Improving Borehole Instability Analysis by Investigating the Impacts of Stress and Rock Anisotropy

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Summary

This paper assesses the mechanical stability of a borehole subjected to both an internal pressure and a far-field stress as a function of rock elastic anisotropy. First, as a fundamental step, an anisotropic model is present to visualize the stress distribution around an arbitratily orientated borehole utilizing an earlier analytical solution. Second, lower hemisphere diagrams are present to demonstrate the rock strength and wellbore pressure required to initiate borehole tensile and compressive failure, as such, we can optimize the borehole orientation and also minimize borehole instabilities caused by inappropriate well pressure. Third, a MATLAB^{TM} based program incorporating anisotropic variables shows tensile fractures traced on the unwrapped borehole wall in inclined holes.

Introduction

Wellbore stability analysis is important in the oil and gas drilling. Assessment of wellbore stability needs a variable of parameters, such as formation elastic properties, pore pressure, etc., but the input mechanical data sometimes cannot be easily accessed. This study presents different models to investigate the impacts of far field stress and rock anisotropy on borehole stability.

Among all those parameters involved in borehole stability analyses, the state of stress in the earth is a critical, but often ignored, factor in the success of geothermal energy and petroleum production. Knowledge of *in-situ* stress enables us to determine the optimum borehole trajectory, evaluate hydrocarbon migration, simulate hydraulic fracture propagation, and so on. Consequently, it is necessary to understand the state of stress in the earth in order to design and efficiently operate engineered petroleum systems.

In-situ stress is usually expressed in three major components: vertical stress (overburden), maximum horizontal stress and minimum horizontal stress. All those components can be evaluated from density log for overburden, mini-frac data, such as leak-off test (LOT), Diagnostic Fracture Infectivity Tests (DFIT's), etc., for minimum horizontal stress Sh, and image log data along with rock property for maximum horizontal stress SH (Reis *et al.*, 2013). Additionally, pore pressure plays an important role in stress determination, which can be derived from DFIT's and drilling-stem tests (DST).

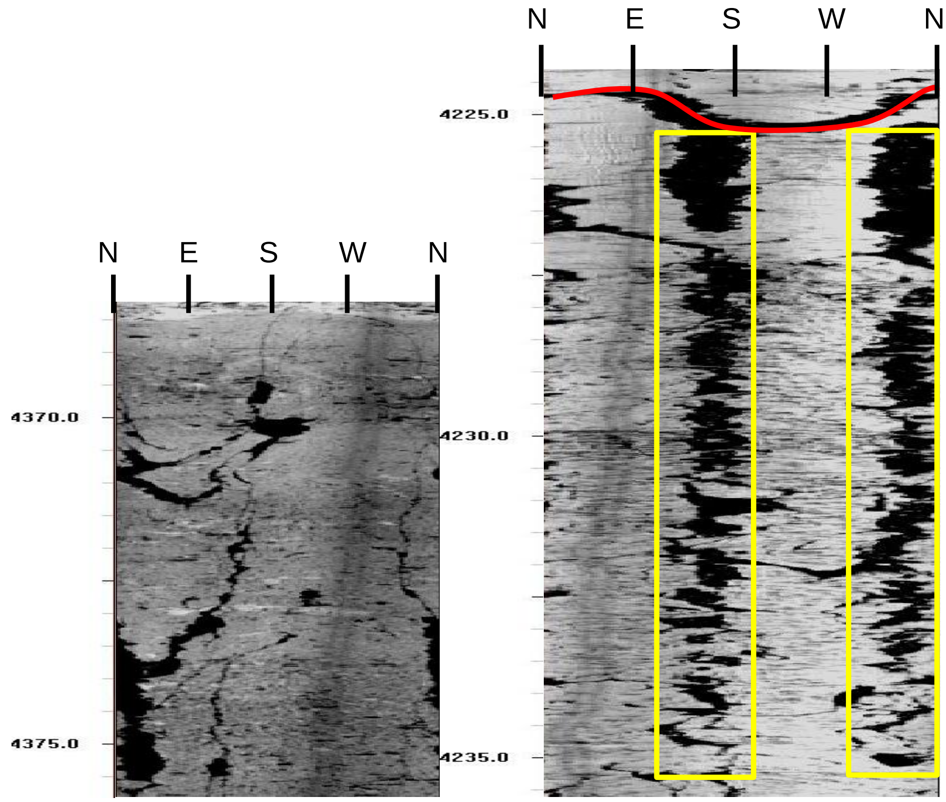

Figure 1. Borehole televiewer image data from southern Idaho shows drilling induced tensile fracture (left) planar feature (right red line) and borehole breakout (right yellow boxes).

Stress will be redistributed and reoriented during and after drilling process, and this may lead to rock failure with high hoop stresses (Simangunsong et al., 2006). Therefore, we need to adjust mud weight and/or borehole orientation to stabilize the borehole. Applying appropriate mud weight is critical in the drilling process. Insufficient mud weight can result in borehole breakout; in contrast, excess mud weight can lead to drilling induced tensile fracture (DITF). And these two types of fracture can both be identified from image logs (Fig. 1).

There are three objectives in this study:

- Modeling the near-wellbore stress distribution in both isotropic formation and anisotropic formation and further tracing tensile fracture on the borehole wall;
- Optimizing mud weight and borehole orientation to minimize borehole instability;
- Updating the stress state in Duvernay Formation in Western Canadian Sedimentary Basin.

Theory and/or Method

To visualize how stress concentration changes at different distances r from the borehole axis, it is more convenient to set the coordinate into cylindrical (r-θ-ξ coordinate). As illustrated in Figure 2, the normal stress components include σ_{rr}, $\sigma_{\theta\theta}$ and $\sigma_{\xi\xi}$, which are the radial, hoop and axial stress, respectively, and $\tau_{r\xi}$, $\tau_{\theta\xi}$ and $\tau_{\theta r}$ are shear stresses. The stresses around the borehole wall in an isotropic formation can be written as the following (Hiramatsu and Oka, 1962):

$$\sigma_{rr} = \alpha_1\left(1-\frac{a^2}{r^2}\right)+\alpha_2\left(1-4\frac{a^2}{r^2}+3\frac{a^4}{r^4}\right)cos2\theta+\alpha_3\left(1-4\frac{a^2}{r^2}+3\frac{a^4}{r^4}\right)sin2\theta,$$

$$\sigma_{\theta\theta} = \alpha_1\left(1+\frac{a^2}{r^2}\right)+\alpha_2\left(-1-3\frac{a^4}{r^4}\right)cos2\theta+\alpha_3\left(-1-3\frac{a^4}{r^4}\right)sin2\theta,$$

$$\tau_{\zeta\zeta} = \beta_1-4\nu\left(\alpha_2\frac{a^2}{r^2}cos2\theta+\alpha_3\frac{a^2}{r^2}sin2\theta\right),$$

$$\tau_{\theta\zeta} = \gamma_1 \left(1 + \frac{a^2}{r^2}\right) cos\theta + \gamma_2 \left(1 + \frac{a^2}{r^2}\right) sin\theta,$$

$$\tau_{r\zeta} = \gamma_1 \left(1 - \frac{a^2}{r^2}\right) sin\theta - \gamma_2 \left(1 - \frac{a^2}{r^2}\right) cos\theta,$$

$$\tau_{r\theta} = \alpha_2 \left(-1 - 2\frac{a^2}{r^2} + 3\frac{a^4}{r^4}\right) sin2\theta + \alpha_3 \left(1 + 2\frac{a^2}{r^2} - 3\frac{a^4}{r^4}\right) cos2\theta$$

where ν is Poisson's ratio, α_1, α_2, α_3, β_1, γ_1 and γ_2 are the coefficients as a function of direction cosines, *in-situ* stress magnitudes and the inclination ϕ of the borehole axis. For the anisotropic model, stress calculation was established utilizing the earlier analytical solutions (Lekhnitskii, 1981; Amadei, 1983; Ong, 1994). Based on all these theories, a MATLAB™ based program was created to calculate the stress concentrations for an arbitrarily oriented borehole in an isotropic or an anisotropic medium subject to stresses (Fig. 3).

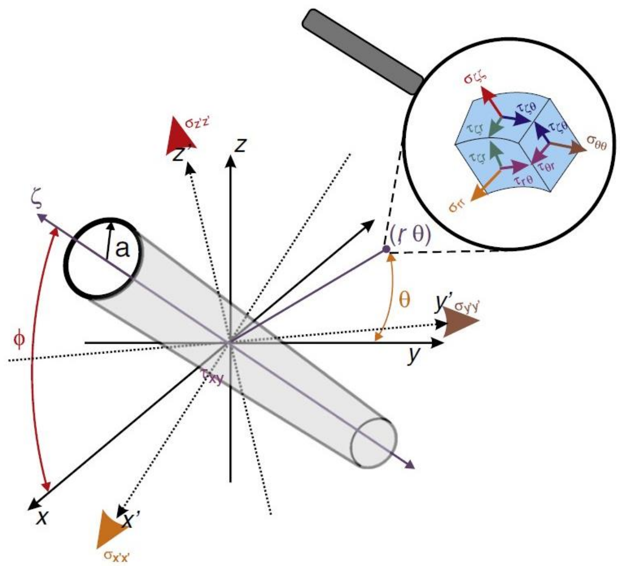

Figure 2. Stresses acting on the borehole wall and different coordinate frames (Schmitt *et al.*, 2012).

As mentioned earlier, two types of fracture can be identified from image logs, and they are tensile fracture and borehole breakout indicating tensile failure and shear failure. Tensile fractures can occur when the effective tensile stress on the borehole wall exceeding the formation tensile strength, and tensile fractures initiate at the place where effective tensile stress is the smallest (Fjaer *et al.*, 2008). However, rock tensile strength is often negligible, and in this case, we assume it is zero.

There are several rock failure criteria in wellbore stability analyses, and the commonly used criteria are the Mohr-Coulomb criterion, the Drucker-Prager criterion and the modified Lade criterion. All except the modified Lade don't take the influence of the intermediate stress into consideration (Ewy, 1999). In our study, the Mohr-Coulomb criterion will be utilized when dealing with borehole breakout initiations.

Examples

Figure 3 shows the stress distribution around an arbitrarily orientated borehole in an isotropic formation (left side of each panel) and a transversely isotropic formation (right side of each panel). The full set of 5 elastic stiffnesses (C_{11} = 33.2GPa, C_{13} = 5.0GPa, C_{33} = 22.2GPa, C_{44} = 11.0GPa, C_{66} = 14.6GPa) under the assumption that the rock is transversely isotropic is obtained from quasi-static laboratory measurements on a real shale sample by Martínez and Schmitt (2013). As illustrated in Figure 3, despite the fact that this material is relatively anisotropic (Thomsen ε = 0.25, γ = 0.17, δ = 0.25), the stress concentrations are not significantly different from those for a borehole in an isotropic material with C_{11} = 33.2 GPa and C_{44} = 11.0 GPa.

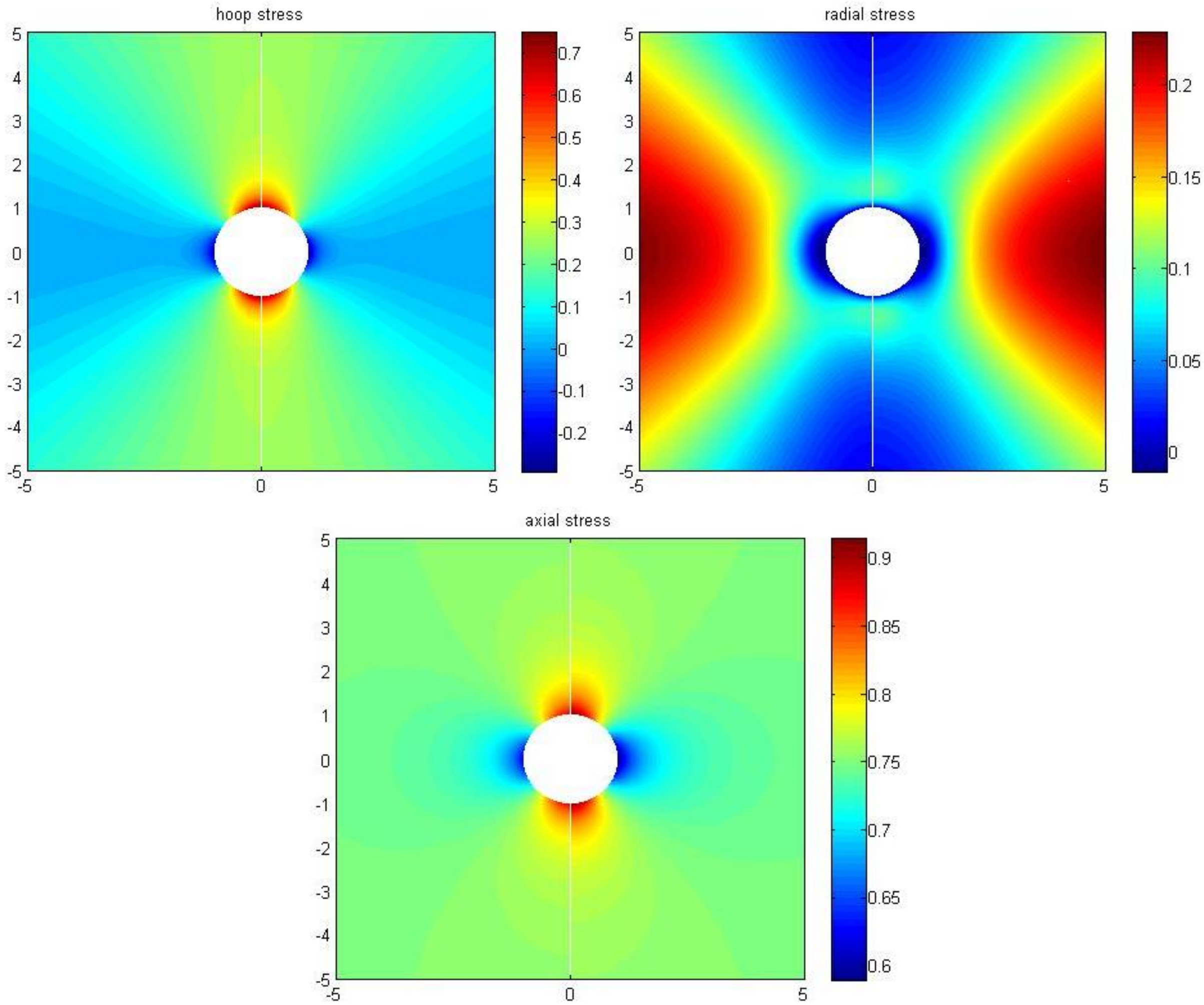

Figure 3. Stress Distribution around an inclined borehole in an isotropic formation (left half of each panel) and a vertical transversely isotropic formation, also called VTI (right half of each panel). In this case, SH = 1MPa; Sh = Sv = 0MPa; ΔP = 0MPa; the borehole is inclined 60° with respect to the vertical principal *in situ* stress whose direction co-incides with the axis of symmetry for the transversely isotropic material.

Figure 4 presents the tendency of fracture initiation (both tensile fractures and borehole breakouts) for an arbitrarily deviated well. Based on the concept developed by Peska and Zoback (1995), a MATLAB^{TM} based program was created showing the lower hemisphere diagram to investigate the stability of wells in isotropic formation.

According to Ong and Roegiers (1996), the tensile fracture inclination angle is calculated. As illustrated in Figure 5, the tensile fractures (green lines) are traced on the unwrapped borehole wall in an isotropic formation (left) and an anisotropic formation (right), and the background color indicates the minimum effective principal stress. The result surprisingly shows that tensile fractures are not symmetrical, which agrees with the behavior of tensile fractures in image logs. Moreover, the rock anisotropy indeed changes the direction of tensile fracture propagation.

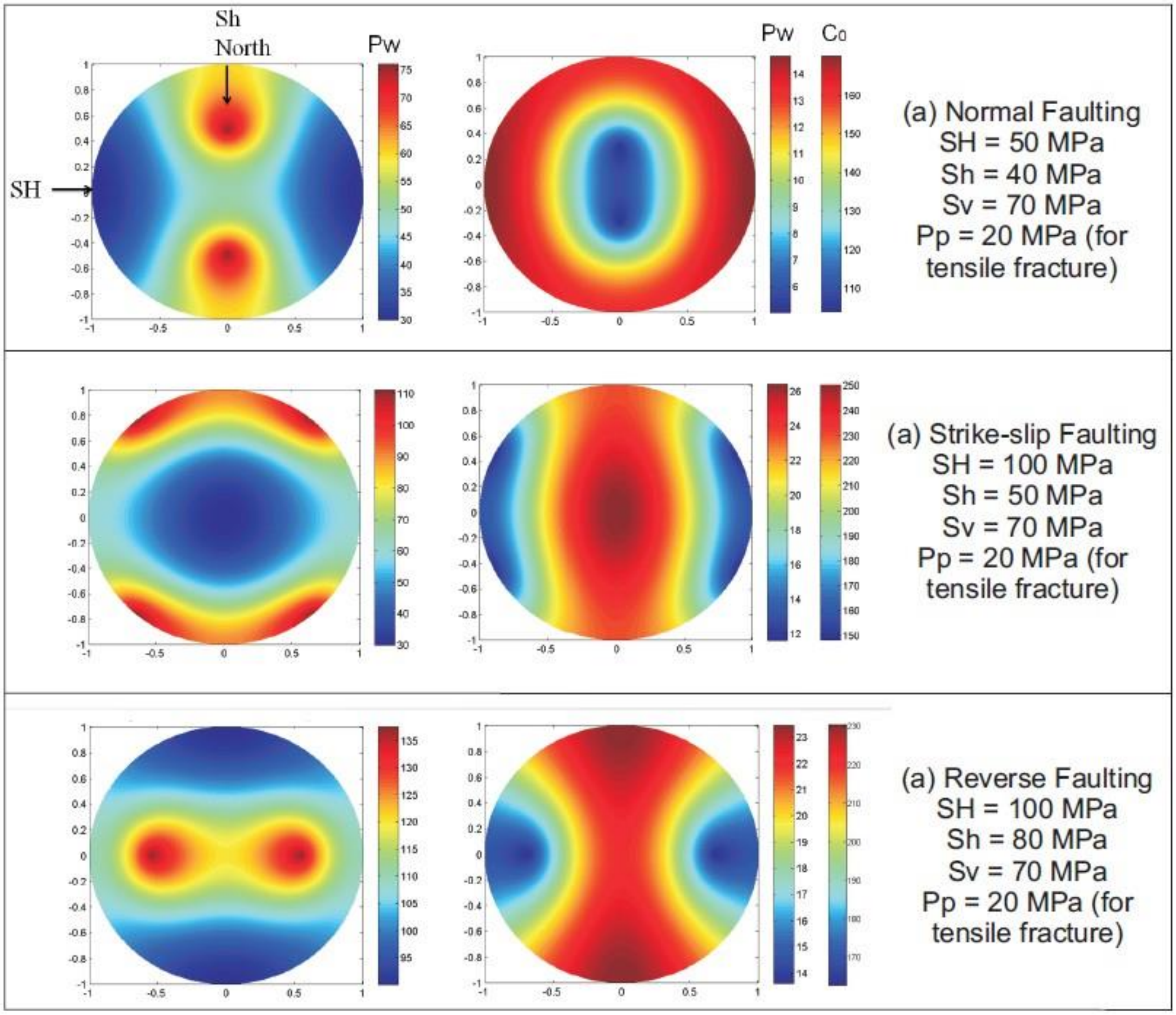

Figure 4. Tendency for the initiation of tensile fractures (left) and wellbore breakouts (middle) in wells of different orientations for normal, strike-slip and reverse faulting stress regimes. *In-situ* stress conditions and pore pressure are shown.

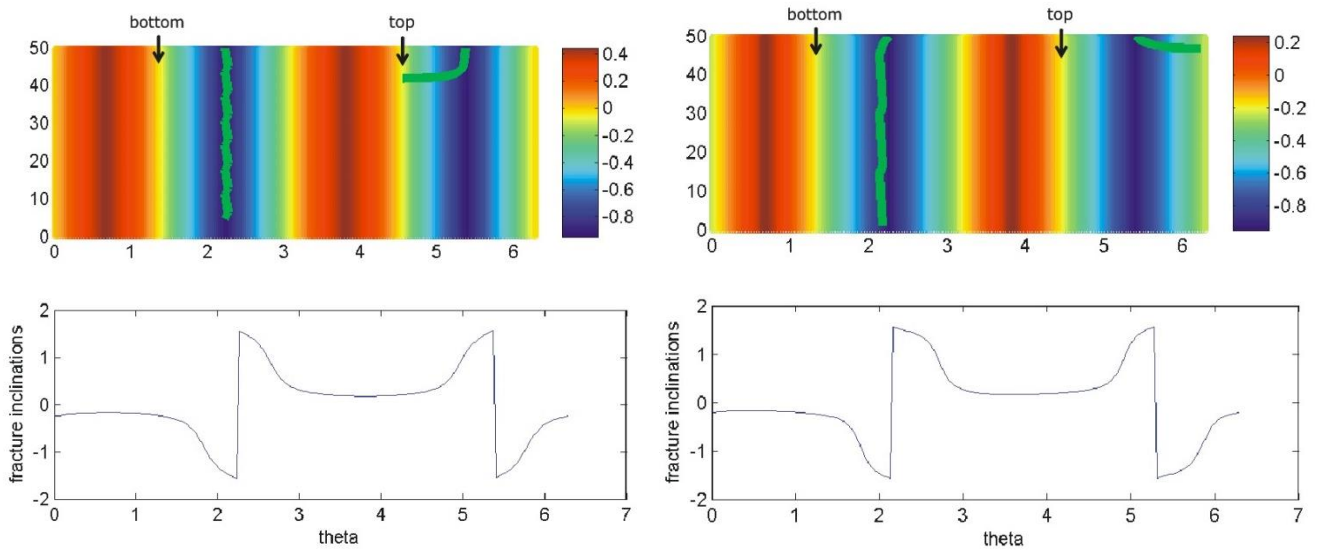

Figure 5. tensile fracture tracing (green lines) on the unwrapped borehole wall in an isotropic formation (left) and an vertical transversely isotropic (VTI) formation (right). In this case, SH = 1MPa, Sh = Sv = 0MPa, ΔP = 0MPa, inclination = 20°, azimuth = 50°. The top and bottom side of the borehole are indicated. The background colour is the minimum effective stress.

Conclusions

This study investigates the impacts of rock anisotropy and far-field stress on borehole stability. Several models are created using MATLAB™, and some numerical models will also be created using ANSYS™ to validate our analytical models. Based on these models, the following conclusions can be drawn:

- Comparing with the isotropic case, rock anisotropy can affect stress distribution in some degree but the whole stress pattern doesn't change;
- Tensile fractures are not symmetrical on the borehole wall;
- The rock anisotropy can affect the direction of tensile fracture propagation.

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