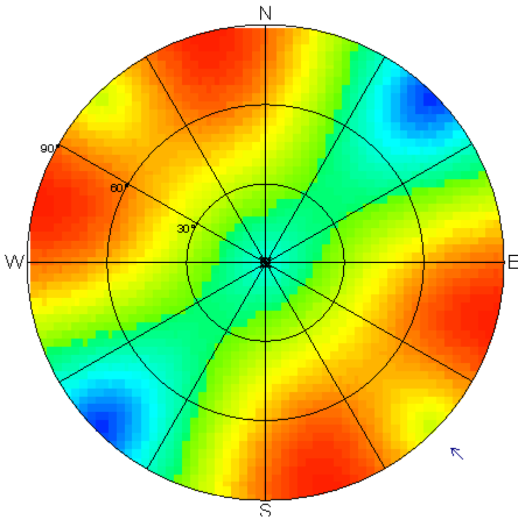
Fault Reactivation Predictions: Why Getting the In-situ Stresses Right Matters



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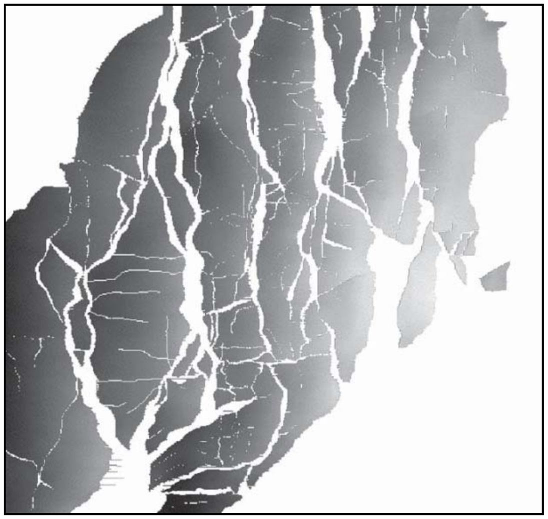


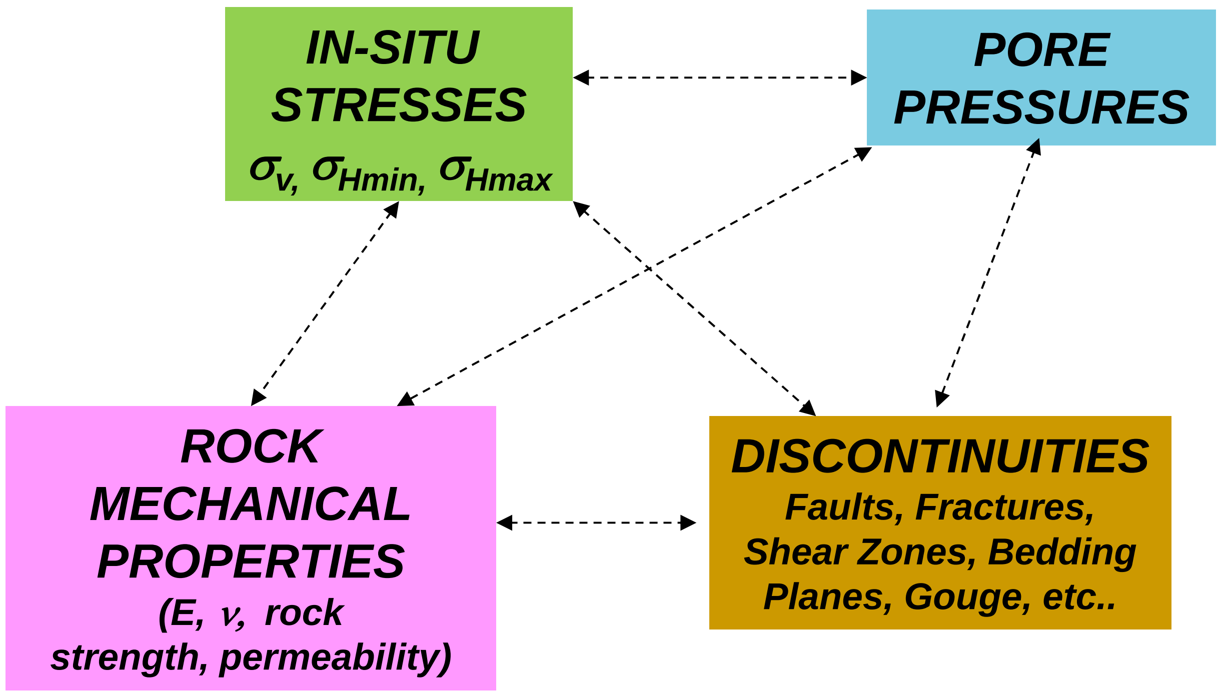
May 8, 2015

Presented at the CSEG Induced Seismicity Workshop, Calgary

Outline

- Fault Slip 101: Mohr Diagrams
- Classification of Slip-on-a-Plane Models
- Basic Equations for Fault Re-activation
- Some Missing Physics: poro- and thermal elastic effects, real fault friction, real fracture geometries, and more
- Farrell Creek Montney Gas Field NEBC
  - 32 DFIT or mini-frac tests
  - Polar plots of fault re-activation tendency for 3 stress states
  - Critically stressed fractures for one pad in σ_n - τ space
  - Recorded earthquakes with $M_L > 2.0$, 2010-2014
- Take Away Points

Basic Geomechanical Elements of The Fault Slip Problem



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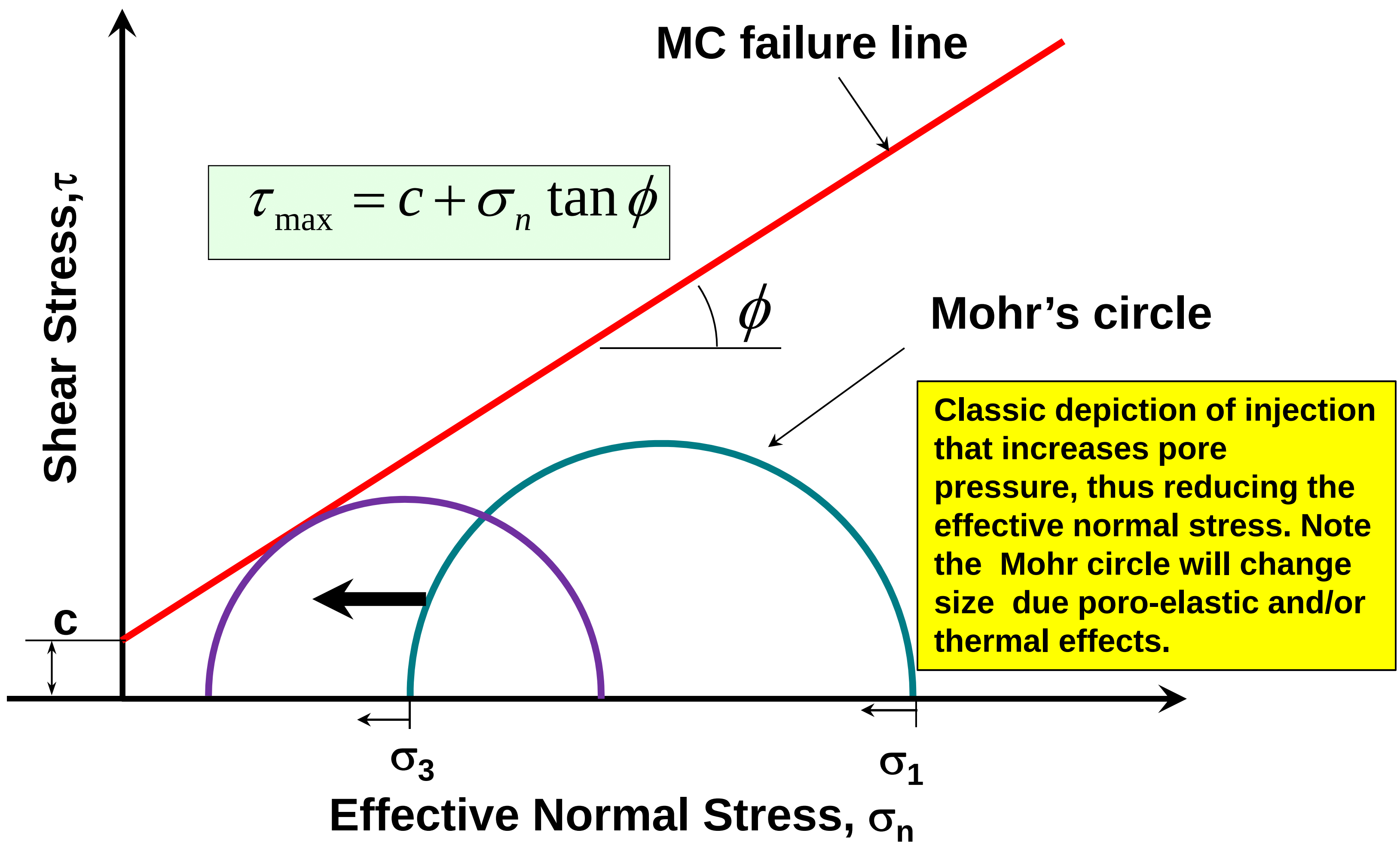
INDUCED STRESSES & PRESSURES *(Hydraulic Fracturing, Water Disposal or Fluid Production)*

Classic Mohr-Coulomb Failure Criteria for A Fault with an "Apparent" Cohesion"



Early Example of the Mohr-Coulomb Failure Criteria and Its Application to Induced Seismicity

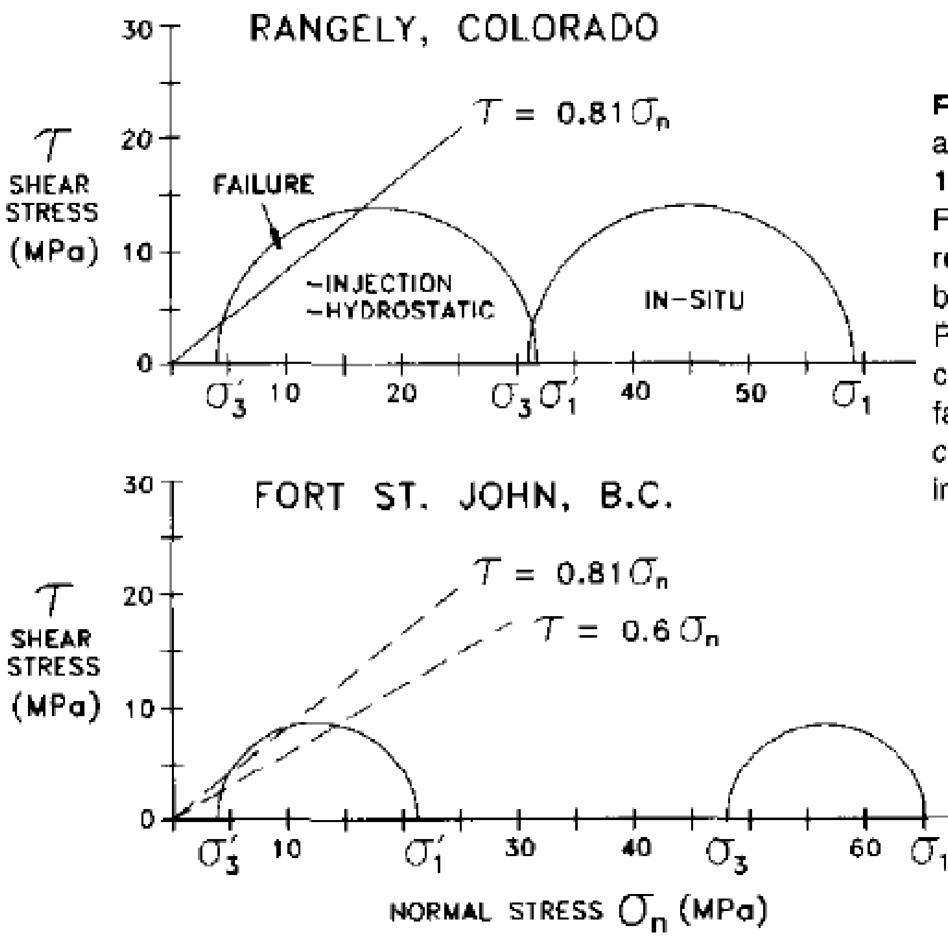


Fig. 12. Mohr circle diagrams showing the inferred stress conditions at the bottom of injection wells at Rangely, Colorado (Raleigh et al., 1972) and at the Eagle field near Fort St. John, B.C. (Table 4 and Figure 13). σ_1 and σ_3 are maximum and minimum principal stresses, respectively. σ_1' and σ_3' are effective stresses indicating the combined influence of hydrostatic and surface injection pressure. Portions of the circle to the left of the Mohr-Coulomb failure line indicate pressures are more than sufficient to induce movement on favourably oriented preexisting faults with zero strength. The failure *criterion for Fort St. John is not known so two lines are plotted to* indicate a possible range.

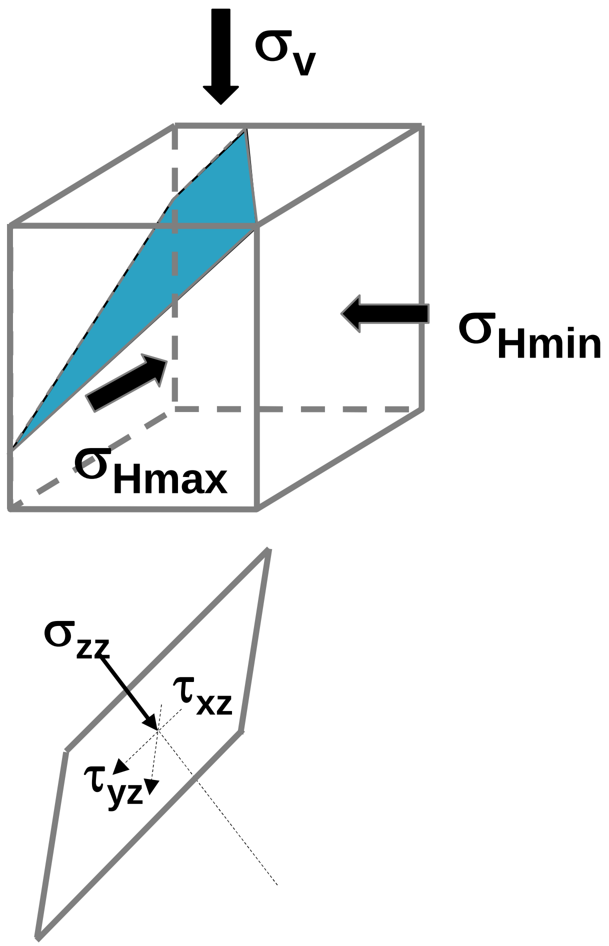
Horner et al, Earthquakes and Hydrocarbon Production in the Fort St. John Area, British Columbia, Canadian Journal of Exploration Geophysics, June 1994.

A Classification of "Deterministic" Modelling Approaches for Fault Re-activation (aka *the Slip on a Plane Problem*)

Model Type	Type/Properties	Example
Analytical	Basic Mohr-Coulomb Criteria • Slip Tendency, Ts • Factor of Safety, Safety Factor • Critical Stress Perturbation (CSP) • Critical Failure Function (CFF)	 Various STABView Sibson, 1990 MohrFracs
Analytical (Field Scale)	Field scale visualization with critically stressed structures	TrapTester Fracman
General Purpose Numerical Models	• Finite Elements • Finite Differences • Distinct Elements • Boundary Elements • Coupled reservoir-geomechanical	ABAQUS FLAC UDEC, 3DEC Map3D GEOSIM
Seismology Models	Large scale earthquake simulators with advanced capabilities, rate-dependent friction, etc..	RSQSim DYNA3D

Partial list of software examples only

Calculation of Shear Stresses on an Inclined Fault Plane in a Triaxial In-situ Stress State



$$\sigma_{zz} = \sigma_{Hmax} \sin^2\delta \cos^2\gamma + \sigma_{Hmin} \sin^2\delta \sin^2\gamma + \sigma_V \cos^2\delta$$

$$\tau_{yz} = \sigma_{Hmax} \sin\delta \cos\gamma \sin\gamma - \sigma_{Hmin} \sin\delta \sin\gamma \cos\gamma$$

$$\tau_{xz} = -\sigma_{Hmax} \sin\delta \cos\delta \cos^2\gamma - \sigma_{Hmin} \sin\delta \cos\delta \sin^2\gamma + \sigma_V \cos\delta \sin\delta$$

Shear failure occurs when:

$$\tau_{max} = c_{frac} + (\sigma_{zz} - p)\tan\phi_{frac}$$

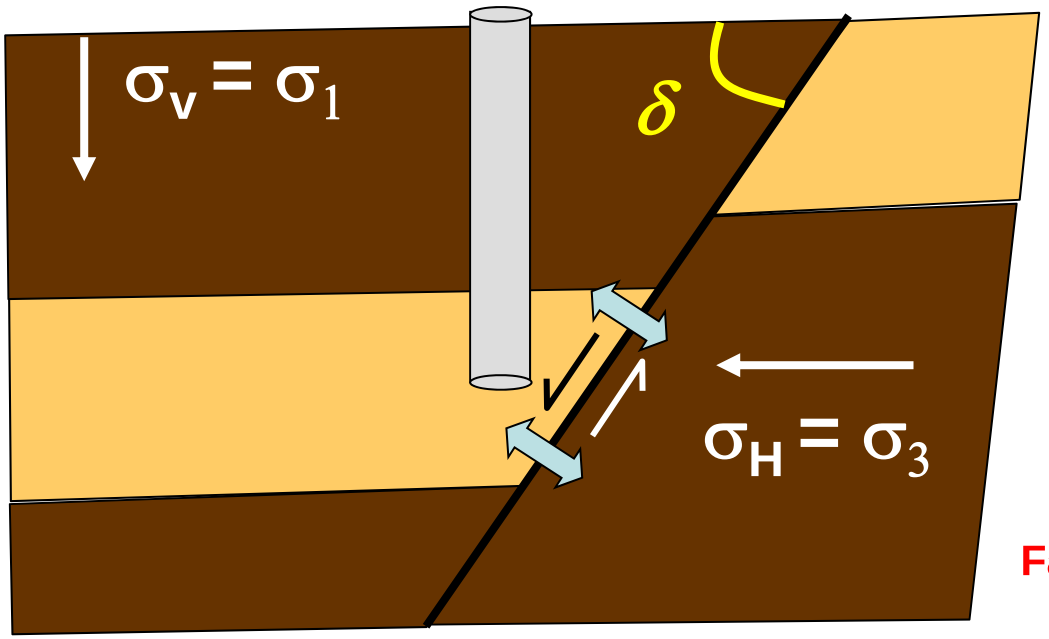
Where:

$$\tau_{max} = \sqrt{\tau_{xz}^2 + \tau_{yz}^2}$$

Limiting Assumption: one principal stress is vertical; the other two are horizontal. NOT TRUE everywhere!

- δ = *dip angle*
- γ = *dip azimuth (wrt σ_{Hmax})*
- c_{frac} = *apparent cohesion of the fault plane*
- ϕ_{frac} = *friction angle of the fault plane*
- p = *fluid pressure within the fault plane*

Modified Slip Tendency T_{sm} - A Simple Model for Assessing the Propensity for Fault Re-activation



Example of Fault Re-activation in a Normal Fault Stress Regime

Hawkes and McLellan, JCPT, 2005

Fault Dip Angle

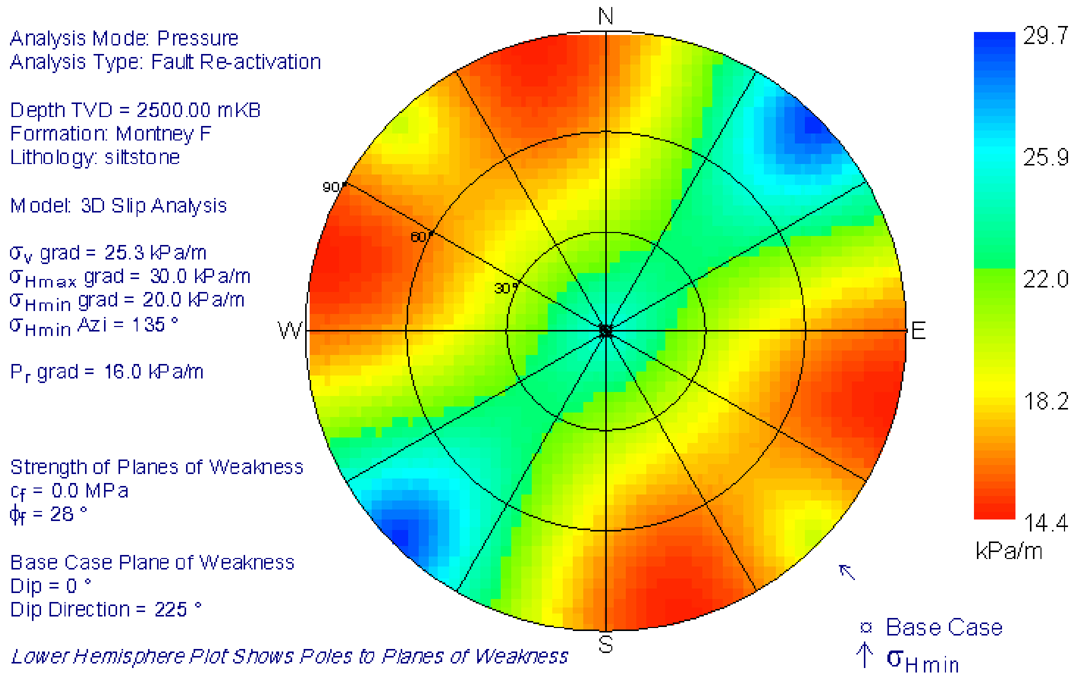
New Fluid Pressure on the Fault

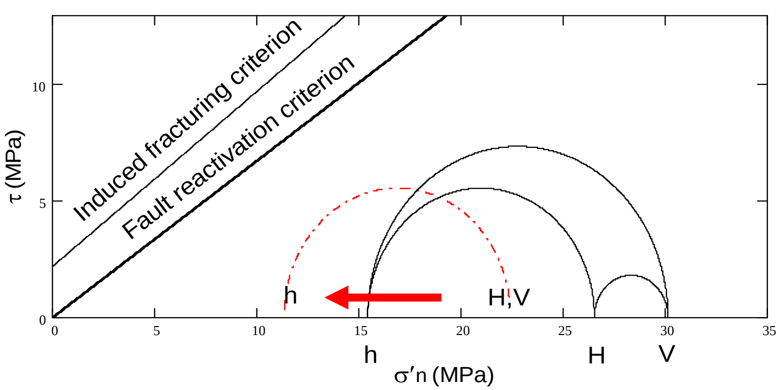
Fault Friction Angle

$$T_{sm} = \frac{\tau}{\tau_{slip}} = \frac{(\sigma_1 - \sigma_3)\sin 2\delta}{[(\sigma_1 + \sigma_3) + (\sigma_1 - \sigma_3)\cos 2\delta - 2p]\tan\phi_{fault}}$$

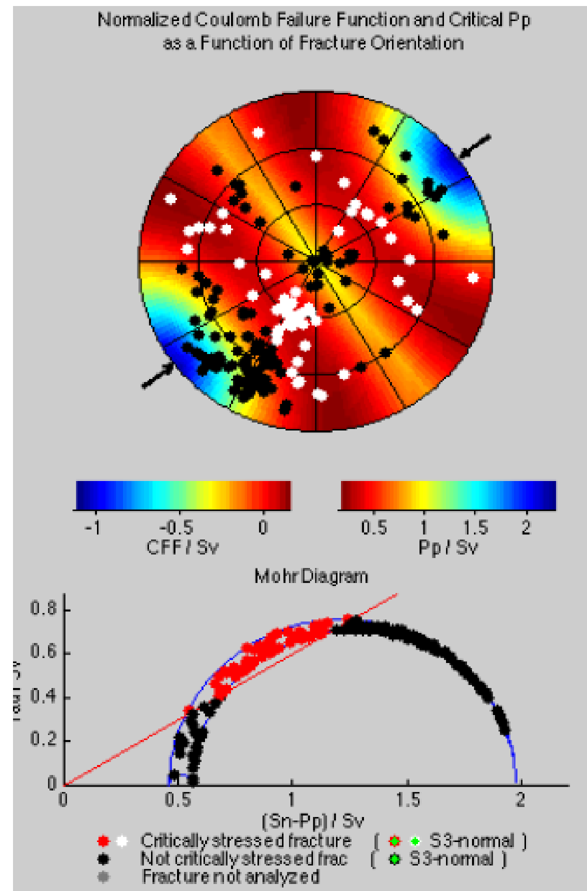
Analytical Models for Assessing Fault Reactivation

STABVIEW Slip on a Plane Polar Plot Analysis





GMI (now Baker Hughes) MohrFracs for Critical Stressed Fractures



But Are We Missing Something?
Typical Assumptions That Can Get Us in Trouble

Missing Bits of Physics

- *Poro-elastic effects on the vertical and horizontal stresses DUE to the injection, can change the local stresses on the fault*
  - *Better known consequences of depletion causing changes in horizontal stress. Dependent on the stress regime, mechanical properties, boundary conditions. Also known as "stress path" effects.*
- *Thermal elastic effects on the vertical and horizontal stresses DUE to the injection of fluids cooler than the ambient reservoir temperature*
  - *Typically leads to a reduction in the horizontal in-situ stresses*
- *Well-known "stress shadow effects" from adjacent frac stages are not usually accounted for in these analytical models*

But Are We Missing Something?
Typical Assumptions That Can Get Us in Trouble

Missing Bits of Physics (cont.)

- *Coefficient of static friction (tangent of the fault friction angle) is often set to 0.6 (=>31º). This can be a sensitive parameter in many analyses . Depending upon the host rock mineralogy and the fault-filling material it can range from 0.4 to 0.8. For example, lab derived Montney bedding plane residual friction angles averaged 28º (μ =>0.53)*

- *Typically a uniform fluid pressure along the fault is assumed, although the real fluid pressure is a consequence of friction drop and fluid loss. Fracture Net Pressure (ISIP-σ_{Hmin}) is the clue to the real BHP.*

- *The fault plane geometry is approximated by a single plane whereas it is often a more complicated rough, sometimes irregular, branching set of smaller faults and fractures.*

Classic Poro-elastic Stress Relationship – Passive Basin

$$\Delta\sigma_H = \frac{(1-2\nu)}{(1-\nu)}\alpha\Delta p_{fm}$$

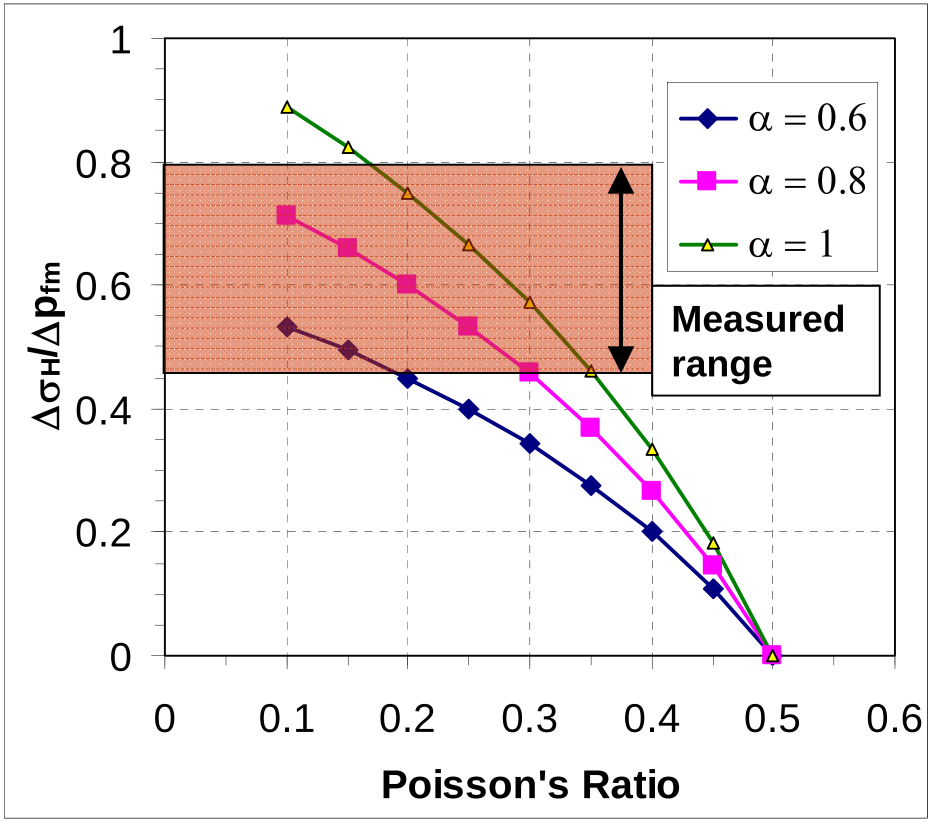
Where:

$\Delta\sigma_H =$ **Change in average horizontal in-situ stress due to injection or production**

$\Delta p_{fm} =$ **Change in formation pore pressure due to injection or production**

$\nu =$ **Static Poisson's Ratio**

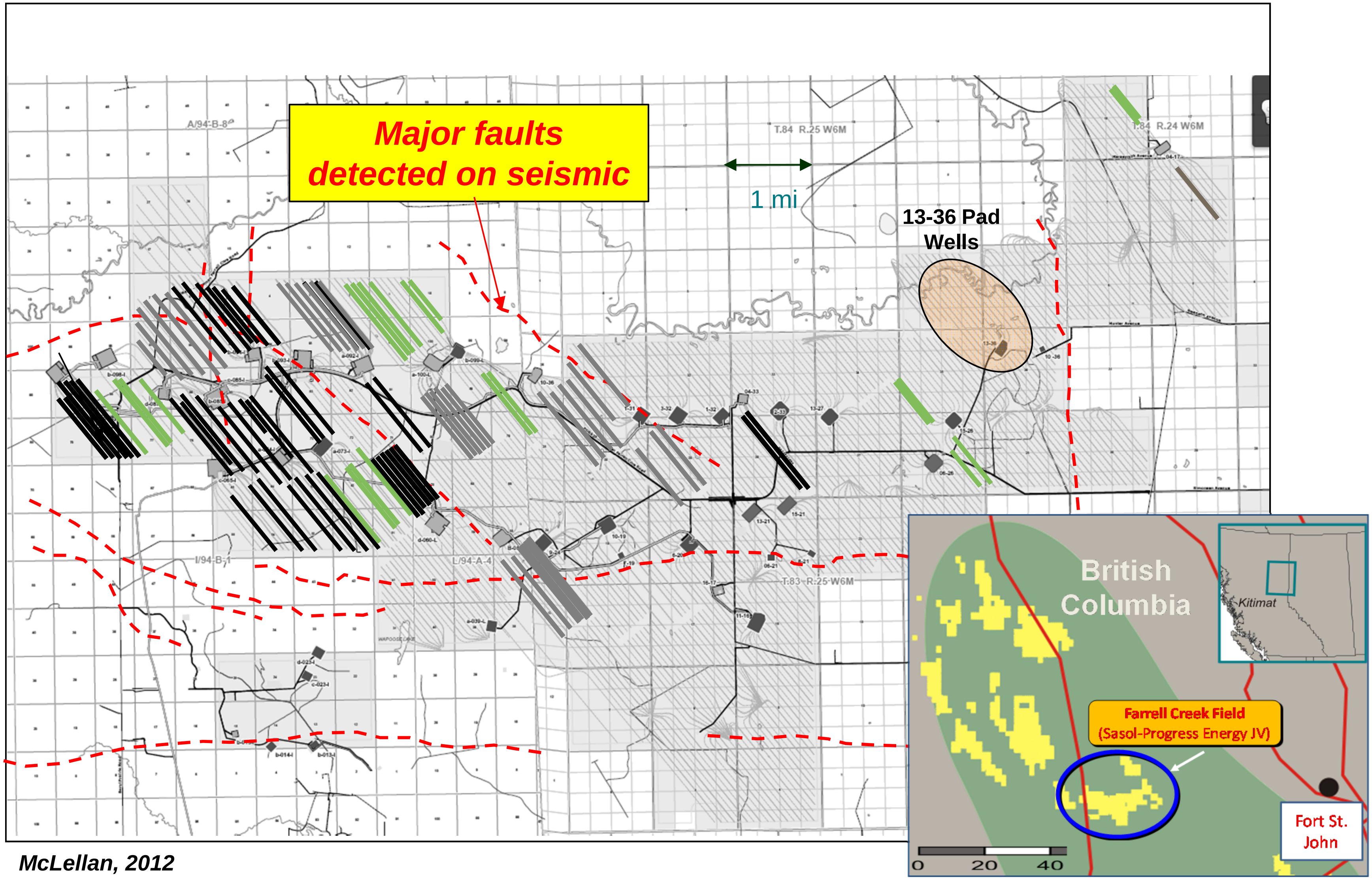
$\alpha =$ **Biot's Parameter**



Other relationships exist that can account for:

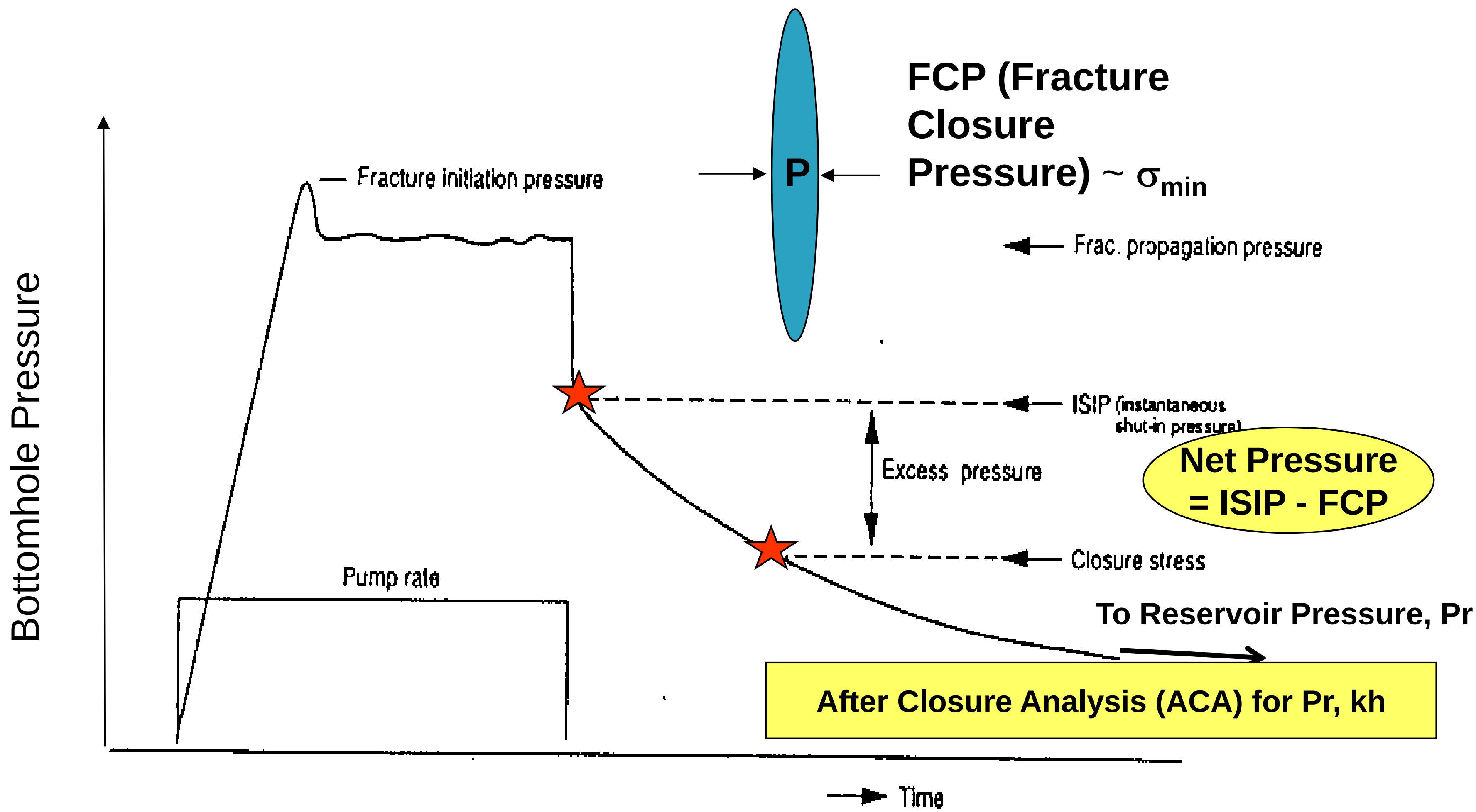
- **Strike slip or thrust fault initial stress states**
- **Reservoir shape (aspect ratio, axisymmetric, plane strain)**
- **Elastic properties of the reservoir and surrounding rocks**
- **Thermo-elastic effects (conduction)**
- **Natural fractures**

Farrell Creek Field, NEBC Showing Faults and the Location of Horizontal Wells, April, 2012



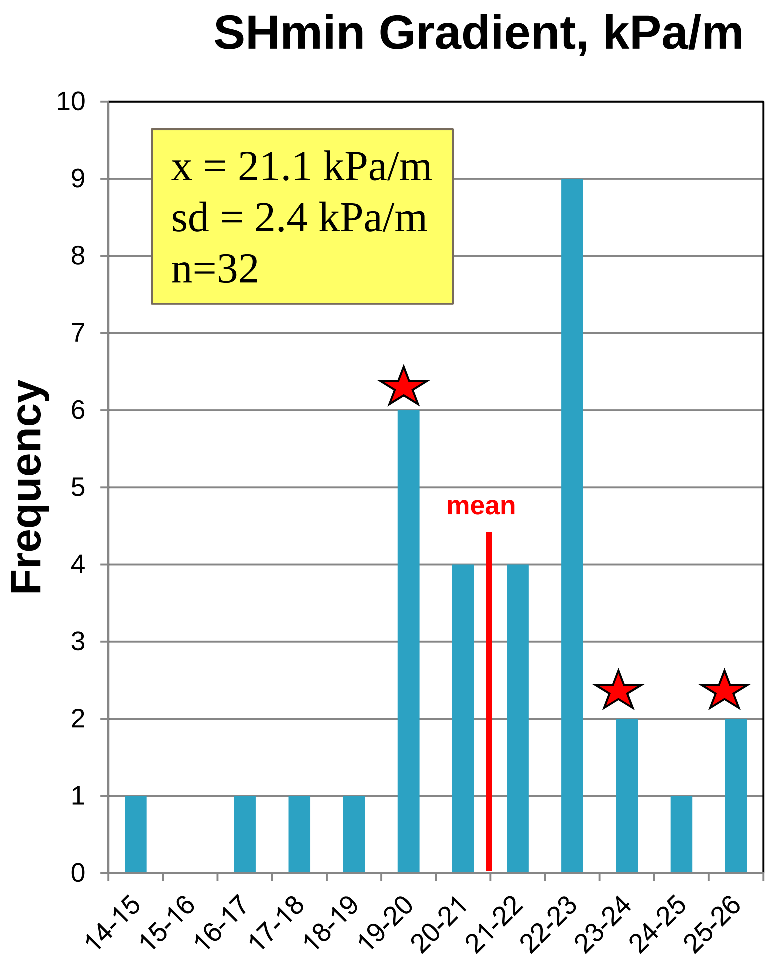
McLellan, 2012

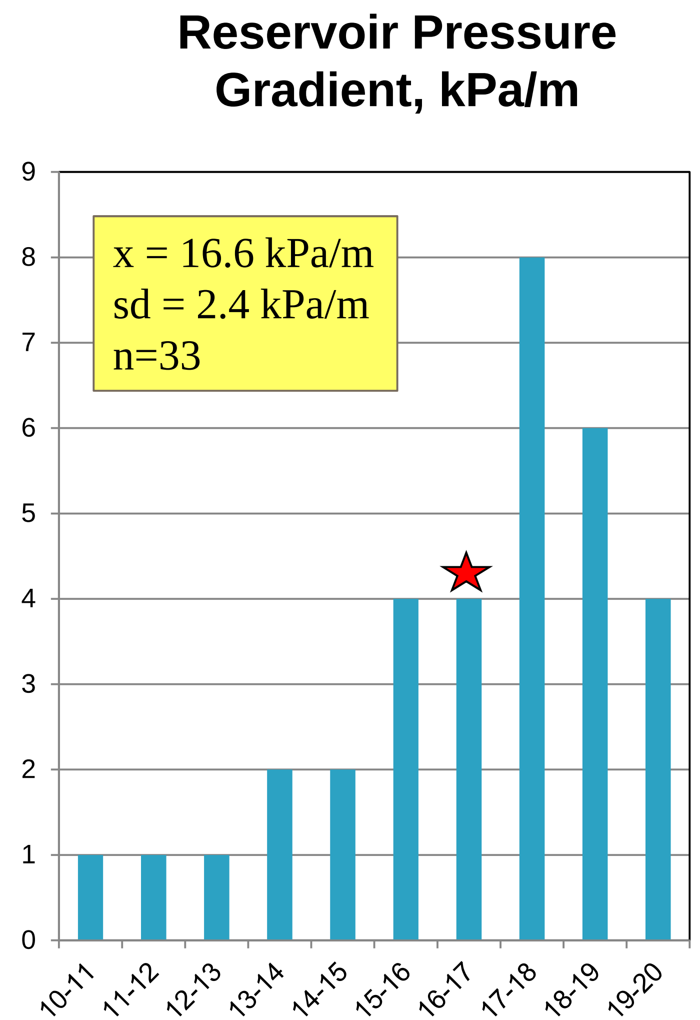
Typical Pressure vs Time Record in a Diagnostic Fracture Injection Test (DFIT) or Mini-frac



McLellan et al, CSPG Gussow Conference, 2013

DFIT Derived In-situ Stress and Pore Pressure Data, Farrell Ck Field





★ **Fault re-activation test cases**

Data from McLellan et al, GeoConvention, Calgary, 2014

The Effect of the In-Situ Stress State and Injection Pressure Gradient on Fault Re-activation
Case 1: Strike Slip Fault Stress Regime

Analysis Mode: Pressure
Analysis Type: Fault Re-activation

Depth TVD = 2500.00 mKB
Formation: Montney F
Lithology: siltstone

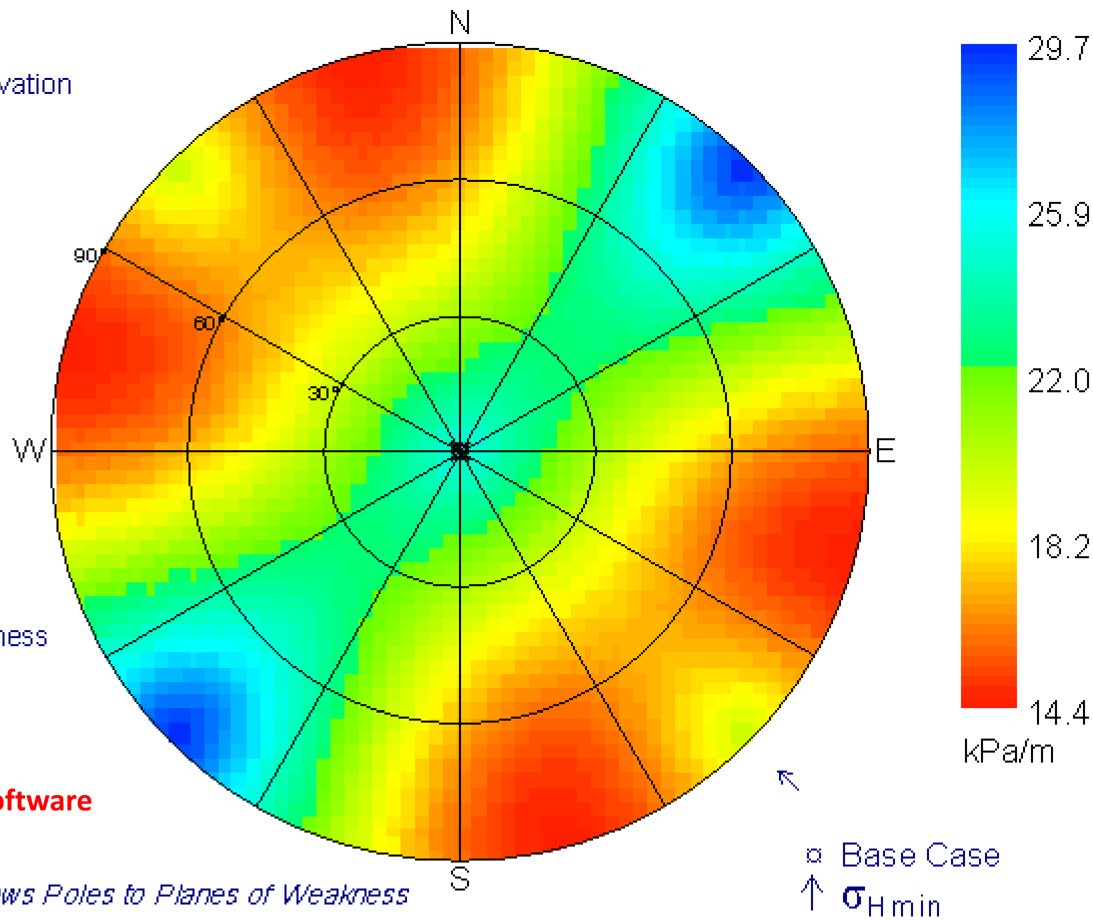
Model: 3D Slip Analysis

σ_V grad = 25.3 kPa/m
σ_{Hmax} grad = 30.0 kPa/m
σ_{Hmin} grad = 20.0 kPa/m
σ_{Hmin} Azi = 135 °

P_r grad = 16.0 kPa/m

Strength of Planes of Weakness
c_f = 0.0 MPa
ϕ_f = 28 °

Analysis with STABView software



Lower Hemisphere Plot Shows Poles to Planes of Weakness

Note: Poro-elastic effects due to injection NOT accounted for in this example.

The Effect of the In-Situ Stress State and Injection Pressure Gradient on Fault Re-activation
Case 2: Strike Slip Fault Stress Regime

Analysis Mode: Pressure
Analysis Type: Fault Re-activation

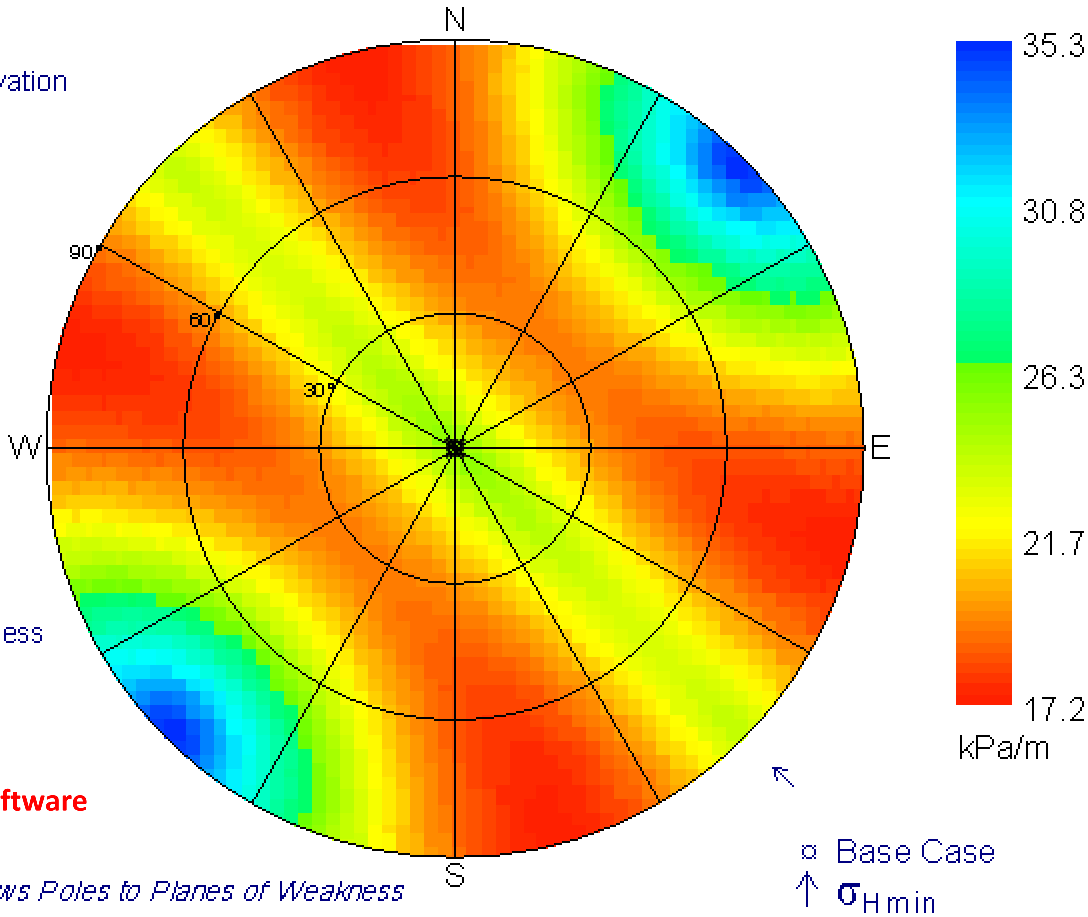
Depth TVD = 2500.00 mKB
Formation: Montney F
Lithology: siltstone

Model: 3D Slip Analysis

σ_V grad = 25.3 kPa/m
σ_{Hmax} grad = 36.0 kPa/m
σ_{Hmin} grad = 24.0 kPa/m
σ_{Hmin} Azi = 135 °

P_r grad = 16.0 kPa/m

Strength of Planes of Weakness
c_f = 0.0 MPa
ϕ_f = 28 °



Analysis with STABView software

Lower Hemisphere Plot Shows Poles to Planes of Weakness

The Effect of the In-Situ Stress State and Injection Pressure Gradient on Fault Re-activation Case 3: Thrust Fault Stress Regime

Analysis Mode: Pressure
Analysis Type: Fault Re-activation

Depth TVD = 2500.00 mKB
Formation: Montney F
Lithology: siltstone

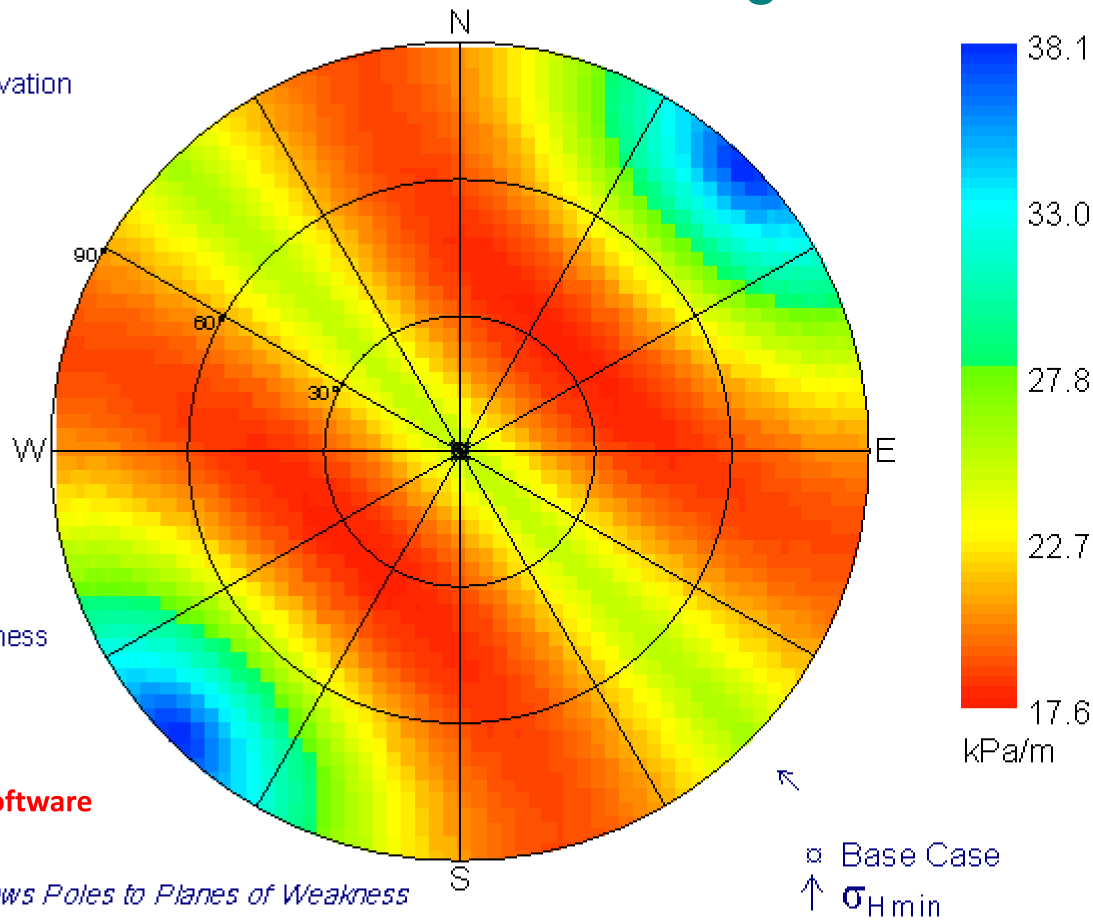
Model: 3D Slip Analysis

σ_V grad = 25.3 kPa/m
σ_{Hmax} grad = 39.0 kPa/m
σ_{Hmin} grad = 26.0 kPa/m
σ_{Hmin} Azi = 135 °

P_r grad = 16.0 kPa/m

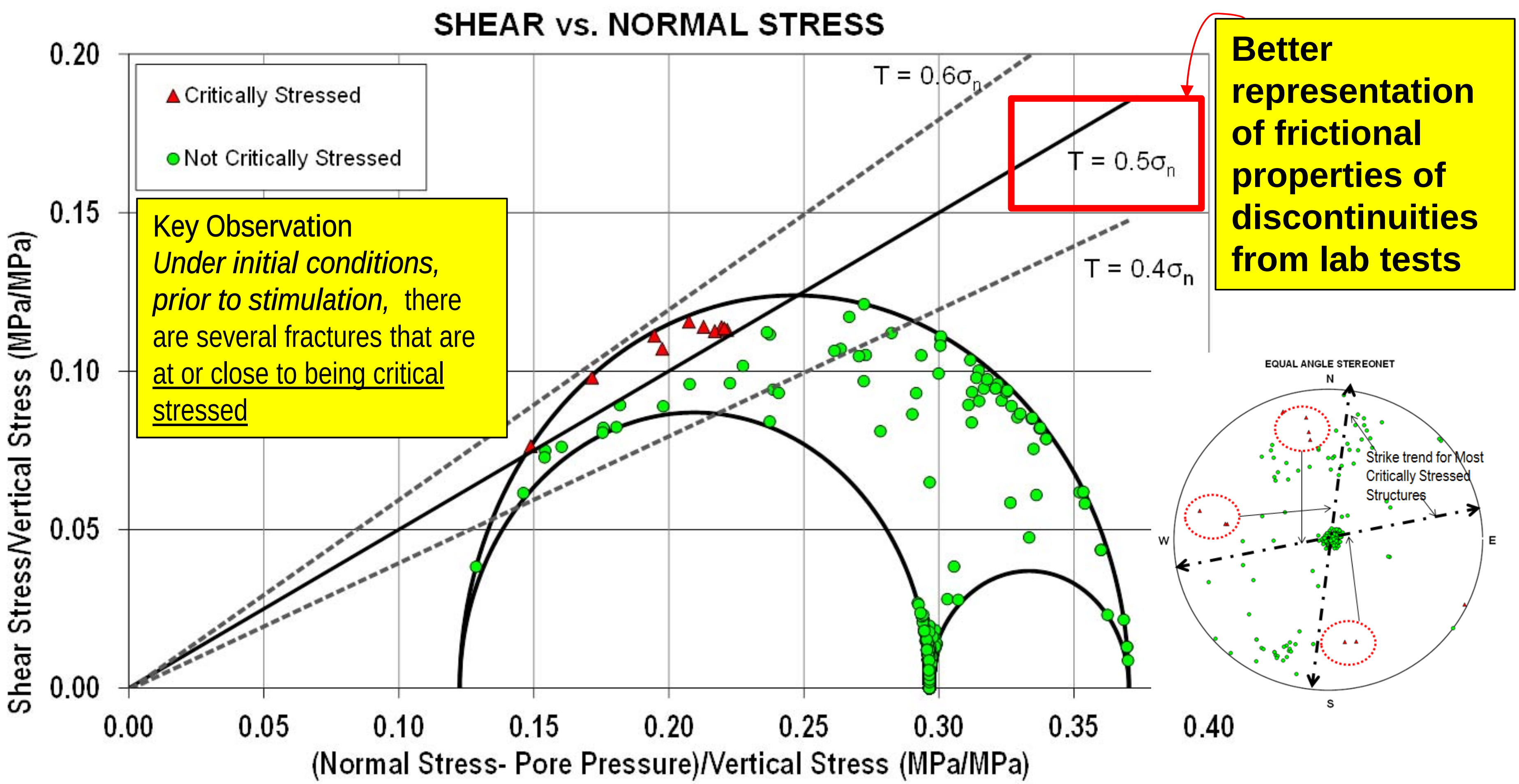
Strength of Planes of Weakness
c_f = 0.0 MPa
ϕ_f = 28 °

Analysis with STABView software



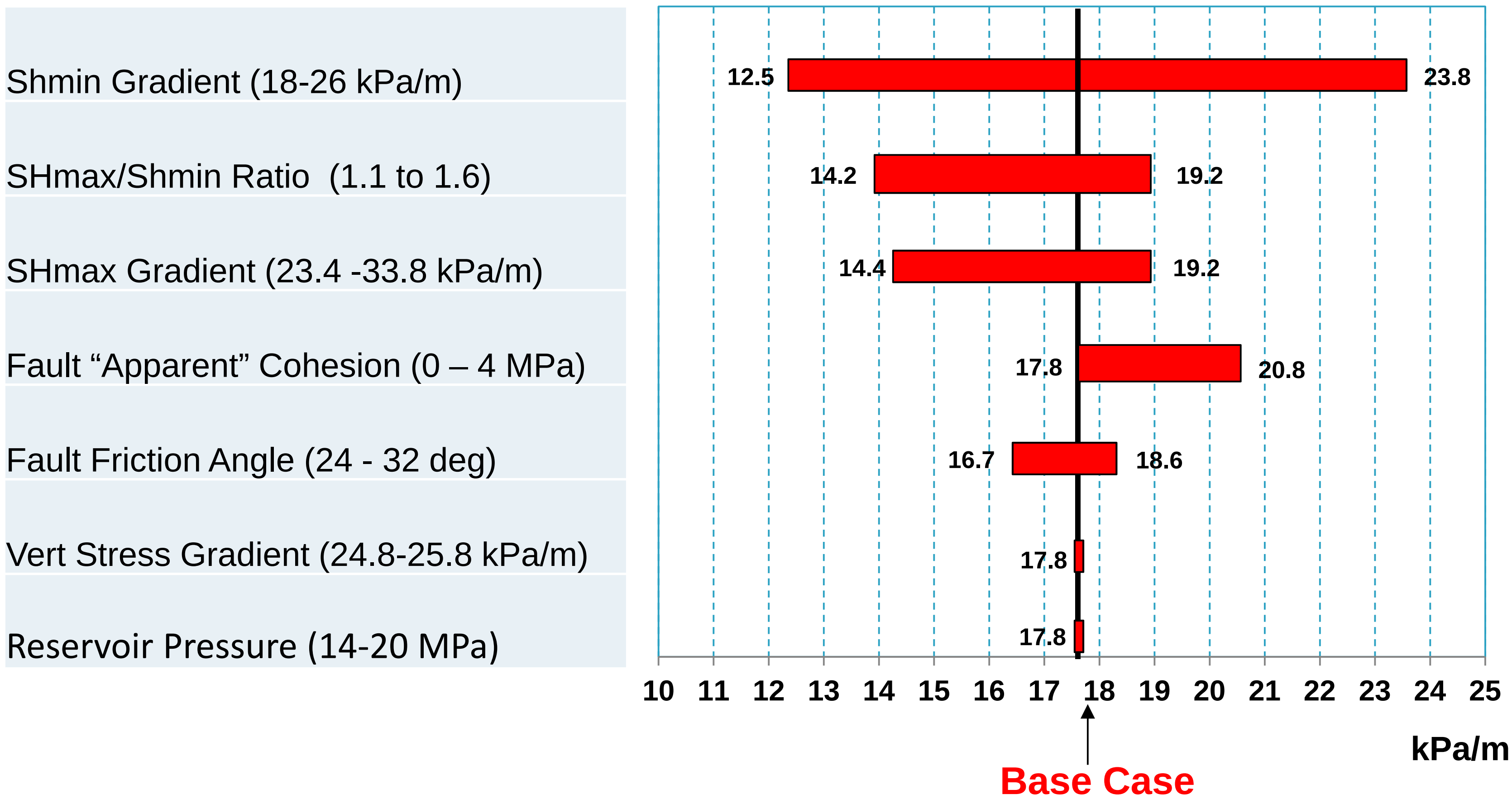
Lower Hemisphere Plot Shows Poles to Planes of Weakness

Mohr Circle Representation of Critically Stressed Natural Fractures from a Montney Horizontal Well, Farrell Ck Field



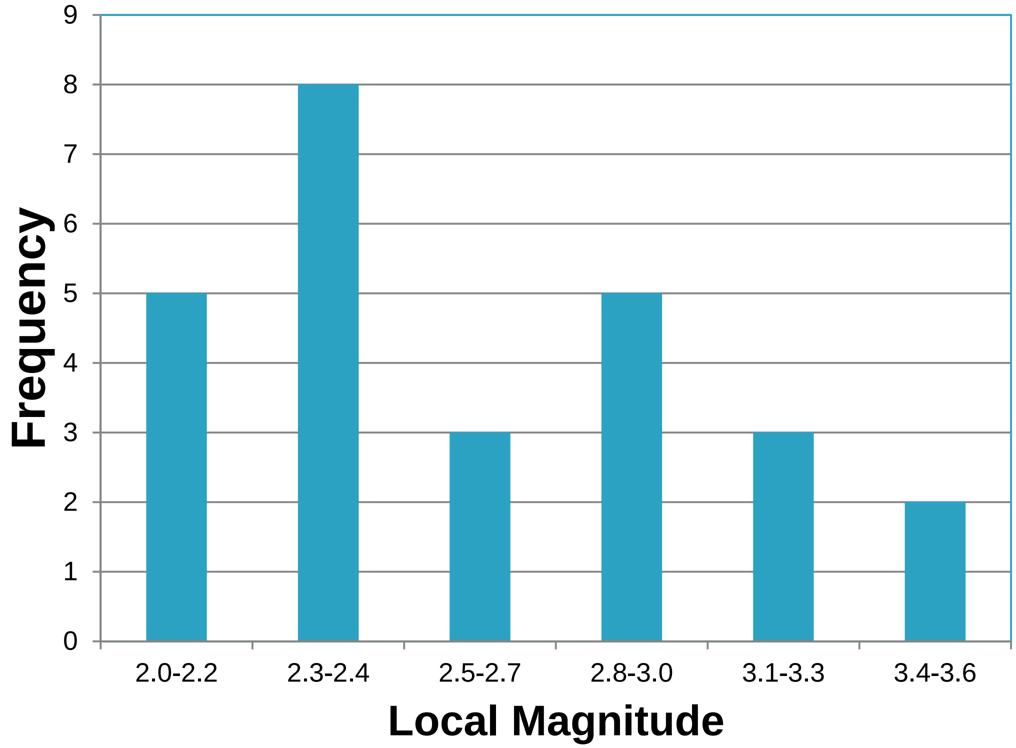
Rogers, S., McLellan , P., Webb, G., *Investigation of the Effects of Natural Fractures and Faults on Hydraulic Fracturing in the Montney Formation, Farrell Creek Gas Field, British Columbia, DFNE 2014 - 224 , Vancouver, BC, October, 2014.*

Tornado Chart Sensitivity of the Predicted Minimum Injection Pressure Gradient to Cause Fault Slip



Analyzed with STABView

26 NRCan Recorded Earthquakes Greater than M_L2.0 in the Farrell Ck - Altares Area, July 2010-June 2014 (excluding suspected Wastewater Disposal Events)



After Walker and Gaucher, 2014**, Montney Trend , Frac and Disposal Well Induced Seismicity in NEBC **(Poster)

Take Away Points

- For deterministic fault predictions simple slip-on-a-plane models are a useful starting point to understand the problem and the most important causal factors
- Horizontal in-situ stress differences drive the fault re-activation problem in typical overpressured strike-slip fault stress regimes in NEBC
- There are rare cases where low angle bedding planes can be inflated and sheared during hydraulic fracture operations in thrust fault stress regimes where $\sigma_3 = S_v$
- DFIT-derived Fracture Closure Pressure (FCP) or SHmin are needed for first-order predictions of fault slip
- For a known seismic derived fault geometry the relative importance of the input data is summarized as:

Stresses > Fault Properties > BHP > Elastic Properties

Cited References

Advanced Geotechnology Inc. (now Weatherford International), STABView Users Manual, Version 3.8, 2008.

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McLellan, P.J., Anderson, I., Mini-frac tests show variable and high horizontal in-situ stresses in the Montney Formation, Farrell Creek, Northeast British Columbia, Presented at an SPE Workshop Characterizing Unconventional Reservoirs and Bounding Intervals Using In-situ Tests, Banff, Alberta, April 24-25, 2012.

McLellan, P., V. Mostafavi, and I. Anderson, Geomechanical Characterization of an Unconventional Montney Reservoir: In-situ Stresses, Rock Properties and Natural Fractures. Presented at the Canadian Society of Petroleum Geologists Gussow Conference, Banff, Alberta, October 15-17, 2013.

McLellan, P, I. Anderson, J. Wong and V. Mostafavi, Geomechanical Characterization of the Farrell Creek Montney Reservoir, Northeast British Columbia. CSPG CSEG CWLS GeoConvention, May 2014, Calgary, Alberta.

Walker, D. and Gaucher, M., 2014, Montney Trend , Frac and Disposal Well Induced Seismicity in NEBC (Poster), BC Oil and Gas Commission.