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Modeling of Effect of Thermal Stresses and Mud Flow on Wellbore Stability Analysis of HPHT Wells

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Abstract
Maintaining good borehole condition to acquire quality logs and avoiding any NPT in challenging environment like high temperature high pressure wells is a major concern of growing petroleum industry. With quest to reach deeper target reservoirs, different models are being used worldwide to determine safe mud window to avoid drilling risks proactively. The state of stress is the key element of these models which varies depending on mechanical, hydraulic and thermal effects. Purpose of this study is to quantify the effect of thermal effect through combination of heat transport properties and thermal expansion behavior. Analytical solution has been presented for coupled heat-fluid diffusion equations with robin type boundary condition between borehole and mud. Results have shown that effect of thermal induced stress can be controlled with the help of circulation rates and mud temperature. Raising the mud temperature increases tangential stresses near borehole leading to higher tendency of breakouts while cooling inhibits it and raises chance of tensile failures. These effects are found to be more prominent where fluid diffusivity is small, like in shale. Wellbore stability analysis has been conducted for two wells to showcase validation of model. Comparison is shown between models with or without taking thermal effect in final mud weight model.

Introduction
Effective stress concentration around the borehole is of primary importance from the perspective of wellbore instability. Stresses near the borehole are mainly due to lithostatic and tectonic activity. But in HPHT fields thermal stresses play a vital role. Temperature near the wellbore is altered by the temperature of mud in well. In such cases stresses induced by thermal effect should be taken into consideration in the wellbore stability analysis as they change the stress distribution. Because of the thermal expansion and the different expansion coefficient of the rock skeleton and the fluid contained inside the pores, thermal stresses may be induced leading to borehole yield and failure. There may be several effects of thermal stresses on the wellbore stability. It changes the breakout mud weight limit and breakdown mud weight limit associated with the mud weight window. Alternate cooling and reheating during drilling due to mud circulation interruption may cause instability issues. Cooling may induce many small fractures and cause the mud loss to these small fractures. Closure of these fractures on reheating is responsible for the transient pressure build up and back flow.

After the hole is drilled, the heat exchanges between the formation near the hole and the mud in the hole. So, the temperature is varied near the borehole. During the mud circulation in a well balance trends to be reached between the mud in the hole and formation. Otherwise the bottomhole mud is cooler than the formation, whereas tophole mud is warmer than formation. So, the temperature decreases near the bottom section of the formation because the heat on the wall is taken away by circulating mud, but on the upper section, the temperature increases owing to the heat in the circulating mud is taken in by the formation, The vary of the temperature causes the rock expanding or shrinking near the hole, However, the thermal expansion or shrinkage of the rock in the formation is restrained by the confined rock Then the thermal stresses occur. The tensile thermal stress is produced by the decreasing tempera-. The compressive heat stress is caused by the increasing ternperature. To determine the thermal stress, first the distribution of the varied temperature near the hole has to be determined. Them the thermal stress distribution near the hole is established from the theory of the thermal elastic mechanics. Finally, its effect on the stability is analyzed,

Thermal Stress Distribution

Thermal expansion is a phenomenon, which occurs under increasing temperature, in all substances, and in all forms of matter. The phenomenon includes also contraction of matter in decreasing temperature. During the thermal expansion shape, length and volume of the substance change as the temperature changes. The total thermal deformation is equal to the deformation caused by restraining stress and free deformation. From continuum mechanics, assuming the rock is elastic, homogeneous and isotropic, for a temperature perturbation of Delta (Greek) T, thermally induced strains can be expressed in terms of stresses as shown by equation.1

$$\left.\begin{aligned} \boldsymbol{\varepsilon_{rt}} &= \frac{\mathbf{1}}{\boldsymbol{E}} * [\boldsymbol{\sigma_{rt}} - \boldsymbol{v}(\boldsymbol{\sigma_{\theta t}} + \boldsymbol{\sigma_{zt}})] + \boldsymbol{\alpha T} \\ \boldsymbol{\varepsilon_{\theta t}} &= \frac{\mathbf{1}}{\boldsymbol{E}} * [\boldsymbol{\sigma_{\theta t}} - \boldsymbol{v}(\boldsymbol{\sigma_{zt}} + \boldsymbol{\sigma_{rt}})] + \boldsymbol{\alpha T} \\ \boldsymbol{\varepsilon_{zt}} &= \frac{\mathbf{1}}{\boldsymbol{E}} * [\boldsymbol{\sigma_{zt}} - \boldsymbol{v}(\boldsymbol{\sigma_{rt}} + \boldsymbol{\sigma_{\theta t}})] + \boldsymbol{\alpha T} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

For conditions of uniaxial plane strain (e.g. in both tangential axis and vertical axis where the thermal strains are zero), the initial thermal induced stresses on the borehole wall are shown by equation.2

$$\left.\begin{aligned} \sigma_{\theta t} &= \alpha\left(\frac{E}{1-v}\right)\Delta T \\ \sigma_{zt} &= \alpha\left(\frac{E}{1-v}\right)\Delta T \\ \sigma_{rt} &= \mathbf{0} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The net effective stress is given by

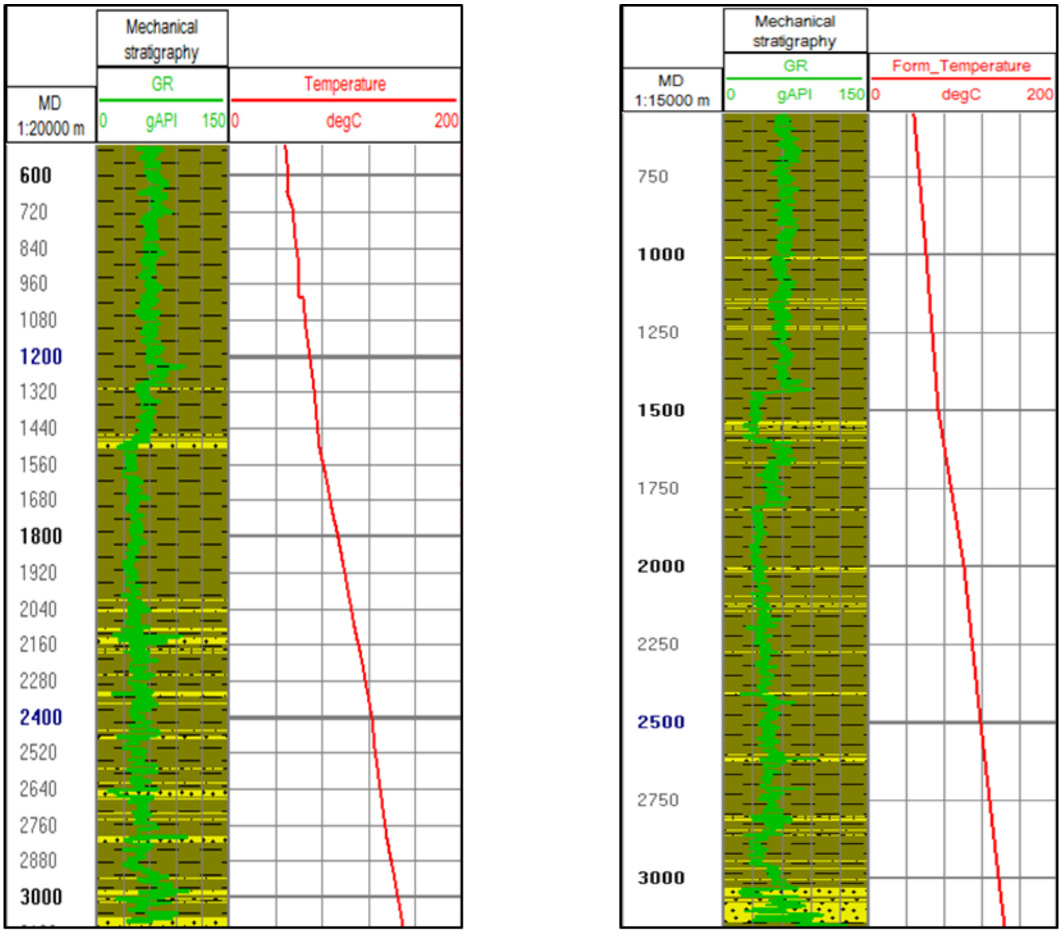
$$\left.\begin{aligned} \sigma_r &= \sigma_{rr} + \sigma_{rt} \\ \sigma_\theta &= \sigma_{\theta r} + \sigma_{\theta t} \\ \sigma_{\boldsymbol{z}} &= \sigma_{zr} + \sigma_{zt} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The effective stress in Eq.3 can be combined with Mohr-Coulomb criterion to analyze the effects of thermal stress on the wellbore stability. Thermal stresses require input of Thermal Expansion Coefficient (α), Young's Modulus (E), Static Poisson's Ratio (v) and temperature difference (Delta Temp). The Delta Temp is defined as mud temperature minus formation temperature. It means that the DeltaTemp is a negative value if there is cooling on the formation, otherwise will be positive if there is heating on the formation. Temperature distribution is very critical in the estimation of thermal stresses.

Coefficient of thermal expansion is different for different rocks. Different studies shows that:

- Thermal Expansion Coefficient(α), of different formation rocks are in the range of 5 ~ 12 x 10-6/°C.
- Values are temperature-dependent (increasing slightly as temperature increases) but for the temperature ranges and rock types, there is probably very little variation.
- Quartz-rich rocks (most sands) have relatively high values (around 10 x10-6/°C) because of the higher volume expansion coefficient of quartz.
- Shales are usually about the same. Very dense hard carbonates are around 5 x 10-6 /°C. More often carbonates are around 6~8 x 10-6/°C.

As the rock types in the study are mainly sand and shale. To study effect of thermal stresses coefficient of thermal expansion is assumed to be α=10 x 10-6/°C.



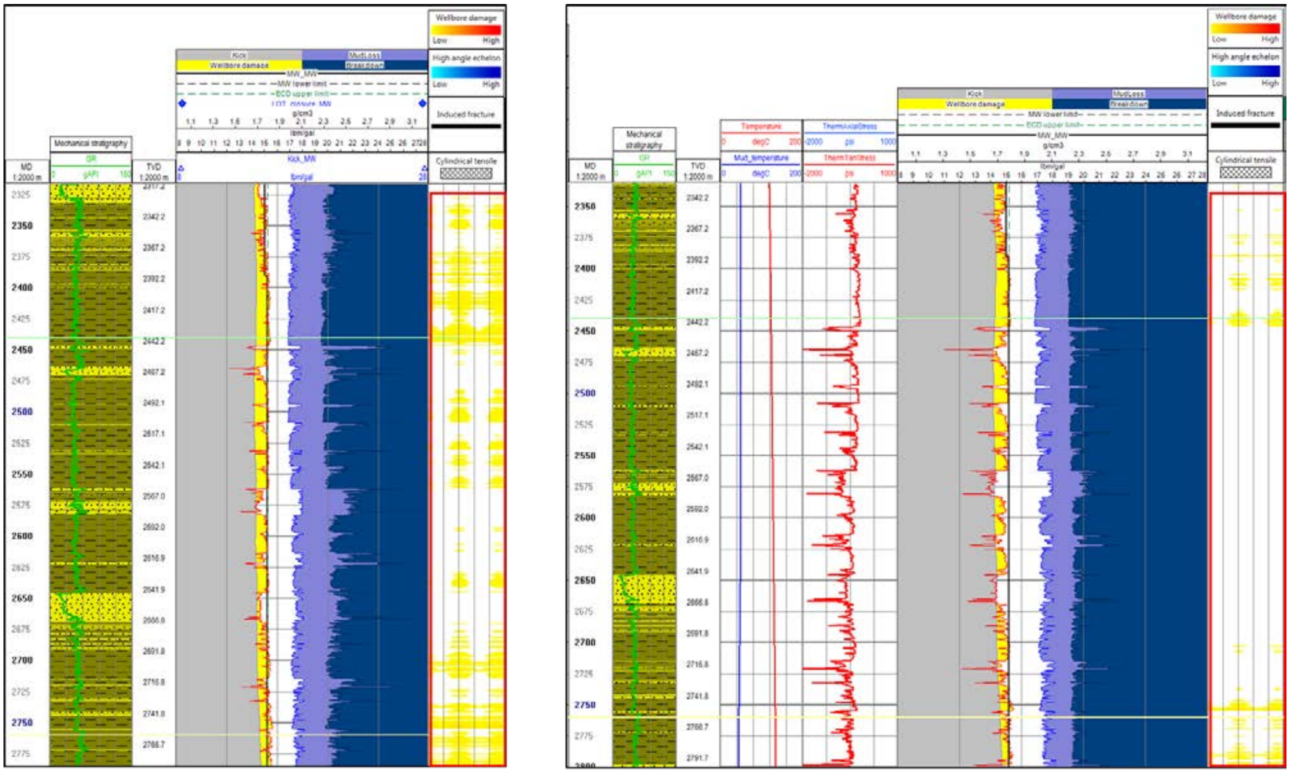
(a) Well-X (a) Well-Y

Figure 1. Thermal stresses profile for (a) Well-X and (b) Well-Y

It should be noted that the thermal stresses calculated by the Eq. 2 are called instantaneous thermal stresses as it is corresponding to the induced thermal stress at the moment. A temperature perturbation ΔT is applied on the borehole wall and just before any heat exchange occurs cross the borehole wall. Once the heat exchange occurs, the formation temperature will unavoidably change (increase or decrease), and temperature difference between formation and borehole wall will reduce, consequently, induced thermal stresses will reduce. Both Well-X and Well-Y lie in the HPHT fields with a maximum temperature of 150degC and 146 degC. Temperature profile for the two wells under study are shown in Figure.1

The Results

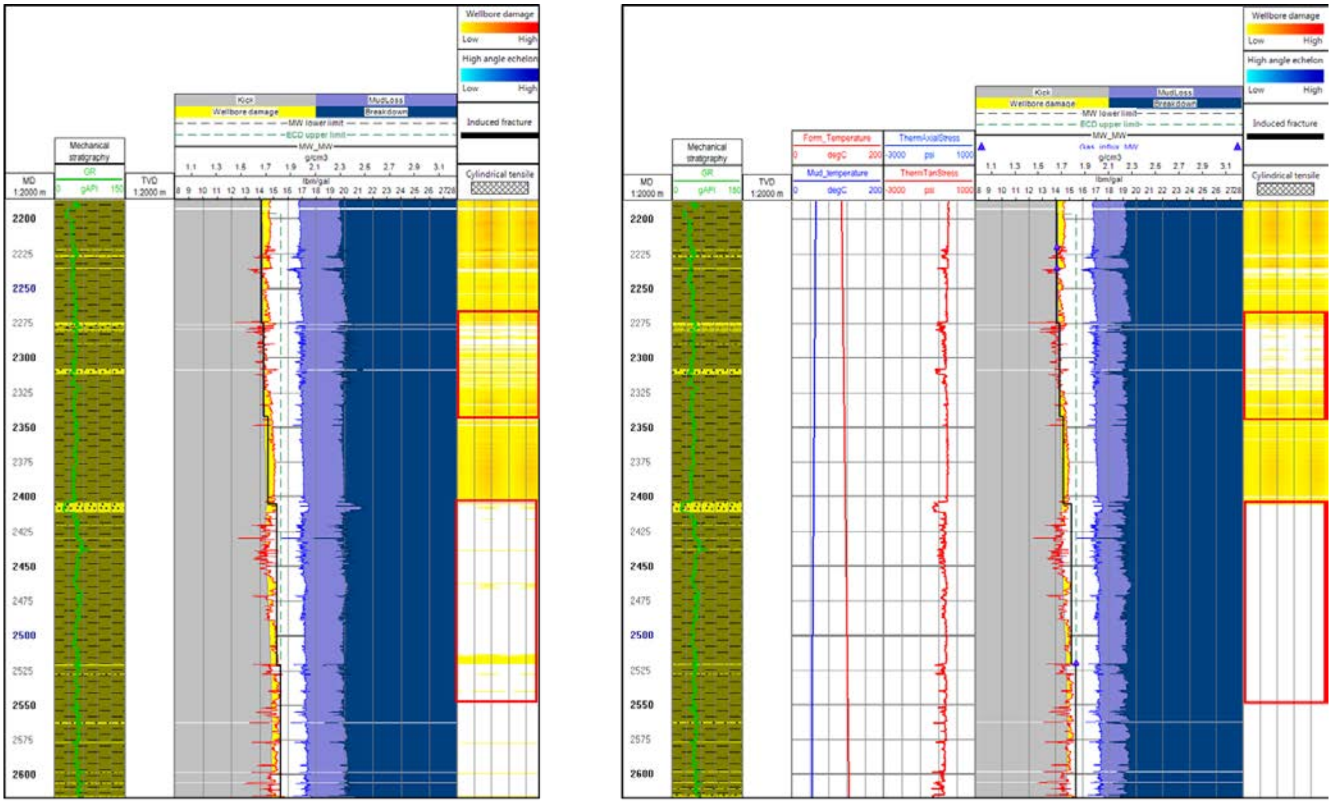
The stress distribution and the failure forms of the wall are controlled by the in situ stress and the vanes of disturbing pressure in the hole. The effect of the heat disturbing stress on the stability of the well can be analyzed based on the wellbore stress state by combining the in-situ concentrated stress with the thermal stress. Then the effective stress near wellbore stresses can be used to analyze the wellbore stability. Thermal stresses calculated are found to be varying from -100 psi to -1000psi for Well-X and -10 psi to -900psi for Well-Y. Two Wellbore Stability Model (WBS) are prepared for each well using Mohr Coulomb failure criteria. (Figure 2 and Figure 3). One model neglects the effect of thermal stresses and one includes its effect. It is observed that WBS in which effect of thermal stresses is considered show a wider mud weight window. It is because mud with lower temperature have been used while drilling. Cooling the formation basically affects the effective compressive tangential stress which ultimately changes the breakout and breakdown mud weights. For Well-X an change of ~0.2ppg to 0.4ppg in breakout MW and ~0.3ppg to 0.6ppg in breakdown MW as visible in Figure 4 (a) whereas for Well-Y an change of ~0.1ppg to 0.15ppg in breakout MW and 0.4ppg to 0.6ppg in breakdown MW as visible in Figure 4 (b). Breakdown pressure is lower with consideration of thermal stresses. In case of extreme tight sand formation, there could be chance of mud loss near borehole in fracture developed due to thermal stresses.



(a) WBS Neglecting Thermal Stresses

(a) WBS Considering Thermal Stresses

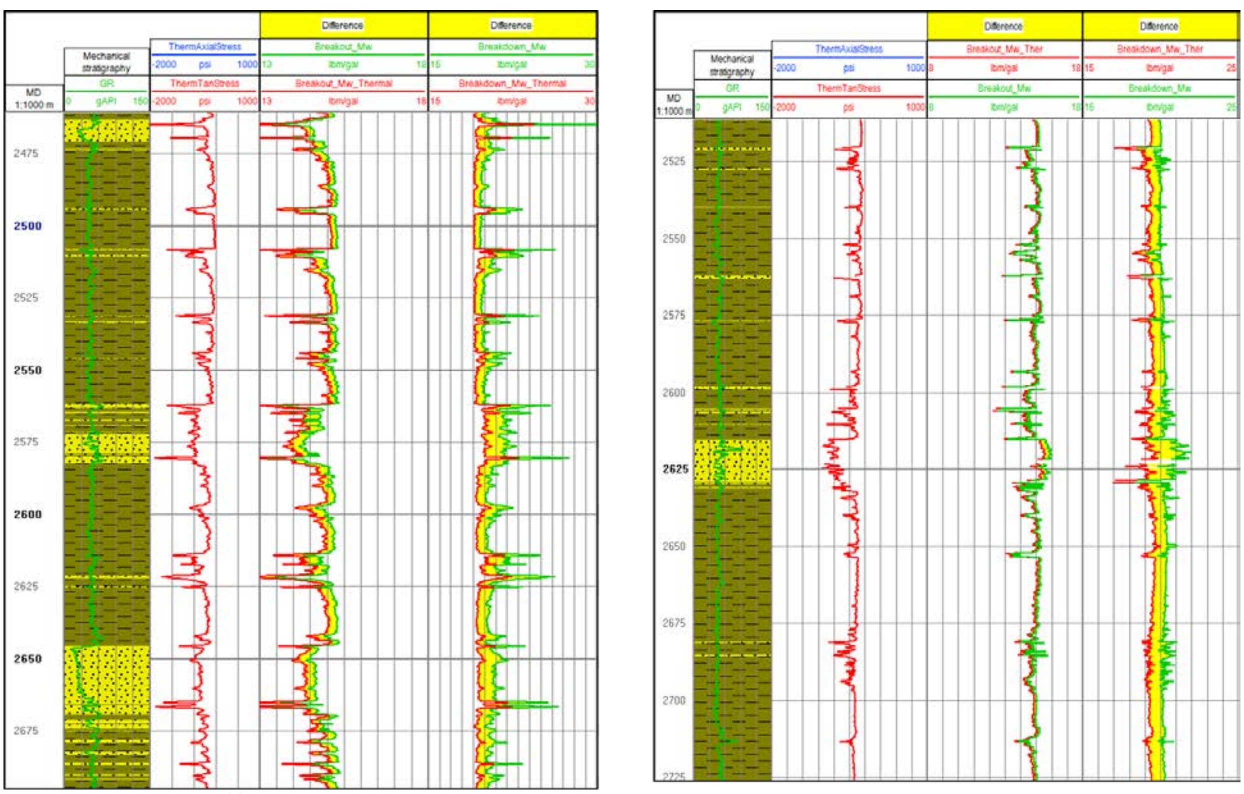
Figure 2. Wellbore Stability Model (WBS) for Well-X (a) Without thermal stresses (b) with thermal stresses



(a) WBS Neglecting Thermal Stresses

(a) WBS Considering Thermal Stresses

Figure 3. Wellbore Stability Model (WBS) for Well-Y (a) Without thermal stresses (b) with thermal stresses



(a) Well-X: Change in MW window

(a)) Well-Y Change in MW window

Figure 4. Increment of Breakout MW and Breakdown MW for (a) Well-X (b) Well-Y

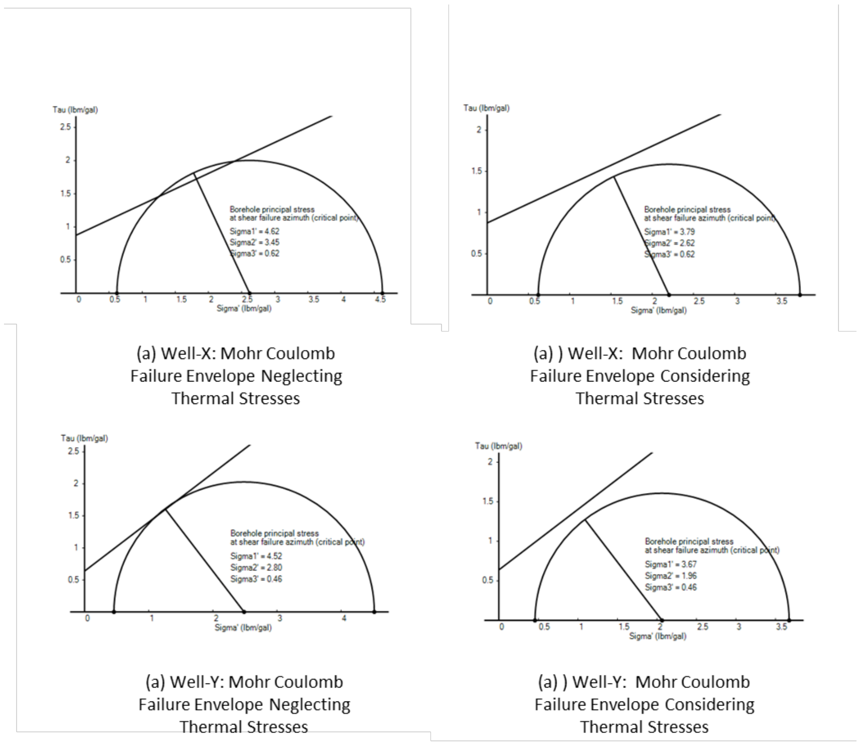


Figure 5. Effect of thermal stresses on Mohr Coulomb failure envelope for both wells.

Effect of thermal stresses can also be visualized by Mohr Coulomb criterion. Figure 5 shows the variation of borehole principle stresses (Sigma1', Sigma2' and Sigma3') at the shear failure azimuth. When thermal stresses are considered the Mohr Coulomb circle reduces in size and comes under the failure envelope because of which failure is not seen in Figure 2(b) and Figure 3(b).

Conclusion

Wellbore stability is a costly problem and is specially challenging in high pressure, high pressure wells (HPHT) resulting in higher NPT during well operations. It is noteworthy to consider thermal stress near wellbore as it has impact on its stability. Study conducted in this paper identifies the effect of thermal stresses on the limits of mud weight window prepared using Mohr Coulomb failure criteria. For cases of borehole heating, the maximum compressive effective tangential stress is increased on the borehole wall, whereas for cooling, it may be displaced inside the formation. Based on the study conducted in this paper it is verified that cool drilling mud may enhance the borehole stability by reducing the compressive tangential stress and promote fracturing by increasing the tangential tensile stress *(Wang et. al, 1996).* In general, heating enhances the compressive stress concentration on a borehole, resulting in a less stable borehole. The pore pressure induced by such heating, however, partially reduces the thermally induced stress. Whether the overall thermal impact may stabilize or destabilize the borehole depends on the ratio of the hydraulic to thermal d diffusivity which has been addressed elsewhere [Wang and Papamichos, 1994]. Thus we may enhance borehole stability by controlling the heating processes through control of mud temperature in the hole. This can be achieved by cooling the mud at the surface, or by altering the circulation rates in the borehole.

Nomenclature

σ_{rt} = radial thermal stress, psi
$\sigma_{\theta t}$ = tangential thermal stress, psi
σ_{zt} = axial thermal stress, psi
ε = strain, dimensionless
$\boldsymbol{\alpha}$ = **thermal expansion coefficient, 1/degC**
$\mathbf{T}$ = **formation temperature**

ΔT = **differnce betwenn mud and formation temperature**
E = **rock Young′smudulus**
v = static posisson ratio
σ_r = effective radial stress, psi
σ_{rr} = radial in − situ mncentration normal stress, psi
σ_z = effiive axial stress, psi
σ_{zr} = axial in − situ concentration normal stress, psi
σ_θ = effective tangential stress, psi
$\sigma_{\theta r}$ = tangential thermal stress, psi

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