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Geomechanical Analysis of Hydraulic Fracturing Induced Seismicity at Duvernay Field in Western Canadian Sedimentary Basin

Suvrat P Lele[1], Timothy Tyrrell[2], Ganeswara R Dasari[1], William A Symington[1]
[1]ExxonMobil Upstream Research Company, [2]XTO Energy

Summary

Induced seismicity due to hydraulic fracturing operations is being observed at increasing frequency at the Duvernay play in Western Canadian Sedimentary Basin, and triggering mechanisms for these events are not clearly understood. This study explores two possible triggering mechanisms for seismic events induced by hydraulic fracturing: (i) poroelastic stress/pressure changes, and (ii) stress/pressure changes due to a direct hydraulic connection between fault and fracture. Geomechanical modeling results indicate that poroelastic stress/pressure changes due to pressurized fractures attenuate quickly and this factor is less likely to trigger seismicity at faults more than a few hundred of meters away from fracture. Hence hydraulic connection is a more likely triggering factor. Preliminary results from finite element analyses for pressure diffusion along a fault plane intersecting a fracture are shown. Study of hydraulic fracturing induced seismicity using quasi-static geomechanical modeling is an emerging field, and the models will be improved as more field data are available for testing various hypotheses.

Introduction

Felt induced seismicity due to produced water injection has been observed at many locations and has been extensively studied, for example, disposal of produced water in layers just above critically stressed geological basement in Oklahoma and North Texas (Ellsworth 2013, McGarr 2014). On the other hand, felt induced seismicity due to hydraulic fracturing operations has been observed only in few unconventional plays (US National Academy 2012), but the number and magnitude of events is increasing. Recently, three events of magnitude >4 have been attributed to hydraulic fracturing in the Duvernay play in the Western Canadian Sedimentary Basin (Schultz et al. 2016, Bao and Eaton 2016). Most published papers on these events so far focused on event location and establishing spatial and temporal relations between the completion parameters and seismic events.

The present study explores mechanics based hypotheses between the hydraulic fracturing and the seismicity. The high horizontal stress gradient attributed to Canadian Rockies to the west and overpressure indicates that the Duvernay formation is close to shear failure. Analysis of observed seismic and micro-seismic events indicates that faults in orientations favorable for slip are present. We explored two hypotheses for the hydraulic fracturing induced seismicity: (i) stress/pressure changes on faults due to hydraulic fracturing assuming the rock mass is homogeneous, and (ii) stress/pressure changes on faults due to hydraulic fracturing through a direct hydraulic connection between fault and fracture. Mohr-circle based analysis of the stress state are used to identify critical fault orientations. Poroelastic stress changes due to pressurized fracture are analyzed using an analytical solution. Finite element modeling approach is used to study fault/fracture intersection with diffusion of fluid along fault zone, including the effects of varying rock properties and fault parameters. Results from these analyses are used to test the above two hypotheses for hydraulic fracturing induced seismicity.

Critical Orientation for Faults

The horizontal stress gradients in Duvernay formation in Fox Creek region range from 0.84–0.99 psi/ft and 1.2–1.4 psi/ft for the minimum and maximum components respectively, the vertical stress is approximately 1 psi/ft, and the pore pressure in Duvernay layer is in range 0.7–0.8 psi/ft (Soltanzadeh et al. 2015, Fox et al. 2015). The maximum horizontal stress azimuth is 45° from North. Mohr circle plots for stress state at two sample wells at 3400m depth are included in Fig. 1. The Vertical faults with Azimuth 15° from North are most susceptible for slip assuming fault friction coefficient of 0.6, indicated by failure line in the plots. Most observed higher magnitude seismic events indicate a North-South orientation for existing faults (Schultz et al. 2016). The observed critical fault orientation is close to or at failure based on plots in Fig. 1.

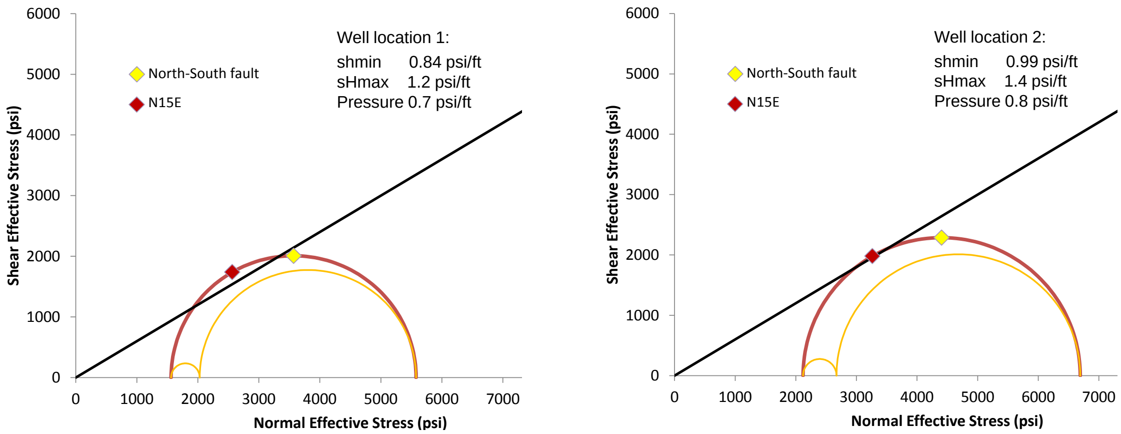

Fig. 1. Mohr circle plots for effective stress state at two sample well locations in Duvernay. The initial stress state is close to shear failure and small stress/pressure perturbations may cause fault slip. Faults oriented N15E are more likely to slip first. Faults assumed to have friction coefficient of 0.6 and negligible cohesion.

Hypothesis 1: Seismic events triggered by poroelastic stress/pressure changes

Hydraulic fracturing can be modeled as a pressurized crack in homogeneous rock mass. Stress/pressure changes in the rock around a pressurized fracture are predicted using an analytical solution (Green and Sneddon 1950), where the fracture is assumed to be an open elliptical crack with internal pressure equal to 500 psi above the horizontal minimum stress (fracturing pressure). As a conservative assumption 50 such individual fractures with 40m spacing are considered for a North-South well; additionally, each fracture is assumed to maintain the fracturing pressure, i.e. pressure reduction due to leakoff, particularly after a fracturing stage is completed, is ignored. Stress/pressure changes due to all fractures are added. Minimum horizontal stress modified due to fracture pressure is shown in Fig. 2.

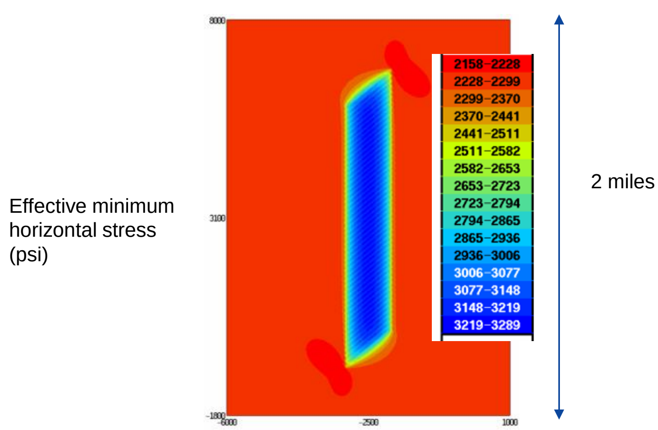

Fig. 2. Effective minimum horizontal stress with changes induced by fracture pressure; stress changes attenuate quickly away from fractures.

The analytical solution predicts total stress changes; these are separated into pore pressure and effective stress components dependent on rock vs. fluid compressibilites using poroelasticity theory and assuming undrained conditions due to low permeability of the Duvernay shale. Horizontal shear stress increases in most of the region near fractures, except small areas Northeast and SouthWest. Moreover, these changes attenuate quickly with distance from the fractures. Hence these stress/pressure changes are less likely to be a triggering factor for seismicity. Note that such stress changes may still cuase seismicity in few cases under certain assumptions such as analysis presented in Deng et al. 2016.

Hypothesis 2: Seismic events triggered by stress/pressure changes due to hydraulic connection

Based on above discussion, poroelastic stress/pressure changes are less likely to be a triggering factor for fault reactiviation. Hence another scenario, a direct hydraulic connection between fracture and fault, is anlyzed, which may be possible due to hydraulic fractures intersecting fault or presence of natual fracture. A 3D finite element model based on representative geology is used to study diffusion of pressure from fault/fracture intersection into the fault gouge zone. The fault zone is assumed to have higher permeability of ~ 1 millidarcy (conservative assumption). Duvernay layer permeability is assumed to be 250 nanodarcy, and that for other layers ranges from 1 microdarcy for other shale layers and 1 millidarcy for Swan Hills and Wabamun layers. A schematic plan view respresentation of fault/fracture intersections and the 3D model finite element geometry are shown in Fig. 3.

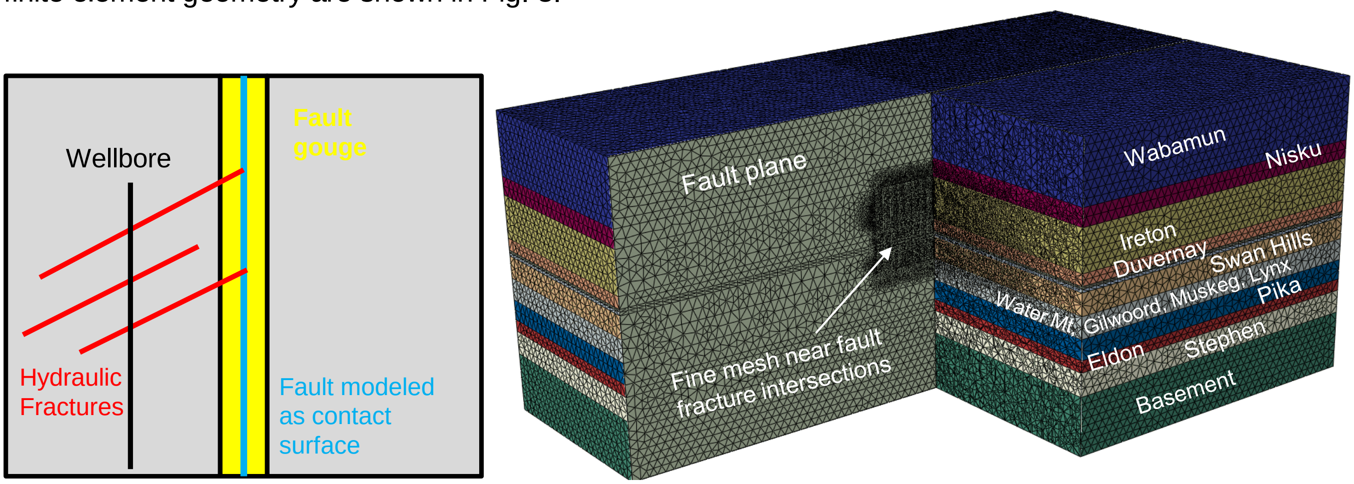

Fig. 3. Schematic plan view of fault-fracture intersection with North-South fault and North-South horizontal wellbore; details of 3D finite element model with geological layers and mesh

Predicted pressure changes due to diffusion into fault zone and leakoff into surrounding layers for a sample analysis are shown in Fig. 4. This case includes 15 fault/fracture intersections, and pressure in all fractures is held constant at 500 psi above the horizontal minimum stress for the entire duration of the simulation; this again is a conservative assumption that ignores pressure drops due to leakoff. Results in Fig. 4 show changes in pore pressure, i.e. excess pressure due to diffusion of fluid, after 10 days of simulated duration, with plot scale maximum limit set to 100 psi to make pressure leakoff visible. These results indicate that fluid can diffuse along fault zones with high permeability and leakoff into surrounding layers. These pressure changes could be sufficient to cause fault reactivation at some locations based on the critical stress state discussed above.

The predicted pressure changes do not propagate further towards the basement layer due to presence of high permeability Swan Hills layer below Duvernay, and is not likely to trigger seismic events in deeper layers. Pressure may propagate further and trigger seismicity in deeper layers if fault zone has significantly higher permeability, or if high permeability natural fractures or other hydraulic pathways exist, and there is no leakoff into higher permeability layers. However, for the current case that already includes conservative assumptions, such as 15 fractures intersecting the fault, higher fault zone permeability of 1 millidarcy, and fracture pressure of shmin+500psi held constant for 10 days with reduction due to leakoff ignored, the pressure does not travel far from Duvernay layer. This result indicates that seismic events are more likely to be located in/near Duvernay layer compared to deeper layers such as the basement.

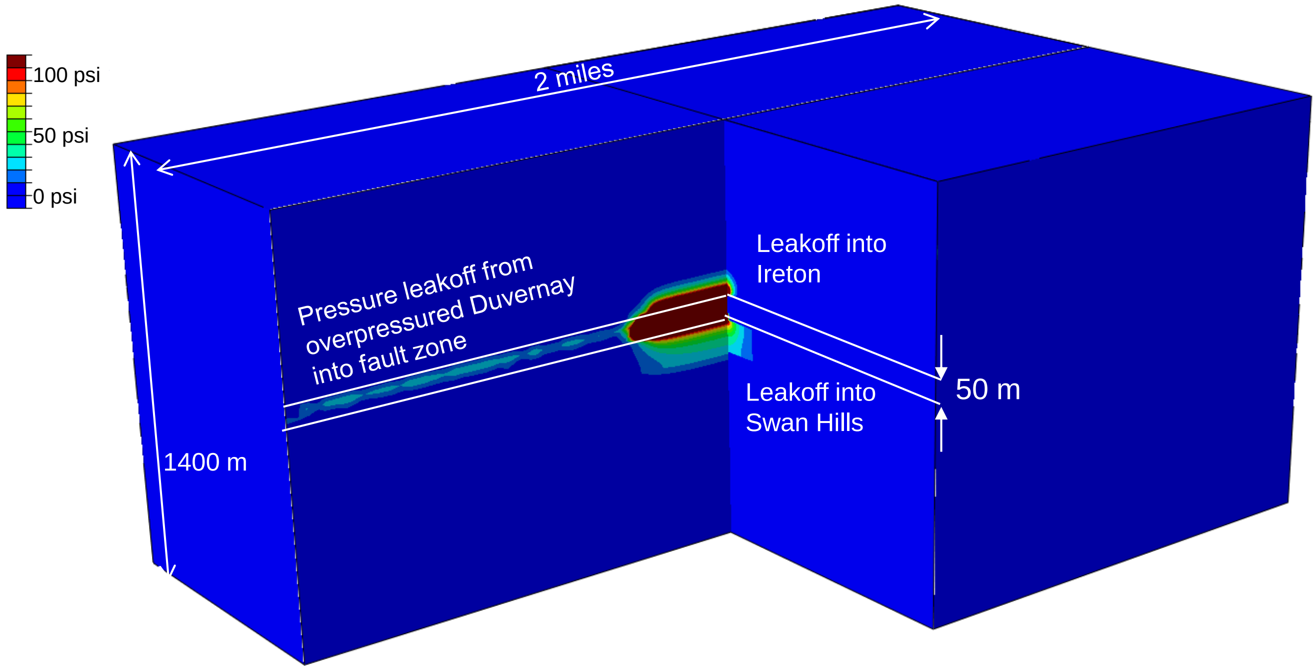

Fig. 4. Excess pressure after 10 days due to pressure diffusion along fault zone and surrounding layers due to fault-fracture intersections; 15 fractures held at pressure of constant shmin+500psi, fault zone 1m wide with 1 millidarcy permeability

Conclusions

Analysis of stress state at Duvernay play indicates that faults in approximately North-South orientation are critically stressed due to high horizontal stress and overpressure due to loading form the Canadian Rockies to the west. Stress/pressure changes on these faults either through poroelastic effect or direct hydarulic connection could trigger felt seismic events.

Poroelastic analysis of hydraulic fracturing indicates that stress/pressure changes attenuate quickly. Hence poroelastic stress/pressure changes are not a likely factor for seismic events on faults located few hundred meters away from fracture. Hence a direct hydraulic connection is more likely factor.

Initial finite element results for pressure diffusion along a fault gouge zone with fractures intersecting the fault are shown. Conservative assumptions, such as the fault zone assumed to have significatly higher permeability than Duvernay shale, and fracture pressure maintained constant at 500psi above the total horizontal minimum stress without reduction due to leakoff, are used. Results indicate that such hydraulic connection, or similar connections via natural fracture(s) intersecting fractures and faults, can cause slip in the fault in/near Duvernay layer. Pressure diffusion to other farther geological layers is likely limited by the presence of more permeable Swan Hills layer below and Ireton/Wabamun layers above the Duvernay layer. However, in extreme cases such as very high fault permeability along with no leakoff into Swan Hills layer, or if other hydraulic channels with high fluid conductivity are present, high pressure can reach and trigger seismic events in basement and/or locations away from the wellbore.

Study of hydraulic fracturing induced seismicity using quasi-static geomechanical modeling is an emerging field, and these models will be improved as more field data are available for testing various hypotheses.

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