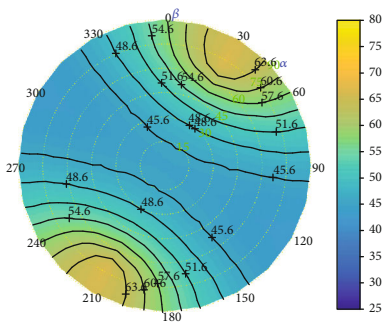
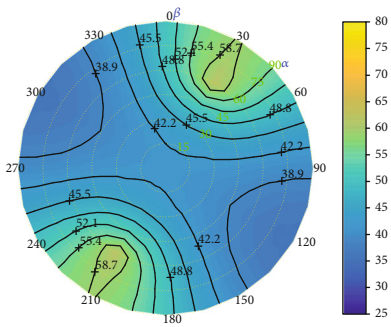
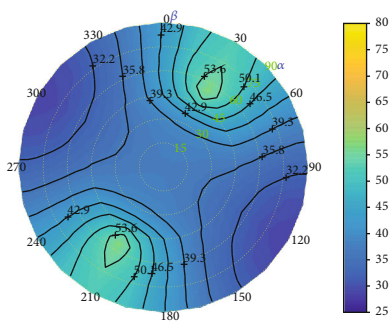
(2) In the medium-term stage of reservoir depletion ($\Delta P_p = 10$ MPa), the fracture modes remain unchanged for the arbitrary directional well drilled in the reverse and strike fault stress regimes. But for the normal fault stress regime, the fracture modes are changed; all of the three fracture modes come out. The fracture modes for some lowly deviated wells drilled towards the direction of maximum and minimum horizontal in situ stress are changed into Mode 3 and Mode 2, respectively

(3) In the later period of reservoir depletion ($\Delta P_p = 20$ MPa), only for the arbitrary directional well drilled in the reverse fault stress regimes, the fracture modes remain unchanged. For strike fault stress regimes, the fracture modes for some lowly deviated wells drilled towards the direction of minimum horizontal in situ stress are changed into Mode 2. And for normal fault stress regimes, the fracture modes for the lowly deviated wells towards arbitrary direction are all changed into Mode 2

The changes of fracture pressure with reservoir depletion of directional wellbore drilled in normal, reverse, and strike fault stress regimes are illustrated in Tables 2–4, respectively. In the table, the polar angle and radius of the pies represent the same meaning as in Table 1. The color represents specific value of the fracture pressure. The results show that the fracture pressure is not always decreased with reservoir depletion which depends on the well azimuth and deviation angle and the in situ stress state; the specific change rules are as follows:

(1) For normal fault stress regimes, all of the four fracture pressures in different modes show basically the same change rule with reservoir depletion; the fracture pressures are all decreased for the arbitrary directional wells

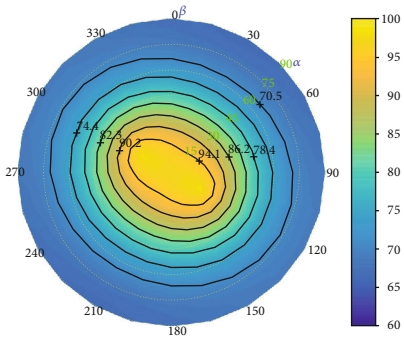
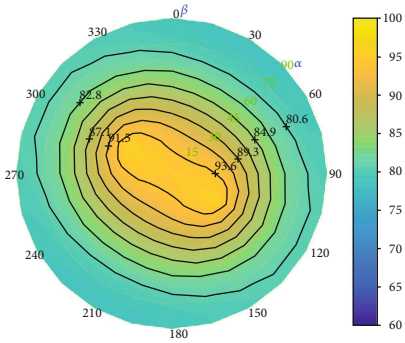
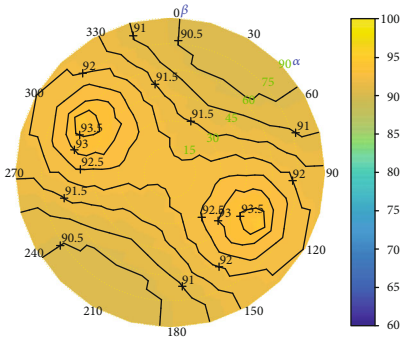
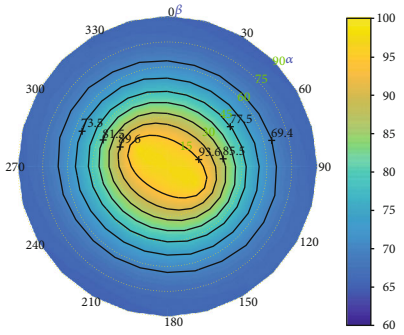
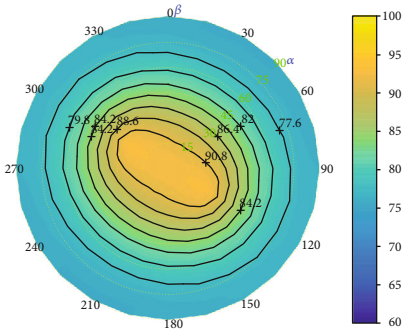
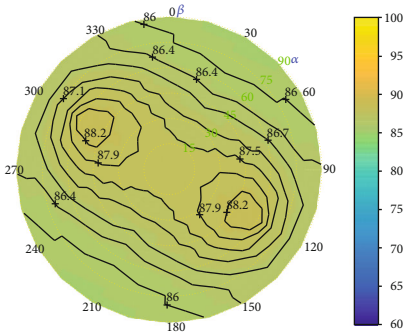
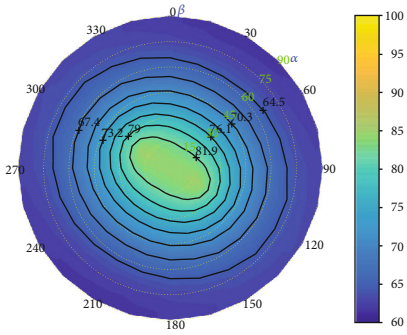
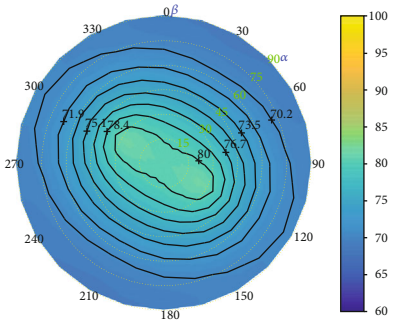
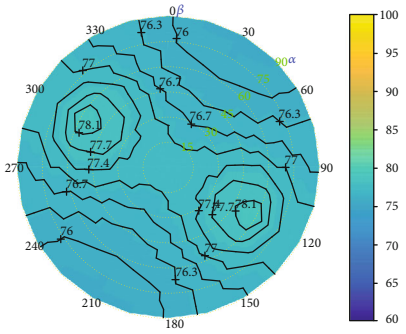
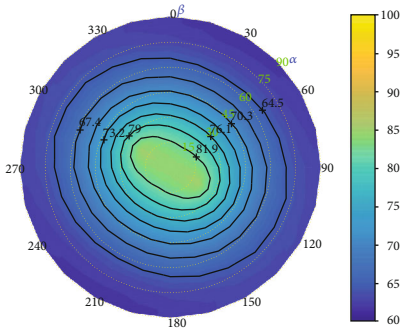
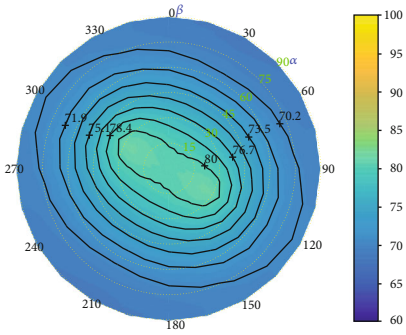
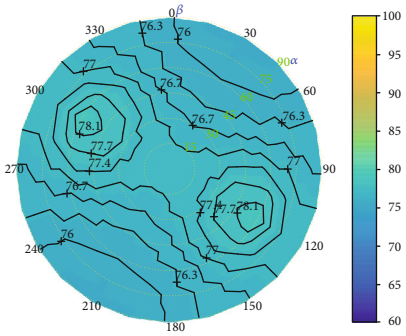
Table 2: The change of fracture pressure with reservoir depletion of directional wellbore drilled in normal fault stress regimes.

Fracture pressure	$\Delta P_p = 0$ MPa	$\Delta P_p = 10$ MPa	$\Delta P_p = 20$ MPa
P_{f1}			
P_{f2}			
P_{f3}			
P_f			

(2) For reverse fault stress regimes, all of the four fracture pressures in different modes also show basically the same change rule with reservoir depletion; the fracture pressures for the some lowly deviated wells drilled towards the direction of maximum horizontal in situ stress are decreased, but the fracture pressure of the other wells showed a pattern of increase

(3) For reverse fault stress regimes, all of the four fracture pressures in different modes also show basically the same change rule with reservoir depletion; the fracture pressures for the some highly deviated wells drilled towards the direction of minimum horizontal in situ stress are first increased and then decreased, but the fracture pressure of the other wells showed a pattern of decrease

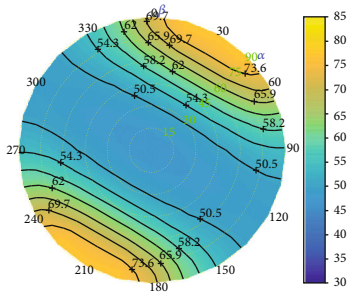
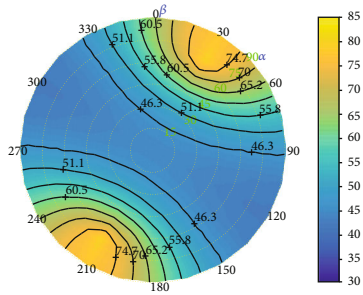
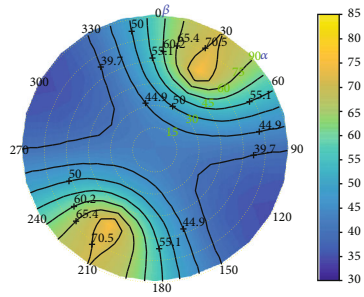
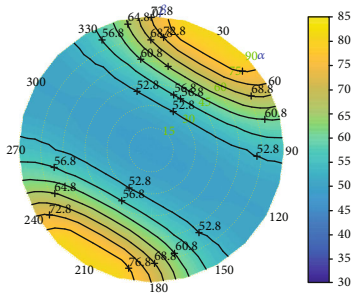
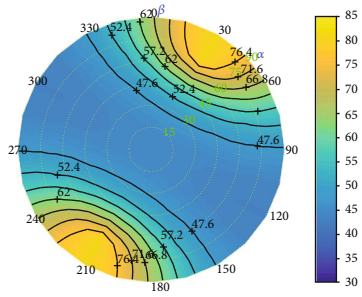
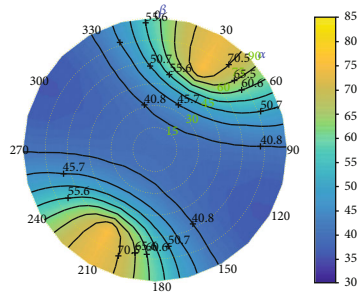
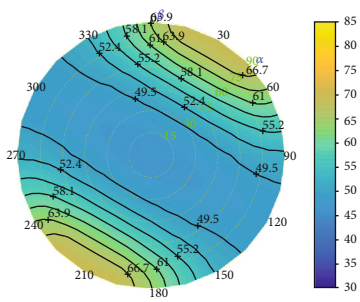
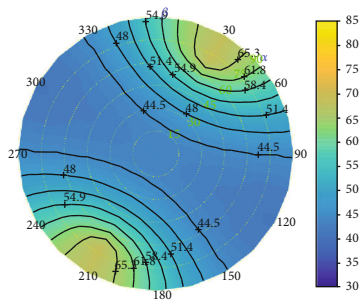
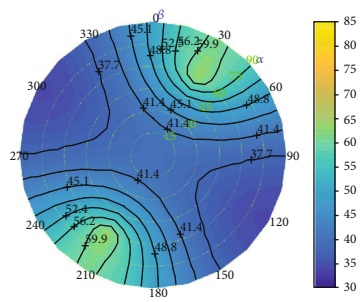
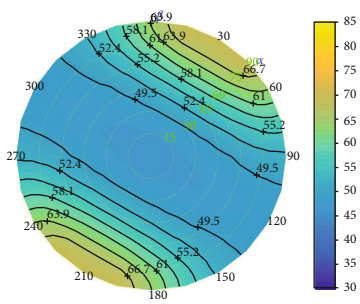
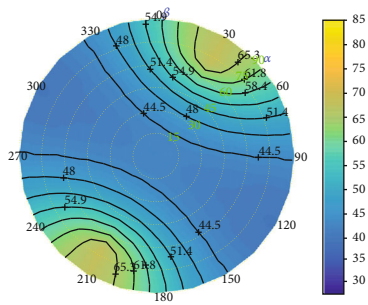
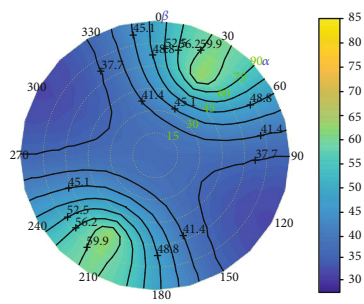
Table 3: The change of fracture pressure with reservoir depletion of directional wellbore drilled in reverse fault stress regime.

Fracture pressure	$\Delta P_p = 0$ MPa	$\Delta P_p = 10$ MPa	$\Delta P_p = 20$ MPa
P_{f1}			
P_{f2}			
P_{f3}			
P_f			

6. Model Validation

The field data are collected from M well drilled in the South China Sea, and the maximum horizontal principal stress orientation is N165°. The reservoir depth is 1300~1400 m, and initial pore pressure is 13.5~14.5 MPa. The gas field has now been in production for nearly 20 years, and pore pressure has been depleted into 6.5~7.0 MPa. In order to stabilize the yield of the gas field, the extended reach horizontal well M was drilled with 88°~94° deviation angle towards N250°E direction. According to the Addis and Li and Gray's model [11, 15], the fracture pressure after reservoir depletion is

Table 4: The change of fracture pressure with reservoir depletion of directional wellbore drilled in strike fault stress regime.

Fracture pressure	$\Delta P_p = 0$ MPa	$\Delta P_p = 10$ MPa	$\Delta P_p = 20$ MPa
P_{f1}			
P_{f2}			
P_{f3}			
P_f			

basically over 21 MPa (Figure 5), and the fluid pressure inside the wellbore was set below the fracture pressure to ensure the borehole stability. But several mud losses were induced during the drilling process.

Based on the analysis by using the model of this study, it is found that the fracture mode belongs to Mode 3, and the pressure of this well is basically below 21 MPa at present. The pressure at the location of mud loss reaches the fracture pressure resulting in mud loss. The model of this study is more consistent with the actual drilling condition, which verifies the effectiveness of the model.

7. Conclusion

Hydrocarbon extraction usually leads to pore pressure decline within a reservoir, which further changes the wellbore fracture mode and fracture pressure drilled in the depleted reservoir. Accurate evaluation of the fracture pressure on the basis of correct judgment of the fracture mode is the foundation of safe and efficient drilling. The expression is somewhat unclear. It is suggested to change it to:Traditional studies have considered that tensile failure is the fracture mode and the fracture pressure should

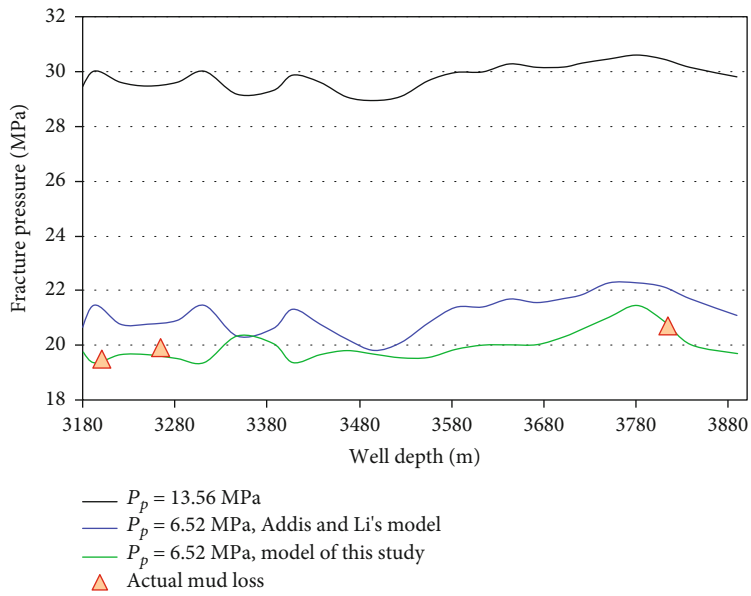


Figure 5: Comparison between the fracture pressure in different models and actual mud loss cases.

be determined by a tensile failure criterion, which are not suitable for the depleted reservoir.

In this paper, the studies focus on the change of the fracture mode and fracture pressure with reservoir depletion; the analysis results show the following:

(1) Tension failure is not the only fracture mode; any of the three fracture modes including shear fracture when the drilling fluid pressure inside the borehole is high enough may first occur in the well drilled in depleted reservoir

(2) Fracture mode will be changed with reservoir depletion, and the fracture mode highly depends on reservoir depletion degree, well azimuth and deviation angle, and the in situ stress state, so different failure criteria at different stages of reservoir depletion should be selected to accurately evaluate the fracture pressure

(3) For the vertical well, the fracture pressure is decreased with reservoir depletion, but the difference from conventional views is that fracture pressure is no longer a single linear reduction with reservoir depletion; instead, three-step and two-step reduction may appear due to the change of fracture mode

(4) For the directional well, the fracture pressure is not always decreased with reservoir depletion; the other patterns such as increase and first increase then decrease may also appear for the wells drilled in reverse and strike fault stress regimes

Data Availability

The data used to support the findings and results of this study are available from the corresponding authors upon request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Acknowledgments

The authors gratefully acknowledge the support of the National Natural Science Foundation of China (Grant No. 52074224 and Grant No. 52074221), the Research Foundation of Key Laboratory of Deep Geodrilling Technology, Ministry of Natural Resources, China University of Geosciences (Beijing) (Grant No. KF201902), and the Key Research and Development Program of Shandong Province (2019GGX103025).

References

[1] F. Meng and G. F. Fuh, "Reservoir depletion effect on in-situ stresses and mud weight selection," in *In Proceedings of the 44th U.S. Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium*, pp. 27–30, Salt Lake City, UT, USA, 2010.

[2] M. A. Addis, N. C. Last, and N. A. Yassir, "Estimation of horizontal stresses at depth in faulted regions and their relationship to pore pressure variations," *SPE Formation Evaluation*, vol. 11, no. 1, pp. 11–18, 1996.

[3] J. F. Jones, G. D. Taylor, and R. D. Barree, "Successfully managing drilling-fluid losses in multiple, highly depleted sands," *SPE Drilling & Completion*, vol. 18, no. 2, pp. 182–187, 2003.

[4] E. Van Oort, J. E. Friedheim, T. Pierce, and J. Lee, "Avoiding losses in depleted and weak zones by constantly strengthening wellbores," *SPE Drilling and Completion*, vol. 26, no. 4, pp. 519–530, 2011.

[5] S. Benaissa, A. Bachelot, J. Ricaud, G. Arquey, X. Yi, and S. Ong, "Preventing differential sticking and mud losses drilling through highly depleted sands. Fluids and geomechanics

approach," in *In Proceedings of the SPE/IADC Drilling Conference*, pp. 23–25, Amsterdam, the Netherlands, 2005.

[6] P. Reid and H. Santos, "Novel drilling, completion and workover fluids for depleted zones: avoiding losses, formation damage and stuck pipe," in *In Proceedings of the SPE/IADC Middle East Drilling Technology Conference and Exhibition*, pp. 20–22, Abu Dhabi, UAE, 2003..

[7] J. D. Fett, F. Martin, C. Dardeau et al., "Case history: successful wellbore strengthening approach in a depleted and highly unconsolidated sand in deepwater Gulf of Mexico," *SPE Drilling and Completion*, vol. 25, no. 4, pp. 500–508, 2010.

[8] A. M. Al-Ajmi, A. S. Al-Rushoud, A. K. Gohain et al., "Nanotechnology improves wellbore strengthening and minimizes differential sticking problems in highly depleted formations," in *In Proceedings of the Abu Dhabi International Petroleum Exhibition & Conference*, pp. 7–10, Abu Dhabi, UAE, 2016.

[9] Y. Feng, J. F. Jones, and K. E. Gray, "A review on fracture-initiation and -propagation pressures for lost circulation and wellbore strengthening," *SPE Drilling & Completion*, vol. 31, no. 2, pp. 134–144, 2016.

[10] Y. Feng and K. E. Gray, "Modeling lost circulation through drilling-induced fractures," *SPE Journal*, vol. 23, no. 1, pp. 205–223, 2018.

[11] M. A. Addis, "Reservoir depletion and its effect on wellbore stability evaluation," *International Journal of Rock Mechanics and Mining Sciences*, vol. 34, no. 3-4, 1997.

[12] X. Q. Kang and Y. J. Xue, "Applied rock mechanics in drilling of depleted reservoirs in deepwater Gulf of Mexico," *Petrophysics*, vol. 50, pp. 231–236, 2009.

[13] M. W. Alberty and M. R. McLean, "Fracture gradients in depleted reservoirs-drilling wells in late reservoir life," in *In Proceedings of the SPE/IADC Drilling Conference*, Amsterdam, the Netherlands, 2001.

[14] A. Manhalawi, A. S. Dahab, A. M. Abdulaziz, A. K. Abbas, and N. AL-Husseini, "Wellbore stability evaluation for depleted reservoir," in *Paper Presented at the 54th U.S. Rock Mechanics/Geomechanics Symposium, Physical Event Cancelled*, June 2020.

[15] X. Li and K. E. Gray, "Wellbore stability of deviated wells in depleted reservoir," in *Paper Presented at the SPE Annual Technical Conference and Exhibition*, Houston, Texas, USA, 2015.

[16] A. M. Al-Ajmi and R. W. Zimmerman, "Stability analysis of vertical boreholes using the Mogi-Coulomb failure criterion," *International Journal of Rock Mechanics and Mining Sciences*, vol. 43, no. 8, pp. 1200–1211, 2006.

[17] E. Fjær, R. M. Holt, P. Horsrud, A. M. Raaen, and R. Risnes, *Petroleum Related Rock Mechanics*, Elsevier, Amsterdam, 2nd edition, 2008.

[18] E. M. Anderson, *The Dynamics of Faulting, and Dyke Formation with Applications to Britain*, Oliver and Boyd, Edinburg, 1951.