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Prediction Method of Safety Mud Density in Depleted Oilfields

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Abstract: At present, many oilfields were placed in the middle and late development period and the reservoir pressure depleted usually, resulting in more serious differential pressure sticking and drilling mud leakage both in the reservoir and cap rock. In view of this situation, a systematic prediction method of safety mud density in depleted oilfields was established. The influence of reservoir depletion on stress and strength in reservoir and cap formation were both studied and taken into the prediction of safety mud density. The research showed that the risk of differential pressure sticking and drilling mud leakage in reservoir and cap formation were both increased and they were the main prevention object in depleted oilfields drilling. The research results were used to guide the practice drilling work, the whole progress gone smoothly.

Keywords: Cap, depleted oilfields, prediction method, reservoir, safety mud density

INTRODUCTION

In the middle and late period of many oil and gas fields, reservoir depletion occurred usually, the risk of differential pressure sticking and drilling mud leakage was increased significantly, which have serious influence on the exploration and development process of the oil and gas. BP Company (Shaughnessy *et al*., 2001) and Marathon Company (Jones *et al*., 2003) have developed the depleted oilfields in the Louisiana of U.S.A and the North Sea respectively, the practice showed that effectively seal is the key of drilling in depleted oilfields. In China, mud leakage also occurred in many depleted oilfields and around 1990, more than 50% wells occurred mud leakage in Zhongyuan, Daqing, Qinghai and Liaohe depleted oilfields (Xu *et al*., 1997). It is closed related to unreasonable mud density. So studying the prediction method of safety mud density in depleted oilfields has great significance for the old oilfields.

Reservoir depletion caused the change of stress and strength both in reservoir and cap formation, resulting in the change of wellbore stability. Ge *et al*. (1994), Addis (1997), Liang *et al*. (2004), Shi and Jin (2008) and Tan *et al*. (2010) have studied the influence on reservoir wellbore stability of reservoir depletion, they all thought reservoir depletion have an affect on reservoir in-situ stress and further on wellbore stability. But they did not consider the reservoir strength change and the change of wellbore stability in cap formation. Morita and Giin-Fa (2009) studied the influence on cap pressure of reservoir depletion, but the cap strength change caused by dehydration was not considered. This study comprehensive studied the change of stress and strength both in reservoir and cap formation and prediction method of safety mud density was established.

THE MECHANICS PARAMETERS CHANGE OF RESERVOIR AND CAP ROCK

The mechanics parameters change of reservoir and cap rock occurred due to reservoir depletion. The specific was as followed:

- For reservoir formation, reservoir depletion caused the subsidence and compaction, which have an effect on the in-situ stress and rock strength
- For cap formation, pressure difference was generated between the reservoir and cap due to reservoir depletion, even for the low permeability shale, pressure transmission also occurred due to long time pressure differential drive, which have an effect on cap in-situ stress, in addition, mass transfer was almost simultaneous with pressure transmission and causing the cap dehydration which have an effect on the cap strength.

Reservoir: After long-term development, reservoir pressure depletion occurred, which caused the change of the horizontal in-situ stress. Based on the generalized Hooke's law, the relationship between stress and strain of reservoir rock before development is:

$$\begin{cases} \varepsilon_v = \frac{1}{E}\left[\sigma_v - \alpha P_p - \mu\left(\sigma_h - \alpha P_p + \sigma_H - \alpha P_p\right)\right] \\ \varepsilon_H = \frac{1}{E}\left[\sigma_H - \alpha P_p - \mu\left(\sigma_v - \alpha P_p + \sigma_h - \alpha P_p\right)\right] \\ \varepsilon_h = \frac{1}{E}\left[\sigma_h - \alpha P_p - \mu\left(\sigma_v - \alpha P_p + \sigma_H - \alpha P_p\right)\right] \end{cases} \quad (1)$$

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For the situation that the reservoir is deeper and the ratio of the reservoir thickness to the distribution area is too small, the two assumptions are made as followed:

- The reservoir is homogeneous isotropic elastic body
- Pressure depletion only causes the vertical deformation without horizontal deformation of the stratum. So the reservoir horizontal in-situ stress after pressure depletion was achieved:

$$\begin{cases} \sigma_{H1}=\sigma_H-\dfrac{1-2\mu}{1-\mu}\alpha\Delta P_p \\ \sigma_{h1}=\sigma_h-\dfrac{1-2\mu}{1-\mu}\alpha\Delta P_p \end{cases} \quad (2)$$

where, σ_{H1} and σ_{h1} are the maximum and minimum horizontal in-situ stress respectively after pressure depletion, MPa; σ_H and σ_h are the original maximum and minimum horizontal in-situ stress respectively, MPa; μ is the Poisson's ratio; α is the effective stress coefficient ; ΔP_p is the pressure depletion, MPa;.

From the above formula, we can see that along with the reservoir pressure depletion, the minimum in-situ stress also reduced and their depletion was remarkably linear correlation.

In addition the in-situ stress reduced, the reservoir strength also changed due to pressure depletion. Usually the overburden stress remain unchanged, so the effective stress on the rock matrix will increase accordingly, resulting in most of the upper rock load transfer to the rock matrix and finally the reservoir was compaction and its porosity reduced. Furthermore, rock porosity is an important indication of the strength, as a general rule, the bigger rock porosity and the less compressive strength, the phenomenon is the concrete embodiment of the rule that the compressive strength usually decreased with rocks density lower. So we can using the porosity to establish the relation between the reservoir strength change and pressure depletion.

Using the rock compression coefficient and the overburden stress was assumed the same; the porosity change with reservoir pressure depletion was gained (Liu *et al*., 2010):

$$d\varphi=[C_s\varphi(1-2\varphi)+(C_b-C_s)(1-\varphi)]dp \quad (3)$$

where,

$d\varphi$ = The porosity change, %
C_s = The rock matrix compression coefficient per MPa
φ = The rock porosity, %
C_b = The rock compression coefficient per MPa
dp = The pressure depletion

According to the Wylie's model (Wang and Shi, 2010), the original porosity before pressure depletion can be gained by logging data of the exploratory well at the early development,

$$\varphi=(\rho_{ma}-\rho_b)/(\rho_{ma}-\rho_f) \quad (4)$$

where,

φ = The rock porosity, %
ρ_{ma} = The rock matrix density, g/cm^3
ρ_f = The formation water density, g/cm^3
ρ_b = The rock density, g/cm^3

So, the present porosity after pressure depletion can be predicted by making the formula (4) substituted into formula (3):

$$\varphi_1=(\rho_{ma}-\rho_b)/(\rho_{ma}-\rho_f)-[C_s\varphi(1-2\varphi)+(C_b-C_s)(1-\varphi)]dp \quad (5)$$

The rock porosity has closed relation with the strength and the sandstone strength can be calculated using the porosity (Chang *et al*., 2006):

$$UCS=277\exp(-10\varphi) \quad (6)$$

where UCS is the uniaxial compression strength, MPa.

We can use the reservoir core gained from the early exploratory well to correct the above formula and the uniaxial compression strength after pressure depletion can be predicted:

$$UCS_1=USC_0/\exp(-10\varphi_0)\times\exp(-10\varphi_1) \quad (7)$$

where,

UCS_1 = The present uniaxial compression strength after pressure depletion, MPa
UCS_0 = The original reservoir strength gained by testing the reservoir core from the early exploratory well in research area, MPa

For the other rock strength parameters using in the wellbore stability calculation to confirm the safety mud density, they are closely related to the UCS, so they can be obtained by establishing the relation between themselves and the UCS. The parameters mainly include tensile strength, cohesion and internal friction angle.

Generally, the UCS is generally 8 to 15 times of the tensile strength, so we can approximate evaluate the rock tensile strength after pressure depletion as follow (Jin *et al*., 2011):

$$S_{t1} = UCS_1/12 \quad (8)$$

where, S_{t1} is the rock tensile strength after pressure depletion, MPa.

According to the Mohr-Coulomb criterion, Al-Awad (2000) established the relationship between cohesion and UCS, so the cohesion after pressure depletion can be predicted as follow:

$$C_1 = -0.417 + 0.289 \times UCS_1 - 0.000519 \times UCS_1^2 \quad (9)$$

where, C_1 is the cohesion after pressure depletion, MPa.

Furthermore, the internal friction angle is related to the cohesion, it can be gained from the simple linear relation (Deng *et al*., 2008):

$$\theta_1 = 36.545 - 0.4952C_1$$

where, θ_1 is the internal friction angle after pressure depletion, deg.

CAP ROCK

The pressure in cap rock also reduced with reservoir depletion, because pressure difference was generated between the reservoir and cap rock. The pressure in cap rock after reservoir depletion is gained (Morita and Giin-Fa, 2009):

$$P = P_i - (P_i - P_r)[(1 + \frac{z^2}{2\lambda t_c})\mathrm{erfc}(\frac{z}{2\sqrt{\lambda t_c}}) - \frac{z}{\sqrt{\pi\lambda t_c}} e^{-\frac{z^2}{4\lambda t_c}}] \quad (10)$$

where,

- P = The present pressure in cap rock after reservoir depletion, MPa
- P_i = The original pressure in cap rock, MPa
- P_r = The reservoir pressure after depletion, MPa
- z = The vertical distance from the cap rock to the top reservoir, ft
- t_c = The time, year
- λ = The function of compression coefficient, porosity, permeability and so on.

It can be seen that from the above formula the pressure of some range cap rock above reservoir is influenced by reservoir depletion in some time. The present in-situ stress can be gained by making the formula (10) substituted into formula (2):

$$\begin{cases} \sigma_{H1} = \sigma_H - \frac{1-2\mu}{1-\mu}\alpha(P_i - P_r)[(1 + \frac{z^2}{2\lambda t_c})\mathrm{erfc}(\frac{z}{2\sqrt{\lambda t_c}}) - \frac{z}{\sqrt{\pi\lambda t_c}} e^{-\frac{z^2}{4\lambda t_c}}] \\ \sigma_{h1} = \sigma_h - \frac{1-2\mu}{1-\mu}\alpha(P_i - P_r)[(1 + \frac{z^2}{2\lambda t_c})\mathrm{erfc}(\frac{z}{2\sqrt{\lambda t_c}}) - \frac{z}{\sqrt{\pi\lambda t_c}} e^{-\frac{z^2}{4\lambda t_c}}] \end{cases} \quad (11)$$

The cap rock strength also changed due to pressure depletion, but its mechanism is different from reservoir, which is mainly caused by dehydration together with the pressure transmission. For the porous rock, mass transfer is together with the pressure transmission, which is the main cause of dehydration in cap rock. Furthermore, water content depletion induced the strength change of the cap rock. So the relation between the strength and pressure transmission in cap rock can be gained through establishing the relation between the pressure transmission, mass transmission, water content and the strength parameters.

According to the porous media percolation mechanics principle and mass conservation equation, the relation between the pressure transmission, mass transmission and water content can be gained (Cheng *et al*., 2006):

$$\frac{1}{r}\frac{\partial(ru)}{\partial r} + \varphi\rho C_f \frac{\partial P}{\partial t} = 0 \quad (12)$$

$$\frac{1}{r}\frac{\partial(ru)}{\partial r} = \frac{\partial w}{\partial t} \quad (13)$$

where,

- u = Water flow mass, g/s
- φ = The rock porosity, %
- ρ = The rock density, g/cm^3
- C_f = The fluid compression ratio, per Pa^{-1}
- P = The pore pressure, MPa
- w = Water content, %

The relation between the water content and the strength parameters (cohesion and inter friction angle) was gained though indoor experiment on cores from site cap formation. We tested the uniaxial and triaxial compressive strength in different water content and the cohesion and inter friction angle were gained by the Mohr-Coulomb criterion, then the relation between the water content and the strength parameters (cohesion and inter friction angle) was established through simple linear fitting method (Fig. 1 and 2):

$$\begin{cases} C = -0.172w + 6.106 \\ \theta = -2.331w + 36.283 \end{cases} \quad (14)$$

where,

- C = The cohesion, MPa
- θ = The internal friction angle, deg
- w = Water content, %

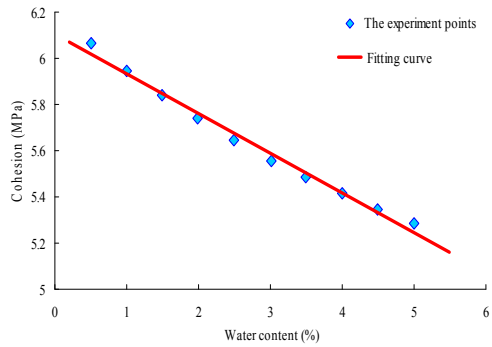

Fig. 1: The change law of rock cohesion with water content

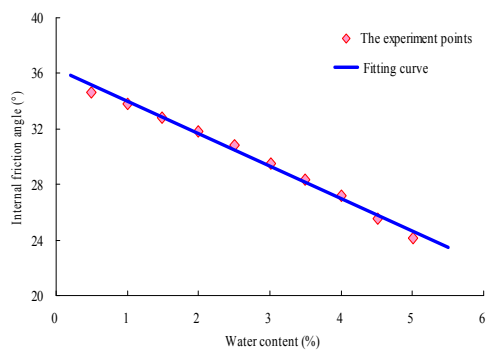

Fig. 2: The change law of rock internal friction angle with water content

Simultaneous Eq. (12) ~ (14), the relation between the strength parameters and pressure transmission in cap rock can be gained. Then, the tension strength in cap rock is changed as followed:

$$S_t = 2 \times C \times \tan(45^o + \theta)/12 \tag{15}$$

DESIGN METHOD OF SAFETY MUD DENSITY

The character of reservoir and cap rock changed in many aspects of depletion oilfields, remarkable performance in pore pressure, in-situ stress and rock strength, which brings the different design method of safety mud density in depletion oilfields. Two points are specially considered:

- Sticking tool and mud leakage in larger pressure difference
- Wellbore mechanical stability change

Prevent sticking tool and mud leakage in larger pressure difference: In depleted oilfields, larger pressure difference generated easily due to lower pore pressure which result in greater risk in sticking tool and mud leakage. Safety mud density design should pay more attention in the two aspects than original oilfields.

Usually, the higher mud density was needed in order to prevent the compression failure in the adjacent shale formation. But not all is favorable with higher mud density, when the mud density increased to the upper value, sticking tool would occur, so the safety mud density should be lower than the upper limit which generated the mud column pressure is called sticking pressure:

$$(\rho_{max} - \rho_{pi}) \times H_i \times 0.00981 \le \Delta P \tag{16}$$

where,

ρ_{max} = The maximum mud density, g/cm^3
ρ_{pi} = The formation pressure confident, g/cm^3
H_i = Formation vertical depth, m
ΔP = The acceptable values of pressure difference avoiding the sticking tool

In addition, if an effective mud cake cannot form, mud leakage into the formation would occur under larger pressure difference drive. Worse still, when the mud leakage speed is more than supply speed, the mud column height would drop resulting in the lower mud column pressure, which would cause the borehole collapse instability. So controlling the mud leakage speed is very important to the successful drilling.

Based on the basic principle of permeation fluid mechanics, the theory analysis of the mud leakage speed was run combining the forming process of the mud cake. The mud cake thickness on borehole wall was assumed to be constant during the mud circulation process, that is to say the dynamic balance between flushing and forming is reached. The permeation process is assumed to be a quasi-steady state process, then the mud leakage speed can be obtained according to the principle of permeation fluid mechanics:

$$Q = \frac{2a\pi h(P_w - P_o)}{\mu\left(\frac{1}{K_1}\ln\frac{R_w}{R_m} + \frac{1}{K_2}\ln\frac{R_o}{R_w}\right)} \tag{17}$$

where,

Q = The leakage volume rate, m^3/d
h = Thickness of the leakage zone, m
P_w = The bottom-hole pressure, MPa
P_o = The formation pore pressure, MPa
μ = The viscosity of mud filtrate, MPa/s
K1 = The permeability of mud cake, um^2
K_2 = The formation permeability, um^2
R_w = The drill bit diameter, m
R_m = The sum of the mud cake thickness and drill bit diameter, m
R_o = The seepage radius, $R_o >> R_w$, m
a = A coefficient, which is related to unit system, skin factor and so on

In the overbalance drilling process, drilling fluid density is larger than formation pressure coefficient, so the mud permeation to the formation exists usually in theory, this phenomenon is not obviously in lower permeability shale, but in the higher permeability sandstone, especially in depleted sandstone reservoir with larger pressure difference, this phenomenon is obviously and need prevention and treatment emphasis. According to the formula 17, the larger well bottom pressure difference under the fixed other conditions, the faster leakage speed and the mud leakage speed is not allowed beyond the upper value in drilling engineering, corresponding mud column pressure is defined as leakage pressure. At present, the allowed mud leakage speed in the drilling engineering has no explicit standards, so we investigated on-site drilling engineering in some oilfields and found that 1~2 m^3/h leakage speed is not thought as serious which can be controlled through on-site technical measures. So the leakage pressure can be obtained through inverse computation formula 17:

$$P_l=P_o+\frac{Q_l\mu(\frac{1}{K_1}\ln\frac{R_w}{R_m}+\frac{1}{K_2}\ln\frac{R_0}{R_w})}{2a\pi h} \tag{18}$$

where,

P_l = The leakage pressure, MPa
Q_l = The allowed leakage speed, m^3/d

Prevent borehole instability: Unreasonable mud density often causes borehole instability mainly including borehole collapse and fracture. Because the mechanics parameters change of reservoir and cap rock in depleted oilfields, resulting in the change of stress state and strength on the borehole wall, finally borehole mechanics stability is changed. So the drilling well safety mud density in depleted oilfields is different from that in early stage. The calculation model of collapse and fracture pressure in vertical well has been obtained with analytical solution (Roegiers, 2002), so we can take the mechanics parameters after pressure depletion into the calculation model to analyze the collapse and fracture pressure in depleted oilfields:

$$\rho_m=\frac{\eta(3\sigma_{H1}-\sigma_{h1})-2C_l\cot(45^o-\frac{\theta_l}{2})+\alpha P_{pl}(\cot^2(45^o-\frac{\theta_l}{2})-1)}{(\cot^2(45^o-\frac{\theta_l}{2})+\eta)\times H}\times 100 \tag{19}$$

$$\rho_f=\frac{3\sigma_{h1}-\sigma_{H1}-\alpha P_{pl}+S_{tl}}{H}\times 100 \tag{20}$$

where,

ρm = The equivalent mud density of collapse pressure, g/cm^3
ρ_f = The equivalent mud density of fracture pressure, g/cm^3
η = Stress nonlinear correction coefficient;
σ_{H1}, σ_{h1} = The maximum and minimum horizontal in-situ stress respectively after pressure depletion, MPa
C_1 = The cohesion after pressure depletion, MPa
θ_1 = The internal friction angle after pressure depletion, deg
P_{p1} = the formation pore pressure after pressure depletion, MPa
H = The formation vertical depth, m
S_{t1} = The rock tensile strength after pressure depletion, MPa.

But for the deviated well, the collapse and fracture pressure cannot be obtained though analytical solution, so we should recalculated the stress state and strength on the borehole wall using the mechanics parameters after pressure depletion and choose reasonable failure criteria to ensure the collapse and fracture pressure.

The in-situ stress tensor in borehole coordinate system can be obtained through coordinate transformation (Fairhurst, 1968) and the one in depleted oilfields can be obtained through taking the in-situ stress after pressure depletion into the transformation formula:

$$\begin{bmatrix}\sigma_{xx} & \sigma_{xy} & \sigma_{xz}\\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz}\\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz}\end{bmatrix}=\begin{bmatrix}\cos\alpha\cos\beta & \cos\alpha\sin\beta & -\sin\beta\\ -\sin\beta & \cos\beta & 0\\ \sin\alpha\cos\beta & \sin\alpha\cos\beta & \cos\beta\end{bmatrix}\begin{bmatrix}\sigma_{Hl} & 0 & 0\\ 0 & \sigma_{hl} & 0\\ 0 & 0 & \sigma_z\end{bmatrix}\begin{bmatrix}\cos\alpha\cos\beta & \cos\alpha\sin\beta & -\sin\beta\\ -\sin\beta & \cos\beta & 0\\ \sin\alpha\cos\beta & \sin\alpha\cos\beta & \cos\beta\end{bmatrix}^T \tag{21}$$

where,

α = Hole azimuth angle, deg
β = Hole deviation angle, deg

Under the principle of general plane strain, for small deformation, the rock effective stress state around the borehole can be obtained though superposition of the above six in-situ stress components and mud column pressure:

$$\sigma_r=\frac{R^2}{r^2}P_w+\frac{(\sigma_{xx}+\sigma_{yy})}{2}(1-\frac{R^2}{r^2})+\frac{(\sigma_{xx}-\sigma_{yy})}{2}(1+\frac{3R^4}{r^4}-\frac{4R^2}{r^2})\cos2\theta+\sigma_{xy}(1+\frac{3R^4}{r^4}-\frac{4R^2}{r^2})\sin2\theta-aP_{P1} \tag{22}$$

$$\sigma_\theta=-\frac{R^2}{r^2}P_w+\frac{(\sigma_{xx}+\sigma_{yy})}{2}(1+\frac{R^2}{r^2})-\frac{(\sigma_{xx}-\sigma_{yy})}{2}(1+\frac{3R^4}{r^4})\cos2\theta-\sigma_{xy}(1+\frac{3R^4}{r^4}-\frac{4R^2}{r^2})\sin2\theta-aP_{P1}$$

$$\sigma_z=\sigma_{zz}-v[2(\sigma_{xx}-\sigma_{yy})(\frac{R}{r})^2\cos2\theta+4\sigma_{xy}(\frac{R}{r})^2\sin2\theta]-aP_{P1}$$

$$\sigma_{r\theta}=\sigma_{xy}(1-\frac{3R^4}{r^4}+\frac{2R^2}{r^2})\cos2\theta-aP_{P1}$$

$$\sigma_{\theta z}=\sigma_{yz}(1+\frac{R^2}{r^2})\cos\theta-\sigma_{xz}(1+\frac{R^2}{r^2})\sin\theta-aP_{P1}$$

$$\sigma_{zr}=\sigma_{xz}(1-\frac{R^2}{r^2})\cos\theta+\sigma_{yz}(1-\frac{R^2}{r^2})\sin\theta-aP_{P1}$$

where,

$\sigma_r, \sigma_\theta, \sigma_z, \sigma_{r\theta}, \sigma_{\theta z}, \sigma_{rz}$ = The effective stress components in borehole cylindrical coordinate system, MPa
P_w = Mud column pressure, MPa
R = Borehole radius, m
r = The distance from the formation to the hole center, m
θ = The well round angle, deg
ν = Poisson ratio.

From the above formula, we can see that σ_r is a principal stress on the borehole wall, the other two principal stresses can be obtained as followed:

$$\sigma_{1,2}=\frac{\sigma_z+\sigma_\theta}{2}\pm\sqrt{\left[\frac{\sigma_z-\sigma_\theta}{2}\right]^2+\sigma_{\theta z}^2} \quad (23)$$

So the maximum and minimum principal stress is:

$$\sigma_{max}=\max\left(\sigma_1,\sigma_2,\sigma_r\right);\sigma_{min}=\min\left(\sigma_1,\sigma_2,\sigma_r\right) \quad (24)$$

The rock stress state around the borehole has been obtained; the next key is to choose reasonable failure criteria. Mohr-Coulomb criterion is usually used as the criterion of borehole collapse instability:

$$(\sigma_{max}-\sigma_{min})-\sin\theta_1(\sigma_{max}+\sigma_{min})-2C_1\cos\theta_1=0 \quad (25)$$

where,
C_1 = The cohesion after pressure depletion, MPa
θ_1 = The internal friction angle after pressure depletion, deg

The fracture instability occurs when the tensile stress on the borehole wall beyond itself tensile strength:

$$\sigma_\theta=-S_{t1} \quad (26)$$

where,
σ_θ = The tangential stress on the borehole wall, MPa
S_{t1} = The rock tensile strength after pressure depletion, MPa

According to the stress distribution of borehole and combining with failure criterions which are given in Eq. (25) ~ (26), borehole collapse pressure and fracture pressure can be obtained. This process can be solved through iterative method.

DISCUSSION THE INFLUENCE ON DRILLING SAFETY MUD DENSITY OF RESERVOIR DEPLETION

Original formation parameters before reservoir depletion were achieved from the exploratory well at the early development: the vertical depth of reservoir top is 3000 m; formation pore pressure is 30 MPa; overburden pressure is 64.6 MPa; maximum horizontal in-situ stress is 57.8 MPa; minimum horizontal in-situ stress is 44 MPa; effective stress coefficient in reservoir and cap rock is 0.80 and 0.65 respectively; Poisson's ratio in reservoir and cap rock is 0.20 and 0.22 respectively; reservoir porosity is 25%; compression coefficient of rock matrix is 0.23×10^{-4}/MPa; rock compression coefficient is 0.18×10^{-4}/MPa.Using the above formation parameters, we calculated the change of safety mud density with reservoir depletion of vertical and deviated well drilling in reservoir and cap formation.

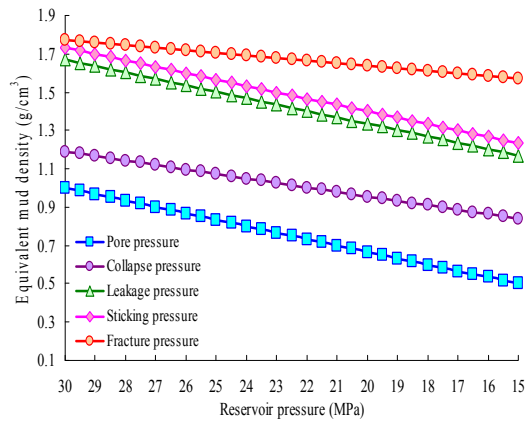

Fig. 3: The change law of pore pressure, collapse pressure, leakage pressure, sticking pressure and fracture pressure of the vertical well in reservoir formation with reservoir depletion

Vertical well in reservoir formation: The change law of safety mud density for vertical well in reservoir formation is shown in Fig. 3, from which we can see that: the lower limit of safety mud density is collapse pressure and the upper limit is leakage pressure, in addition, the pore pressure, collapse pressure, leakage pressure, sticking pressure and fracture pressure all reduced with reservoir depletion and in all of these, the reduce speed of pore pressure, leakage pressure and sticking pressure is faster than that of collapse pressure and fracture pressure, so the safety mud density window reduce with reservoir depletion and the leakage risk in the main prevention subject.

Deviated well in reservoir formation: From the formula 16 and 18, we can see that sticking pressure and leakage pressure is not related to the borehole deviation angle, so we only calculated the change of collapse pressure and facture pressure with reservoir depletion when drilling deviated well in the two different directions towards the maximum and minimum principal stress direction respectively (Fig. 4 and 5).

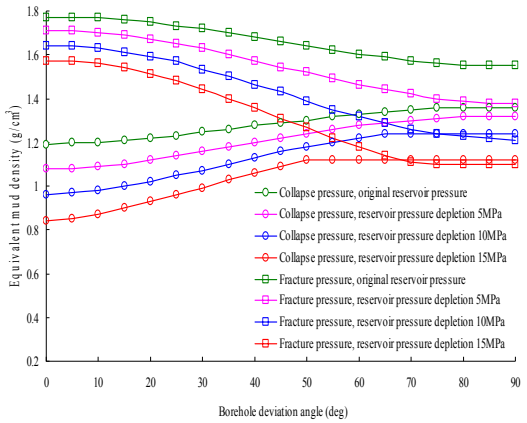

Fig. 4: The change law of collapse pressure and fracture pressure of the deviated well towards maximum principal stress direction in reservoir formation with reservoir depletion

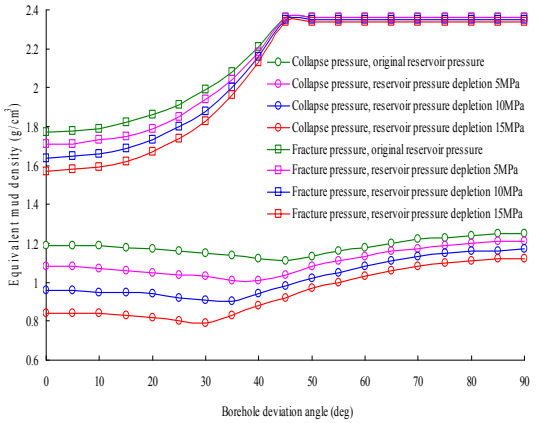

Fig. 5: The change law of collapse pressure and fracture pressure of the deviated well towards minimum principal stress direction in reservoir formation with reservoir depletion

The calculation results showed that, after reservoir depletion, the collapse pressure and fracture pressure both reduced in both different directions towards the maximum and minimum principal stress direction respectively. In the direction of maximum principal stress, the reduction of collapse pressure is lower with increase of deviation angle, which is opposite to that of fracture pressure, in addition, the collapse pressure and fracture pressure both reduced with reservoir depletion, so the safety mud density window of highly-deviated well with higher depletion is narrowest and the fracture risk is largest, when the deviation angle and the reservoir depletion is higher than 70° and 10 MPa respectively, the safety mud density window do not exist and we should improve the formation loading ability or allow moderate collapse to broad the safety mud density window to guarantee the safety of the drilling. But in the direction of minimum principal stress, the reduction of collapse pressure and fracture

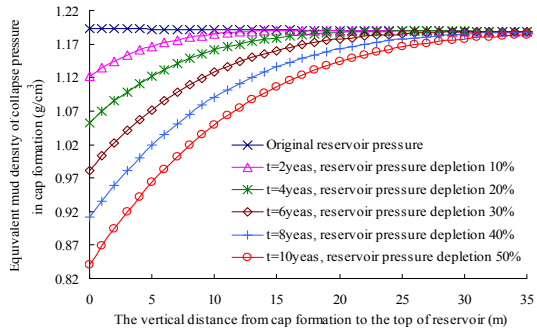

Fig. 6: The change law of collapse pressure of the vertical well in cap formation with reservoir depletion

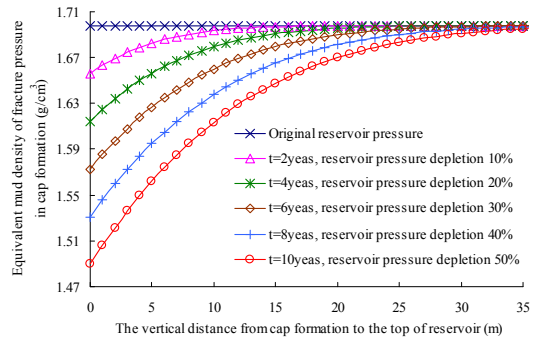

Fig. 7: The change law of fracture pressure of the vertical well in cap formation with reservoir depletion

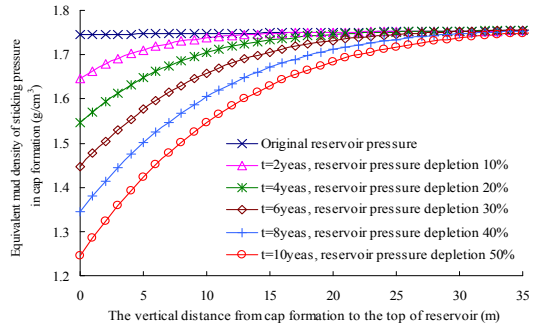

Fig. 8: The change law of sticking pressure of the vertical well in cap formation with reservoir depletion

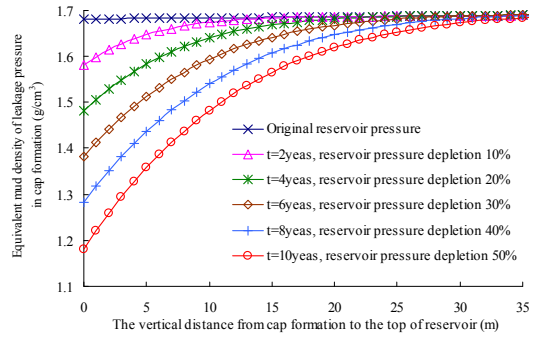

Fig. 9: The change law of leakage pressure of the vertical well in cap formation with reservoir depletion

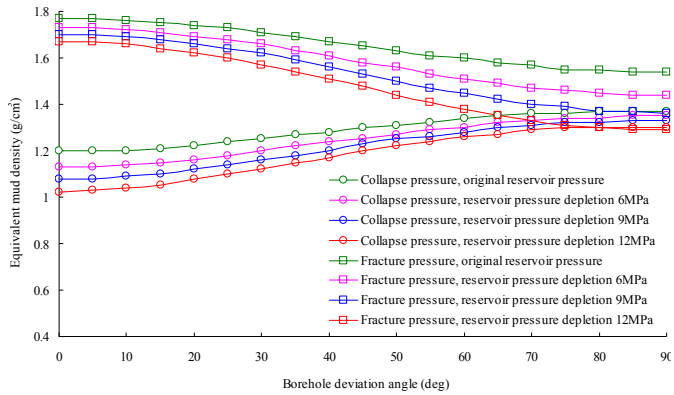

Fig. 10: The change law of collapse pressure and fracture pressure of the deviated well towards maximum principal stress direction in cap formation of 5m above the reservoir top with reservoir depletion

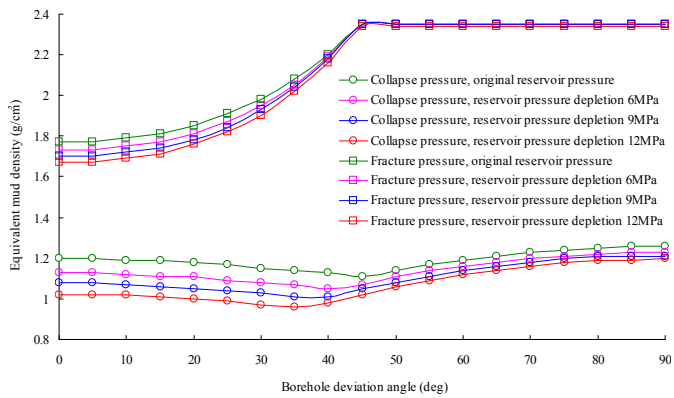

Fig. 11: The change law of collapse pressure and fracture pressure of the deviated well towards minimum principal stress direction in cap formation of 5m above the reservoir top with reservoir depletion

pressure is both lower with increase of deviation angle, the safety mud density window of highly-deviated well is wider and the highly-deviated well towards the direction of minimum principal stress in depleted reservoir is safer.

Vertical well in cap formation: The reservoir depletion is assumed to be linear relation with development time. The change law of collapse pressure, fracture pressure, sticking pressure and leakage pressure for vertical well in cap formation is shown in Fig. 6 to 9 respectively, from which we can see that: the four pressures have similar change law with reservoir depletion, all of which reduced with reservoir depletion and the influence range in cap rock increase with increase of reservoir depletion, the leakage risk is larger, which is the main prevention subject.

Deviated well in cap formation: We take the cap formation in the 5m above reservoir as example to study the change of collapse pressure and facture pressure with reservoir depletion when drilling deviated well in the two different directions towards the maximum and minimum principal stress direction respectively (Fig. 10 and 11). According to the calculation results, we can see that, the change law in cap formation is similar to that in reservoir and we should try to avoid drilling highly-deviated well towards maximum principal stress direction in depleted oilfields, but the influence degree on safety mud density in cap rock in lower than that in reservoir formation and in the direction of maximum principal stress, when the deviation angle and the reservoir depletion is higher than 75° and 12 MPa respectively, the safety mud density window do not exist.

FIELD APPLICATIONS

The above research method was successfully used in the drilling practice of the depleted oilfield in the South China Sea. In the drilling practice of the early exploratory well before reservoir depletion, the lower and upper limit of safety mud density was about 1.15 g/cm^3 and 1.50 g/cm^3, the practical mud density was about 1.20 g/cm^3 and the drilling process gone smoothly. But after many years development, the reservoir pressure coefficient was depleted to about 0.45 from original normal pressure gradient, using the

original mud density to drilling, the mud leakage and logging stuck often occurred, so we predicted the safety mud density again and the lower and upper limit of safety mud density was about 0.95 g/cm^3 and 1.25 g/cm^3, in the next drilling practice, the practical mud density was about 0.99 g/cm^3 and the drilling process gone smoothly.

CONCLUSION

In the depleted oilfields, the pore pressure, collapse pressure, leakage pressure, sticking pressure and fracture pressure both in reservoir and cap formation all reduced with reservoir depletion and in all of which, the reduce speed of the pore pressure, leakage pressure and sticking pressure is faster, the leakage and sticking is the main prevention subject. The influence range in cap rock increases with increase of reservoir depletion. In the direction of maximum principal stress, the safety mud density window of highly-deviated well in higher depletion is narrowest and the mud leakage risk is largest, when the deviation angle and the reservoir depletion is higher than some value, the safety mud density window do not exist and we should improve the formation loading ability or allow moderate collapse to broad the safety mud density window to guarantee the safety of the drilling. In the direction of maximum principal stress, the safety mud density window of highly-deviated well in higher depletion is wider and the direction is the safer one. The new research method was successfully used in the drilling practice of the depleted oilfield in the South China Sea. This study has systematically analyzed the prediction method of safety mud density in depleted oilfields and the method is easy and effective, which can be used for the drilling design of depleted oilfields.

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REFERENCES

Addis, M.A., 1997. Reservior depletion and its effect on wellbore stability evaluation. Int. J. Rock Mech. Min. Sci., 34(4): 3-4.

Al-Awad, M.N.J., 2000. Simple correlation to evaluate mohr-coulomb failure criterion using uniaxial compressive strength. J. King Saud Univ., Eng. Sci., 14 (1): 137-145.

Chang, C., D.Z. Mark and K. Abbas, 2006. Empirical relations between rock strength and physical properties in sedimentary rocks. J. Petrol. Sci. Eng., 51(3-4): 223-237.

Cheng, Y., J. Wang, Y. Zhao and H. Shen, 2006. Strength analysis of formation rock for porous media coupled with mechanical-chemical effects. Chinese J. Rock Mech. Eng., 25(9): 1912-1916.

Deng, J., Y. Cheng, M. Chen *et al*., 2008. Prediction Technology of Wellbore Stability. Petroleum Industry Press, Beijing.

Fairhurst, C., 1968. The phenomenon of rock splitting parallel to a free surface under compressive stress. Proceeding of the 1st Congress of International Society of Rock Mechanics, Lisbon.

Ge, H., J. Qu and R. Huang, 1994. Fracture pressure at horizontal intervals in pressure depletion formations. Petrol. Drill. Techniq., 22(3): 24-26.

Jin, Y., Y. Jianbo, C. Mian, K.P. Chen, Y. Lu and H. Wang, 2011. Determination of rock fracture toughness KIIC and its relationship with tensile strength. Rock Mech. Rock Eng., 44(5): 621-627.

Jones, J.F., G.D. Taylor and R.D. Barree, 2003. Successfully managing drilling-fluid losses in multiple highly depleted sands. SPE Drill. Compl., 6(2): 182-187.

Liang, H., G. Wen, G. Wang *et al*., 2004. The effects of pore pressure alterations on the in- situ stress. Petrol. Drill. Techniq., 32(2): 18-20.

Liu, T., H. Tang, L. Dong-Liang, L. Peng-Chao and Z. Yong-Jie, 2010. Study of rock porosity changes under the formation conditions. J. Oil Gas Technol., 32(2): 299-301.

Morita, N. and F. Giin-Fa, 2009. Parametric analysis of stress reduction in the cap rock above compacting rervoirs. SPE Drill. Compl., 24(4): 659-670.

Roegiers, J.C., 2002. Well modelling: An overview. Oil Gas Sci. Technol., 57(5): 569-577.

Shaughnessy, J., F. Ron and R. Louis, 2001. Successfully Drilling Highly Depleted Sands. SPE/IADC 67744, Drilling Conference, 27 February-1 March 2001, Amsterdam, Netherlands.

Shi, M. and Y. Jin, 2008. Study on wellbore stability of adjustment well at the middle and late stages of oilfield development. J. Oil Gas Technol., 30(3): 353-355.

Tan, Q., H. He, Y. Chen, L. Wang-Hong and D. Fang, 2010. Wellbore stability analysis of directional wells in pressure depleted reservoirs. J. Oil Gas Technol., 32(2): 316-318.

Wang, T. and W. Shi, 2010. Calculate porosity by density logging. Coal Technol., 29(2): 151-165.

Xu, T., Y. Liu, W. Shen *et al*., 1997. Lost Circulation Resistance and Control Technology during Drilling. Petroleum Industry Press, Beijing.