Send Orders of Reprints at bspsaif@emirates.net.ae

The Open Petroleum Engineering Journal, 2013, *6*, 1-6

Effects of Long-term Development on Wellbore Stability: A Case Study of Bohai Bay Basin

Yuan Jun-Liang[1], Deng Jin-Gen*[,1], Tan Qiang[1], Yu Bao-Hua[1], Fan Bai-Tao[2]

[1]*State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing 102249, China;*
[2]*China National Offshore Oil Company, Tianjin Branch, Tianjin 300450, China*

Abstract: This paper describes the method used in the depleted reservoir for analyzing horizontal *in-situ* stresses in order to define a stable mud weight window to maximize the efficiency of drilling process. The method combines wellbore stability modeling, *in-situ* stress prediction, and pore pressure depletion during production process. In the presence of any hydraulically isolated fault blocks or other permeability barriers, the pore pressure depletion will cause horizontal stress changes in both magnitude and orientation. Furthermore, the changes of horizontal stress affect the wellbore stability of inclined wells. The results indicate that the reservoir depletion has notable effect on the safe mud weight window, especially the fracture pressure. The fracture pressure may be overestimated in previous model, and the most stable well azimuth is not static but varies over the lifetime of the oilfield. The research conclusions can provide significant reference for the mud weight design of directional well in depleted reservoir.

Keywords: Long-term development, *in-situ* stress, fault-block oilfield, wellbore stability, fracture pressure.

1. INTRODUCTION

Production of oil and gas from hydrocarbon-bearing reservoir can result in a reduction of the reservoir pore pressure (formation pressure) unless pressure support is provided from an aquifer. Sometimes the pressure coefficient can be reduced less than 0.5. Drilling practices in Bohai oilfield (Fig. **1**) showed that unexpected drilling difficulties were encountered, such as lost circulation, leaking, differential pressure sticking [1], and fault seal breach by reactivation [2, 3]. Therefore the knowledge of pore pressure in depleted reservoir can provide a better understanding of applied geomechanics and has been increasingly studied [4].

Previous research shows that the reduction in pore pressure is associated with a decrease in horizontal stress magnitude, however, relatively little work has been done on the orientation change. To approach the orientation change of horizontal stress, we have analyzed the stress state of depleted fault-block reservoir. The results show that the horizontal stress orientation is not constant but varies with some parameters, such as pore pressure change and rock mechanical properties. Furthermore, the horizontal stress reorientation may cause notable influence on wellbore stability of directional wells. Finally, this paper observes that the trajectory sensitivity of directional well can be affected by reservoir depletion at the same time.

2. *IN-SITU* STRESS MAGNITUDE

Based on numerous field data, the minimum horizontal stress exhibits a linear decrease with the reduction of pore pressure [5]. In fact, both the maximum and minimum horizontal stresses are expected to decrease because of the pore pressure depletion associated with the long-term development. The theoretical expression of the horizontal stress change was derived by Holt first in 1992 [6]. Based on the assumption that the reservoir deforms in an isotropic homogenous linearly elastic (IHLE) manner with a uniaxial strain boundary, the equation used to estimate the horizontal stress change is,

$$\Delta \sigma_H = \Delta \sigma_h = \alpha \frac{1-2\nu}{1-\nu} \Delta P_p \tag{1}$$

where, $\Delta\sigma_H$ and $\Delta\sigma_h$ are the maximum and minimum horizontal stress changes, respectively, g/cm^3, α is the effective stress coefficient, ν is Poisson's ratio; ΔP_p is the deviation from original pore pressure, g/cm^3. This equation also shows that the horizontal stress change value is related to the formation properties. According to Morita's study [7], equation (**1**) is actually a reasonable approximation if the ratio G_R/G_C is between 0.2 and 1.5, h/r<0.1, and D/r>1.

According to equation (**1**), the current horizontal stress can be written as equation (**2**),

$$\begin{cases} \sigma_H' = \sigma_H + \alpha \dfrac{1-2\nu}{1-\nu} \Delta P_p \\ \sigma_h' = \sigma_h + \alpha \dfrac{1-2\nu}{1-\nu} \Delta P_p \end{cases} \tag{2}$$

where, σ_H and σ_h are the original maximum and minimum horizontal stresses, respectively, g/cm^3, σ_H' and σ_h' are the current maximum and minimum horizontal stresses, respectively, g/cm^3.

*Address correspondence to this author at the No. 18 Fuxue Road, Changping District, Beijing, China; Postcard: 102249;
Tel: 010-89733911; E-mail: dengjingen@126.com

1874-8341/13 2013 Bentham Open

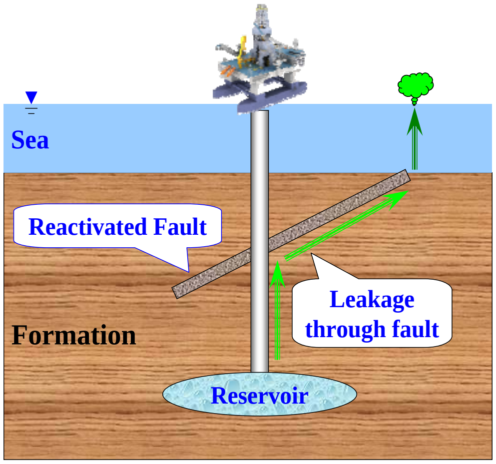

Fig. (1). Fault reactivation when drilling near the fault (Oilfield in Bohai Bay Basin).

3. *IN-SITU* STRESS REORIENTATION

For a simple case in which the reservoir is homogeneous, isotropic, and laterally extensive with elastic properties that do not contrast with the surrounding rock, σ_H and σ_h will change by the same amount, and no change in orientation is expected. However, in case that there is a hydraulically isolated fault separating the reservoir experiencing pore pressure depletion from the one in which pore pressure remains constant, the horizontal stress orientation will rotate at some angel from the original orientation.

The model geometry is illustrated in Fig. (**2**): The original orientation of maximum horizontal stress is in the x-axis. The fault ***F***, which is impermeable, is at the angle θ from the x-axis. The pore pressure of region **A** is depleted during long-term development. In contrast, the pore pressure of region **B** is still the original pore pressure (i.e. 1.0g/cm^3). In the area near the impermeable fault, the orientation of horizontal stress may rotate at the angle γ from the original azimuth [8]. The difference in pore pressure on either region imposes a traction stress, ψ which changes the orientation of horizontal stress by angle γ [9]. Both region **A** and **B** experience the same orientation change in horizontal stress, although this change decays sharply with distance from the fault.

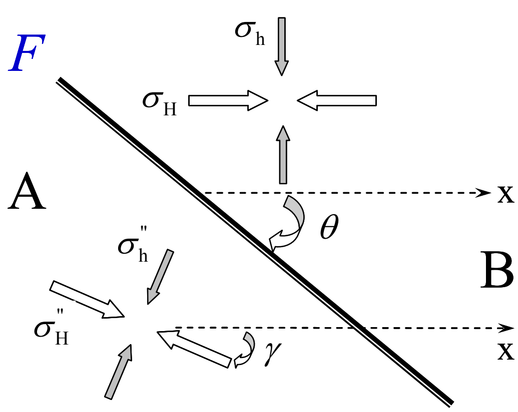

Fig. (2). Model geometry of horizontal stress orientation change.

The new horizontal stress coordinate system, rotated at the angle γ from the original coordinate system [10], near the fault can be calculated by,

$$\left(1+\frac{1-2\nu}{1-\nu}\frac{\Delta P_p}{\sigma_h-\sigma_H}\cos 2\theta\right)\tan 2\gamma=\frac{1-2\nu}{1-\nu}\frac{\Delta P_p}{\sigma_h-\sigma_H}\sin 2\theta \quad (3)$$

where, θ is clockwise positive, °.

Fig. (**3**), shows the amount of horizontal stress rotation expected for values of ΔPp from 0 to 0.5 near fault of any azimuth, corresponding to equation (**3**) with $\acute{o}_H=1.7g/cm^3$, $\sigma_h=1.5g/cm^3, \nu=0.25$ and $\alpha=0.8$. So for depleted reservoir, the maximum horizontal stress will rotate to be more parallel to the fault.

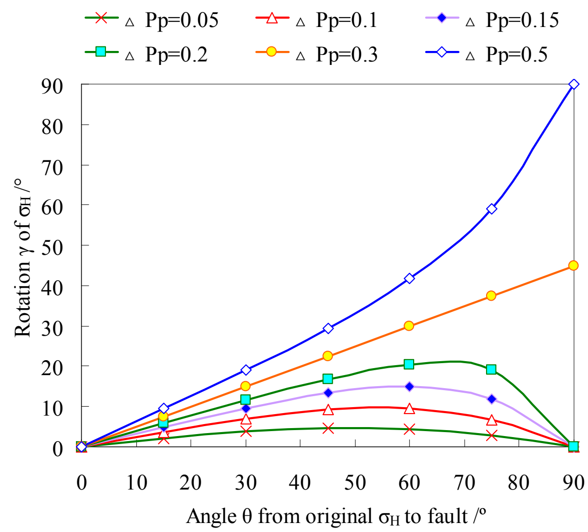

Fig. (3). Rotation angle (γ) of horizontal stress orientation vs. the included angle (θ) between fault strike and original orientation of $\acute{o}_H$.

4. DIRECTIONAL WELL BOREHOLE STABILITY AND EXAMPLE

Borehole instability problems are serious when drilling directional wells in depleted reservoir. The basic approach to study this problem consists of the stress distribution around borehole, the failure criterion, and the safe mud weight window subsequently [11].

The horizontal *in-situ* stresses calculated by equation (**2**) and equation (**3**) should be transformed from the geodetic coordinate system (1, 2, 3) to the borehole coordinate system (x, y, z). The coordinate conversion schema is illustrated in Fig. (**4**). The stress transformation equation is as follows:

$$\begin{bmatrix}\sigma_{xx} & \sigma_{xy} & \sigma_{xz}\\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz}\\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz}\end{bmatrix}=[L]\begin{bmatrix}\sigma_H & 0 & 0\\ 0 & \sigma_h & 0\\ 0 & 0 & \sigma_V\end{bmatrix}[L]^T \cdots\cdots \quad (4)$$

where, L is the coordinate system transformation matrix.

$$[L]=\begin{bmatrix}\cos\beta\cos\alpha & \cos\beta\sin\alpha & -\sin\beta\\ -\sin\alpha & \cos\alpha & 0\\ \sin\beta\cos\alpha & \sin\beta\sin\alpha & \cos\beta\end{bmatrix}\cdots\cdots\cdots\cdots \quad (5)$$

$$\begin{aligned}
\sigma_{xx} &= \sigma_H \cos^2\alpha\cos^2\beta + \sigma_h \cos^2\alpha\sin^2\beta + \sigma_v \sin^2\alpha \\
\sigma_{yy} &= \sigma_H \sin^2\beta + \sigma_h \cos^2\beta \\
\sigma_{zz} &= \sigma_H \sin^2\alpha\cos^2\beta + \sigma_h \sin^2\alpha\sin^2\beta + \sigma_v \cos^2\alpha \cdots \\
\sigma_{xy} &= -\sigma_H \cos\alpha\cos\beta\sin\beta + \sigma_h \cos\alpha\cos\beta\sin\beta \\
\sigma_{xz} &= \sigma_H \cos\alpha\cos\alpha\cos^2\beta + \sigma_h \cos\alpha\sin\alpha\sin^2\beta \\
\sigma_{yz} &= -\sigma_H \sin\alpha\cos\beta\sin\beta + \sigma_h \sin\alpha\cos\beta\sin\beta
\end{aligned} \tag{6}$$

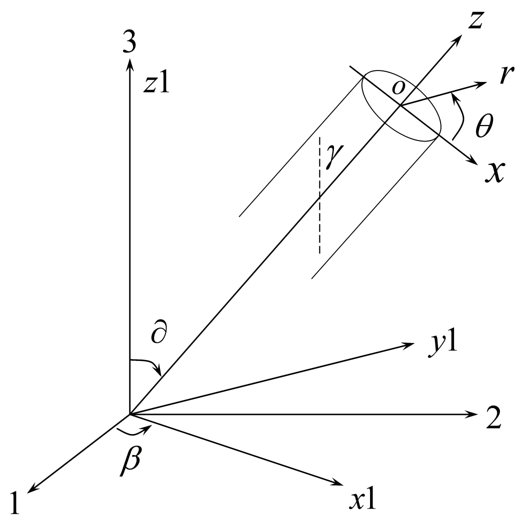

Fig. (4). Coordinate conversion.

Based on the existing research (Jin 1999, Deng 2006), the wellbore stability analysis model is as follows.

The stress conditions are found from the stress transformation equation (**4**) between the geodetic coordinate system and the borehole coordinate system. They are:

$$\sigma_r = \frac{R^2}{r^2}P + \frac{(\sigma_{xx}+\sigma_{yy})}{2}(1-\frac{R^2}{r^2}) + \frac{(\sigma_{xx}-\sigma_{yy})}{2}(1+\frac{3R^4}{r^4}-\frac{4R^2}{r^2})\cos 2\theta + \sigma_{xy}(1+\frac{3R^4}{r^4}-\frac{4R^2}{r^2})\sin 2\theta + \delta[\frac{\alpha(1-2\nu)}{2(1-\nu)}(1-\frac{R^2}{r^2})-\phi](P-P_p) \tag{7a}$$

$$\sigma_\theta = -\frac{R^2}{r^2}P + \frac{(\sigma_{xx}+\sigma_{yy})}{2}(1+\frac{R^2}{r^2}) - \frac{(\sigma_{xx}-\sigma_{yy})}{2}(1+\frac{3R^4}{r^4})\cos 2\theta - \sigma_{xy}(1+\frac{3R^4}{r^4}-\frac{4R^2}{r^2})\sin 2\theta + \delta[\frac{\alpha(1-2\nu)}{2(1-\nu)}(1-\frac{R^2}{r^2})-\phi](P-P_p) \tag{7b}$$

$$\sigma_z = \sigma_{zz} - \nu[2(\sigma_{xx}-\sigma_{yy})(\frac{R}{r})^2\cos 2\theta + 4\sigma_{xy}(\frac{R}{r})^2\sin 2\theta] + \delta[\frac{\alpha(1-2\nu)}{1-\nu}-\phi](P-P_p) \tag{7c}$$

$$\begin{aligned}
\sigma_{r\theta} &= \sigma_{xy}(1-\frac{3R^4}{r^4}+\frac{2R^2}{r^2})\cos 2\theta \\
\sigma_{\theta z} &= \sigma_{yz}(1+\frac{R^2}{r^2})\cos\theta - \sigma_{xz}(1+\frac{R^2}{r^2})\sin\theta \\
\sigma_{zr} &= \sigma_{xz}(1-\frac{R^2}{r^2})\cos\theta + \sigma_{yz}(1-\frac{R^2}{r^2})\sin\theta
\end{aligned} \tag{7d}$$

The stress conditions on the borehole wall, where radius (**r**) equals to the radius of borehole (**R**), can be expressed as equations (**8a** and **8e**), respectively:

$$\sigma_r = P_m - \delta\phi(P_m - P_p) \cdots\cdots \tag{8a}$$

$$\sigma_\theta = A\sigma_h + B\sigma_H + C\sigma_v + (K_1-1)P_m - K_1P_p \cdots\cdots \tag{8b}$$

$$\sigma_z = D\sigma_h + E\sigma_H + F\sigma_v + K_1(P_m - P_p) \cdots\cdots \tag{8c}$$

$$\sigma_{\theta z} = G\sigma_h + H\sigma_H + J\sigma_v \cdots\cdots \tag{8d}$$

$$\sigma_{r\theta} = \sigma_{rz} = 0 \cdots\cdots \tag{8e}$$

where:

$$A = \cos\alpha\{\cos\alpha(1-2\cos 2\theta)\sin^2\beta + 2\sin 2\beta\sin 2\theta\} + (1+2\cos 2\theta)\cos^2\beta$$

$$B = \cos\alpha\{\cos\alpha(1-2\cos 2\theta)\cos^2\beta - 2\sin 2\beta\sin 2\theta\} + (1+2\cos 2\theta)\sin^2\beta$$

$$C = (1-2\cos 2\theta)\sin^2\alpha$$

$$D = \sin^2\beta\sin^2\alpha + 2\nu\sin 2\beta\cos\alpha\sin 2\theta + 2\nu\cos 2\theta(\cos^2\beta - \sin^2\beta\cos^2\alpha)$$

$$E = \cos^2\beta\sin^2\alpha - 2\nu\sin 2\beta\cos\alpha\sin 2\theta + 2\nu\cos 2\theta(\sin^2\beta - \cos^2\beta\cos^2\alpha)$$

$$F = \cos^2\alpha - 2\nu\sin^2\alpha\cos 2\theta$$

$$G = -(\sin 2\beta\sin\alpha\cos\theta + \sin^2\beta\sin 2\alpha\sin\theta)$$

$$H = \sin 2\beta\sin\alpha\cos\theta - \cos^2\beta\sin 2\alpha\sin\theta$$

$$J = \sin 2\alpha\sin\theta$$

$$K_1 = \delta[\frac{\zeta(1-2\nu)}{1-\nu} - \phi]$$

The three principle stresses on the borehole wall are calculated as follows,

$$\sigma_1 = \frac{1}{2}[X - 2K_1P_p + (2K_1-1)P_m] + \frac{1}{2}\sqrt{(Y-P_m)^2 + Z} \cdots \tag{9a}$$

$$\sigma_2 = \sigma_r = P_m - \delta f(P_m - P_p) \cdots\cdots \tag{9b}$$

$$\sigma_3 = \frac{1}{2}[X - 2K_1P_p + (2K_1-1)P_m] - \frac{1}{2}\sqrt{(Y-P_m)^2 + Z} \cdots \tag{9c}$$

where,

$$X = (A+D)\sigma_h + (B+E)\sigma_H + (C+F)\sigma_v$$

$$Y = (A-D)\sigma_h + (B-E)\sigma_H + (C-F)\sigma_v$$

$$Z = 4(G\sigma_h + H\sigma_H + J\sigma_v)^2$$

The collapse pressure (Pt) and fracture pressure (Pf) can be calculated with equation (**10** and **11**), respectively [12],

$$(\acute{o}_1 - \alpha\cdot P_P) \geq (\acute{o}_3 - \alpha\cdot P_P)\cdot\tan^2(\partial/4 + \ddot{o}/2) + \sigma_c \tag{10}$$

$$\sigma_3 - \alpha\cdot P_P \leq -S_t \tag{11}$$

where $\acute{o}_1$ and $\acute{o}_3$ are the maximum and minimum principle stresses on the borehole wall, respectively, MPa, $\acute{o}_c$ is the uniaxial compressive strength, MPa, S_t is tensile strength, MPa, φ is the internal friction angle, °.

A fault-block oilfield in Bohai Bay is chosen to analyze the directional well borehole stability in depleted reservoir. The schematic geological map is illustrated in Fig.(**5**). The values for *in-situ* and borehole parameters are given in Table. **2**. The other parameters such as Poisson's ratio and effective stress coefficient are the same as above.

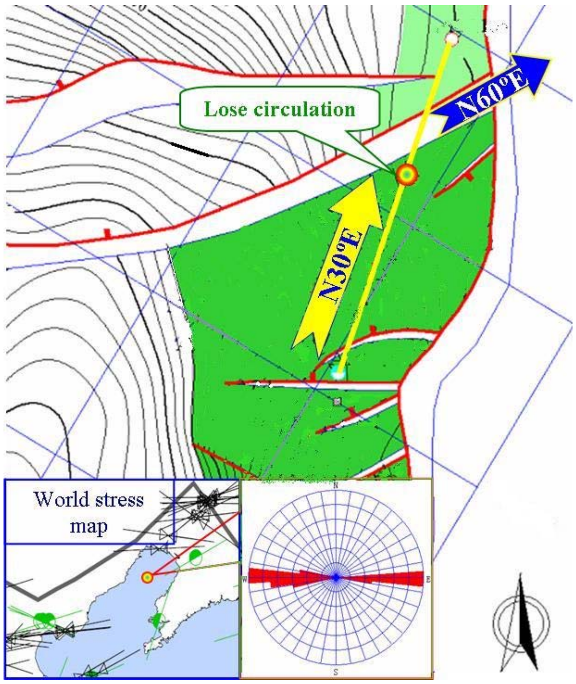

Fig. (5). A directional well in depleted fault-block reservoir in Bohai Bay. (θ=30°, γ=20°).

Table.2. ***In-situ* and wellbore parameters**

***In-situ* parameters**	
Reservoir depth (TVD), D	2000 m
Max. hor. Stress orientation, σ_H	N90ºE
Strike of fault, θ	N60ºE
Azimuth of directional well	N30ºE
Overburden stress, σ_V	2.15 g/cm^3
Original max.hor.stress, σ_H	1.7 g/cm^3
Original min.hor.stress, σ_h	1.5 g/cm^3
Original pore pressure, Pp	1.0 g/cm^3
Depleted pore pressure, ΔPp	0.5 g/cm^3
Rock strength parameters	
Cohesion, C	5 MPa
Friction angle, φ	32º

Figs. (**6** and **7**) show the original critical collapse pressure and fracture pressure with well inclination and azimuth. They illustrate that the Pt ranges from 1.1g/cm^3 to 1.35g/cm^3, and Pf ranges from 1.7g/cm^3 to 2.5g/cm^3 when the pore pressure is in original condition. The most stable azimuth is N0°E. Figs. (**8** and **9**) show the current critical mud weight with well inclination and azimuth. They illustrate that the Pt ranges from 0.75g/cm^3 to 1.2g/cm^3, and Pf ranges from 1.3g/cm^3 to 2.3g/cm^3 when the reservoir has suffered from long-term development. The most stable azimuth is N20°W. Figs. (**10** and **11**) show the current critical mud weight without the consideration of horizontal stress reorientation. They illustrate that the Pt also ranges from 0.75g/cm^3 to 1.2g/cm^3, and Pf also ranges from 1.3g/cm^3 to 2.3g/cm^3 when the reservoir undergoing long-term development, however, the most stable azimuth is N0°E, rather than N20°W. In a word, due to production of oil from hydrocarbon-bearing reservoir, the variation of critical mud weight is apparent.

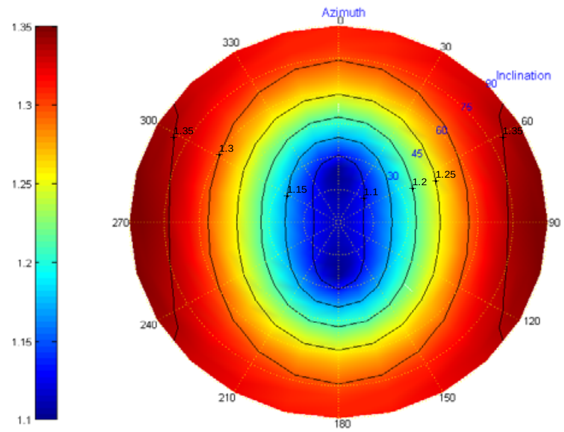

Fig. (6). Critical collapse pressure vs. well azimuth with original pore pressure.

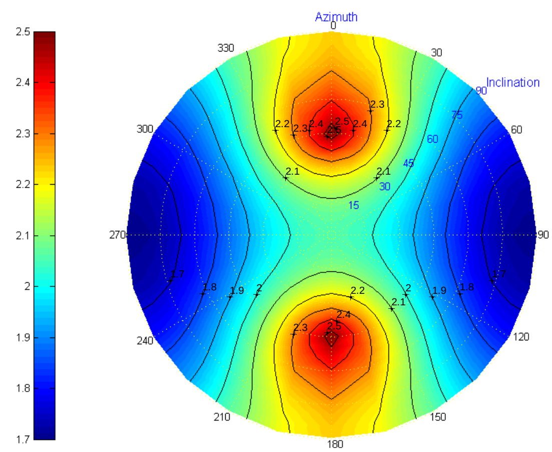

Fig. (7). Critical fracture pressure vs. well azimuth with original pore pressure.

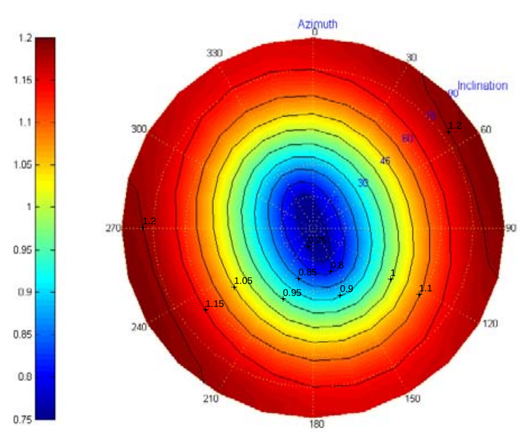

Fig. (8). Critical collapse pressure vs. well azimuth with depleted pore pressure (our model with horizontal stress reorientation).

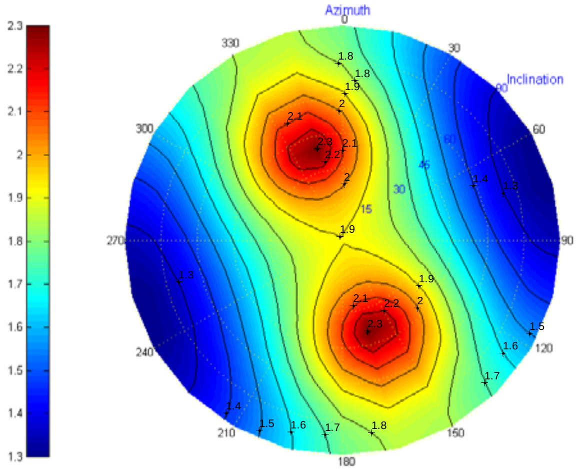

Fig. (9). Critical fracture pressure vs. well azimuth with depleted pore pressure (our model with horizontal stress reorientation).

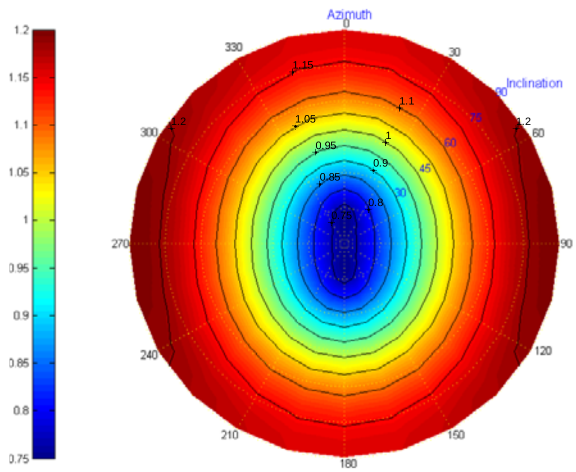

Fig. (10). Critical collapse pressure vs. well azimuth with depleted pore pressure (the previous model neglecting horizontal stress reorientation).

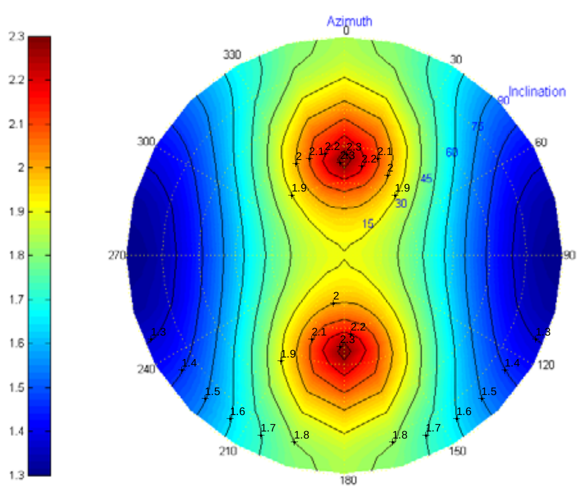

Fig. (11). Critical fracture pressure vs. well azimuth with depleted pore pressure (the previous model neglecting horizontal stress reorientation).

The results show that the magnitude and orientation changes of horizontal stress affect the wellbore stability remarkably, specifically the orientation change. Fig. (**12**) illustrates the safe mud weight window which is the safe range of mud weight to avoid both borehole collapse and fracturing. In the practical drilling operation, serious lost circulation occurred in the near fault area, when the practical mud weight was 1.47g/cm^3. Compared with the predictive fracture pressure (Pf=1.49g/cm^3) which is calculated by our model, it shows that they are in good agreement. However, the fracture pressure calculated by the previous model neglecting the horizontal stress reorientation, is 1.7g/cm^3 (much higher than the real Pf=1.47g/cm^3). Obviously, it is the overestimated fracture pressure that leads to the serious lost circulation.

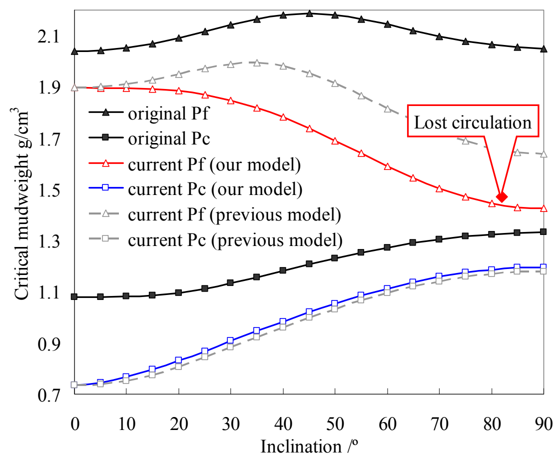

Fig. (12). The safe mud weight window vs. well inclination at azimuth of N30°E.

5. CONCLUSIONS

1. The pore pressure depletion has great effect on the trajectory sensitivity of directional drilling. The most stable well azimuth will reorient, and the fracture pressure tends to be overestimated if the orientation change of horizontal stress is neglected.

2. The orientation change of horizontal stress is just located in the depleted fault-block reservoirs with impermeable barriers. In addition, this change decays sharply with distance from the faults.

3. The pore pressure depletion leads to both the orientation and magnitude changes of horizontal stress. Besides, the angle of reorientation depends on many parameters, such as the deviation from original pore pressure, the included angle between σ_H and fault strike, and rock mechanical properties.

FIELD UNITS CONVERSION FACTORS

m × 3.048*E-01=ft

MPa ×1.450 377*E+02=PSI

g/cm^3 ×8.345 404*E+00=PPG

NOMENCLATURES

Pt	=	The collapse pressure, g/cm^3
Pf	=	The fracture pressure, g/cm^3
Pp	=	The pore pressure, g/cm^3
ΔPp	=	The pore pressure change, g/cm^3
σ_V	=	The overburden stress, g/cm^3

σ_H = The maximum horizontal stress, g/cm^3

σ_h = The minimum horizontal stress, g/cm^3

G_R = The shear modulus of reservoir, GPa

G_C = The shear modulus of cap rock, GPa

D = The reservoir depth, m

h = The reservoir thickness, m

r = The reservoir radius, m

θ = The angle between original orientation of maximum horizontal stress and fault strike, °

γ = The rotation angle of maximum horizontal stress orientation, °

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENTS

This work is supported by the National Science Fund (Project NO. 51174219) and the National Science and Technology Major Project (Project NO. 2011ZX05009-005).

REFERENCES

[1] B.S. Liu, "A study on drilling fluid used for preventing differential pressure sticking in pressure declining formation of cheng-dao oilfield", *Drilling & Production Technology*, vol. 2, 2002.

[2] V.A. Dunayevsky, M.T. Myers, and M.W. Bennett, "Reservoir pressure depletion induced exterior fault activation", *ARMA,Presented at the* 44th U.S. Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, June 27 - 30, Salt Lake City, Utah, 2010.

[3] E.P. Mallman, and M.D. Zoback, "Subsidence in the Louisiana coastal zone due to hydrocarbon production", *Journal of Coastal Research*, Special Issue vol. 50, pp. 443- 449, 2007.

[4] Q. Tan, H. He, and Y.H. Chen, "Wellbore stability analysis of directional wells in pressure depleted reservoirs", *Journal of Oil and Gas Technology*, vol. 2, no, 2, pp. 67-72, 2010.

[5] M.A. Addis, "Reservoir depletion and its effect on wellbore stability evaluation", *International Journal of Rock Mechanics and Mining Science*, vol. 34, pp. 3-4, 1997.

[6] E. Fjaer, R.M. Holt, and P. Horsrud, *Petroleum Related Rock Mechanics*, 1st ed. Elsevier publications, 1992.

[7] N. Morita, "A quick method to determine subsidence, reservoir compaction, and *in-situ* stress induced by reservoir depletion", *Journal of Petroleum Technology*, vol. 41, no. 1, pp. 71-79, 1989.

[8] L. J. Sonder, "Effects of density contrasts on the orientation of stresses in the lithosphere: Relation to principal stress directions in the Traverse Ranges", *TECTONICS*, vol. 9, no. 4, pp. 761-771, 1990.

[9] P. Segall, and S. D. Fitzgerald, "A note on induced stress changes in hydrocarbon and geothermal reservoirs", *Tectonophysics*, vol. 289, no. 1-3, pp. 117-128, 1998.

[10] D. F. Day-Lewis, "*Characterization and modeling of in situ stress heterogeneity*", Ph. D Dissertation Stanford University, 45-52, 2007.

[11] Y. Jin, M. Chen, and G.H. Liu, "Wellbore stability analysis of extended reach wells", *Journal of Geomechanics*, vol. 5, no. 1, pp. 4-11, 1999.

[12] J.G. Deng, and M. Chen, "Petroleum related lock mechanics", *International Journal of Solids Structures*, vol. 12, pp. 81-97, 2006..

Received: July 16, 2012 Revised: October 24, 2012 Accepted: October 28, 2012