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Quantitative Measures of Stress and Pore Pressure: Applications to Fault Stability

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Summary

In the coming decades, the pace of disruption of the subsurface will accelerate as society attempts to extract greater amounts of hydrocarbon and geothermal energy from the subsurface, to annually store methane and hydrogen for shorter time periods, and to permanently sequester waste liquids and greenhouse gases. All these activities perturb subsurface temperatures, fluid pressures, and stress states: perturbations that can in some circumstances induce seismicity. Increasingly, these activities will proceed in greenfields where in situ conditions are not known and there is no historical record of seismicity. Being able to make assessments as to the potential for inducing seismicity of a given area will be increasingly important. Here, we review a straightforward stability assessment that relies uses actual observed stress and pore pressure distributions within the Duvernay Formation of Alberta. We further discuss one geomechanical quandry raised by the fact that high reservoir fluid pressures, as provided by standard industrial methods from boreholes, lead to further questions related to the lack of historical seismicity and and stability of boreholes drilled through this formation.

Background

In greenfields without a seismic history, it is important to apply as many means of assessing the risk as possible. Physics based deterministic approaches often rely on the Mohr-Coulomb friction paradigm, which essentially states that a pre-existing fault will slip once the shear forces acting within the fault's plane overwhelm the counterbalancing clamping, cohesive, and frictional forces holding the fault in place. The Mohr-Coulomb friction law can be expressed as

$$|\tau| \geq \mu(\sigma_N - P_P) + C \qquad (1$$

with the shear τ and normal σ_N tractions resolved parallel and perpendicular to the fault plane as affected by the pore fluid pressure P_p and constrained by the fault cohesive strength C and static coefficient of friction μ. These tractions are easily calculated if one has knowledge of the complete stress tensor relative to the orientation of the prospective fault plane but the expressions need not be repeated here (see Schmitt (2014) for a short tutorial). Eqn. (1 is often rearranged to provide various metrics for stability, one of which is the shear to normal stress ratio *SNR* of Morris et al. (1996)

$$SNR \equiv \frac{|\tau| - C}{\sigma_N - P_P} \geq \mu \qquad (2$$

which essentially indicates the point where friction is overcome.

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Method

Eqn. (2 is straightforward but obtaining appropriate the appropriate input values is not. As noted, a full knowledge of all the components of the stress tensor as is first necessary to find τ and σ_N. Here, the stress tensor is taken to be the simplified Andersonian form that assumes horizontal maximum S_H and minimum S_h and a vertical S_V compressive total stresses. The pore pressure P_P, too, within the rock mass must also be known as failure of the rock mass, be it at the borehole wall or along a potential fault slip plane, is controlled by the Terzhaghi effective stress.

Most efforts to determine stress magnitudes suffer in that numerous presumptions are often made that might rely on extremum values under the critical stress paradigm or on perfect lateral constraint model. More concerningly, the equations used to describe stress concentrations around boreholes are, out of context, being often incorrectly used to calculate stresses in the bulk formations. To overcome the ambiguities or errors associated with these approaches, (Shen et al., 2019a; Shen et al., 2021) made as many direct quantitative measurements of these values as possible in areas that have experienced different levels of seismicity linked to Duvernay Formation hydraulic fracturing operations. These studies were able to take advantage of numerous geophysical logs and pressure tests conducted in these areas. Reviews of the method used may be found in Shen et al. (2019a). Briefly, however:

- S_V was found by vertical integration of over 1000 density logs subsequently combined and corrected for local variations in topography.
- S_h was found by consistent reanalysis of numerous open hole transient pressure tests in the Duvernay Formation (i.e., mini-fracs, micro-fracs, or DFITs$^{\text{TM}}$) that track the pressure at which a small intentional hydraulic fracture closes.
- P_P was determined from reanalysis of a larger number of similar tests within the Duvernay Formation as estimated from extrapolation of borehole pressure changes during long term (often weeks) shut in tests.
- S_H, which still cannot be directly measured from a borehole, was constrained by a combination of borehole image log analyses and inversion of local focal mechanisms. In contrast to the other well constrained values, these analysis provide a distribution of S_H magnitudes.

Care was taken in these studies to further assess the levels of uncertainty expected in each measurement. This stress and pore pressure information were all distilled via Krieging into maps and readily extracted using specially developed applications on the basis of the geographic location within the study areas (Shen et al., 2019, 2021). Overall, these results are also suggest with a strike slip faulting environment with $S_H > S_V > S_h$.

Observations

The high reservoir pressures observed in the Duvernay Formation is one of the key factors driving its development as an unconventional reservoir. And as such, the direct observations of P_P by Shen et al. (2019, 2021) are not at all surprising. That said, however, the observed values are consistently 90% or more of the S_h magnitude. Shen et al. (2019b) pointed out that this leads to high *SNR* on wide ranges of potential fault orientations; that is a wide range of potential fault planes would naturally be unstable and may take very little additional perturbation. This immediately raises the question with regards to if this is the case, then why are these areas so seismically quiescent and why is so little evidence for larger fault displacements?

One can take these observations further to examine the stability of boreholes drilled through the Duvernay Formation under these conditions, and for the sake of illustration a simple case that would related to the development of drilling induced tensile fractures (DITF) that are used commonly as a stress direction indicator are determined. We calculate DITF criterion here primarily because of the paucity of such features within the numerous image logs analyzed as part of the earlier mentioned studies. At the borehole wall, the *total* circumferential stress $\sigma_{\theta\theta}$, for a vertical borehole subject to a mud pressure P_w simplifies to

$$\sigma_{\theta\theta} = (S_H + S_h) - 2(S_H - S_h)\cos 2\theta - P_w \qquad (3$$

where θ is the angle (clockwise looking down the borehole) from the S_H direction. Using the stresses in the example studied in Shen et al. (2019b, Fig. 2) with S_H = 124 MPa, Sv = 84 MPa, and S_h = 65 with a mud pressure at 3300 m calculated using heavier mud weights typically used when drilling through the Duvernay (~1300 kg/m^3) of P_w = 42.9 MPa gives concentrated $\sigma_{\theta\theta}(\theta)$ shown in Fig. 1; and under these conditions the borehole wall is everywhere subject to compression. The *effective stress* that incorporates the pore fluid pressure P_P must be used, however, to determine the level at which a DITF might be produced and the effective circumferential stress here is simply

$$\tilde{\sigma}_{\theta\theta} = \sigma_{\theta\theta} - P_P \qquad (4$$

which is also plotted in Fig. 1 for three cases in which P_P is omitted (blue), P_P = 33 MPa equal to the normal hydrostat (orange), and finally with P_P = 57 MPa as provided from the field measured stress distributions (black) of Shen et al. (2019a).

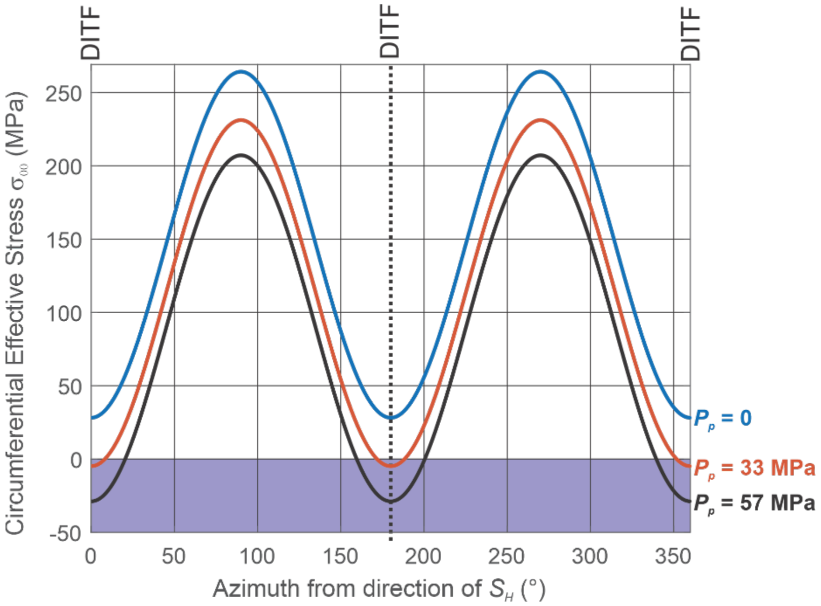

Fig. 1. Illustrative example of the circumferential effective stress $\tilde{\sigma}_{\theta\theta}$ versus azimuth θ from the direction of the greatest horizontal compression S_H at the surface of the borehole for three different pore pressures. Purple zone indicates azimuths in tension. The azimuths of θ = 0° and 180° at which drilling induced tensile fractures would form indicated by DITF.

The key point shown in Fig. 1 is that if the pore pressure is at the presumed ambient value of 57 MPa, then those zones around the borehole in the direction of S_H are subject to significant tensile stresses approaching -30 MPa, values that significantly exceed the tensile strengths of rock. Consequently, one might expect drilling induced tensile fractures to be ubiquitous, but at least in the image logs that we have analyzed only a few such DITF's were observed (Shen et al., 2019a). As with the lack of historical seismicity, attempting to reconcile the apparently high ambient pore fluid pressures with the paucity of drilling induced borehole stress indicators is problematic.

Conclusions

At this time we do not have explanations for these discrepancies between the lack of seismicity and borehole failure in the Duvernay Formation and its high pore pressures. Shen et al. (2019b) suggested that the lack of natural seismicity might result from lower in situ pressures near the planes of weakness due to migration of hydrocarbons into the overlying Mesozoic sedimentary column. But this scenario cannot explain the lack of stress induced borehole features.

A more speculative reason may be that it may not be correct to equate the measured reservoir pressures (important to evaluation of the reservoir) to the pore fluid pressure P_P (important in controlling both slip on faults and failure at the borehole through an effective stress rule). In conventional porous and permeable reservoirs one would not question that these aspects of the fluid pressure would be the same. However, in low permeability unconventional rock the pores are generally much smaller and more poorly connected to one another. Further, the hydrocarbons residing in these pores are often not freely mobile fluids; they remain adsorbed or absorbed within the heavier hydrocarbons. As such, the actual pore pressures that are mechanically active within these rocks may be less than that directly measured in long term pressure tests. Work to test this hypothesis is necessary.

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