OilFieldGeomechanics

On the Geomechanics of Induced Seismicity

Neal B. Nagel, Ph.D.

May 9, 2017

Outline

1. Introduction
2. Geomechanics
3. Stress/Strain
4. Stress & Pressure
5. Faults & Fractures
6. Oklahoma Case History

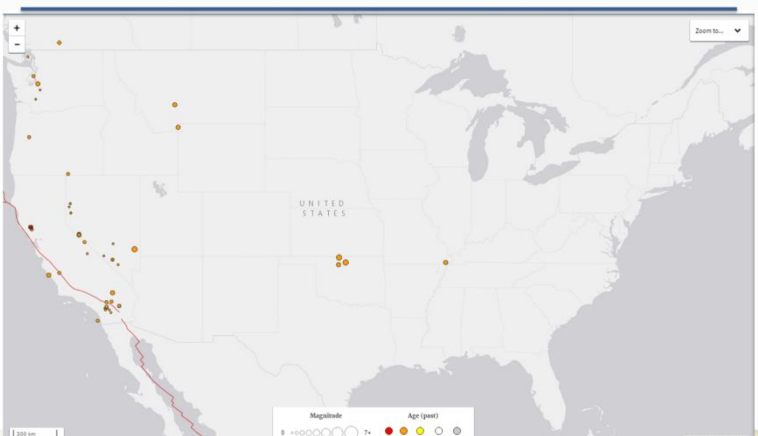
INTRODUCTION

Induced? Or Triggered.....

Is This New?

Figure Histograms showing relation between volume of waste injected into the Rocky Mountain Arsenal well and earthquake frequency. SOURCES: Adapted from Evans (1966); Healy et al. (1968); McClain (1970); Hsieh and Bredehoeft (1981).

US Earthquakes: 05/07/17



US Earthqukes: 05/01 to 05/07/17

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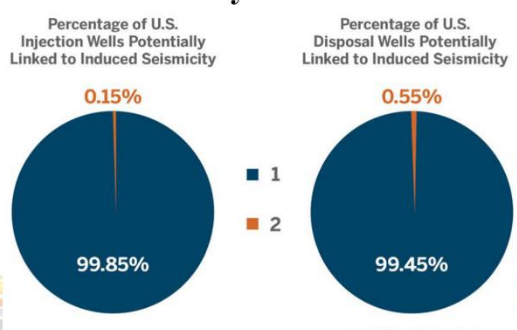
Is It Over-Hyped?

Millions Now at Risk From Oil and Gas-Related Earthquakes, Scientists Say



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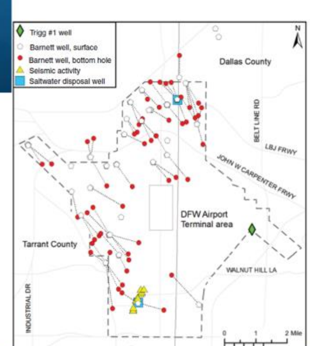
My First Exposure: May 2009

Study links disposal well for gas drilling, small quakes near D/FW Airport

Wendy Hundley / The Dallas Morning News Whundley@dallasnews.com



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GEOMECHANICS

So…Why Geomechanics?

GEOMECHANICS is the evaluation of the interplay between stress, pressure, mechanical properties/strength and geometry in rock and soil.

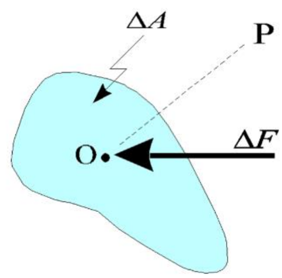
Why is Geomechanics so difficult…..

STRESS/STRAIN

Stress Basics

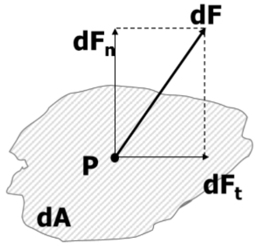
$$\text{Stress} = \frac{\text{Force}}{\text{Area}}\ [N/m^2, \quad lb_f/in^2]$$

$$\sigma_{\overline{OP}} = \lim_{\Delta A \to 0}\left(\frac{\Delta \vec{F}}{\Delta A}\right)$$



Stresses at one point vary with the orientation of plane ΔA!

Stress Decomposition



$$\sigma = \frac{d\vec{F}_n}{dA}$$

$$\tau = \frac{d\vec{F}_t}{dA}$$

So, to evaluate stress on a plane (whether a fault, a natural fracture or a wellbore wall), we resolve the normal stress(es) and shear stress(es) acting on that plane.....

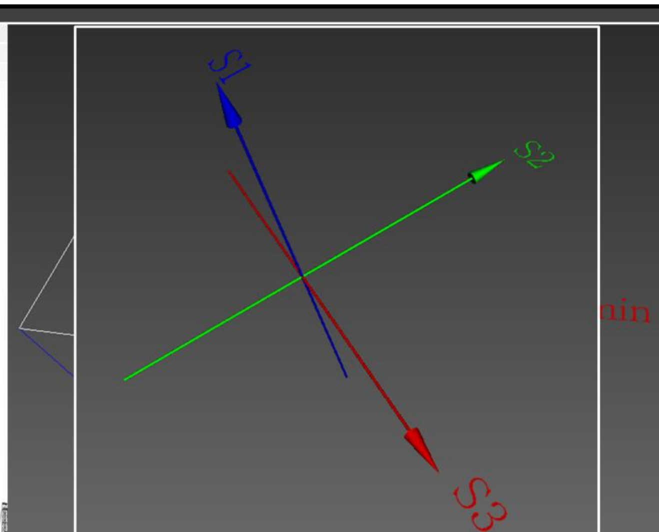
σ= normal stress
τ= shear stress

Stress

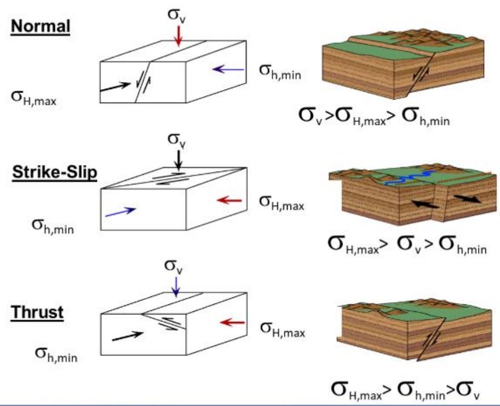
- **Stress, in units of psi or MPa, is simply:**
  Stress=Force/Area=F/A
- **Normal stress is defined as:** $\sigma_n = \lim_{\Delta A \to 0} \frac{\Delta F_n}{\Delta A}$
- **Shear stress is defined as:** $\tau_n = \lim_{\Delta A \to 0} \frac{\Delta F_t}{\Delta A}$
- **Key concepts:**
  - *The general convention is that "compressive" stress is positive, "tensile" stress is negative.*
  - *Stress is a tensor (requiring 3 independent normal and 3 independent shear values).*
  - *A "Principal" stress occurs in an orientation where the shear stress is zero. Three principal stresses exist in an orthoginal orientation.*
  - *"Plane" stress occurs when both the normal and shear stresses in one orthoginal direction are zero.*
  - *"Lithostatic" stress is the stress due to the weight of the overburden. "Hydrostatic" stress is when all three principal stresses are equal.*

Strain

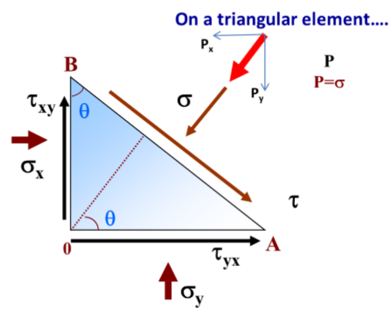
- **Strain, dimensionless (in/in or %), is the deformation of a body in response to a change in stress: Strain=DL/L**
- **Normal strain is defined as:** $\varepsilon = \lim_{\Delta L \to 0} \frac{\delta L}{\Delta L}$
- **Shear strain is defined as:** $\gamma = TAN(\alpha)$
- **Key concepts:**
  - *The general convention is that "compressive" or compactive strain is positive, "tensile" strain is negative.*
  - *Strain is a tensor (requiring 3 independent normal and 3 independent shear values).*
  - *A "Principal" strain occurs in an orientation where the shear strain is zero. Three principal strains exist in an orthoginal orientation.*
  - *"Plane" strain occurs when both the normal and shear strains associated with one orthoginal direction are zero.*



Stress Field Types



Stress on a Plane



To resolve the stress on any orientation (θ) within our chunk of material, we do a force balance...

Stress Rotation

$\overline{AB} = a$

$\overline{OB} = a\,Cos\theta$

$\overline{OA} = a\,Sin\theta$

Equilibrium in x-direction

$$a P_x = a\,Cos\theta\,\sigma_x + a\,Sin\theta\,\tau_{yx}$$

$$P_x = \sigma_x\,Cos\theta + \tau_{yx}\,Sin\theta$$

Equilibrium in y-direction

$$P_y = \sigma_y\,Sin\theta + \tau_{xy}\,Cos\theta$$

$$BUT:\ \sigma = P_x\,Cos\theta + P_y\,sin\theta$$

Stress on a Plane

Normal stress acting on the plane:

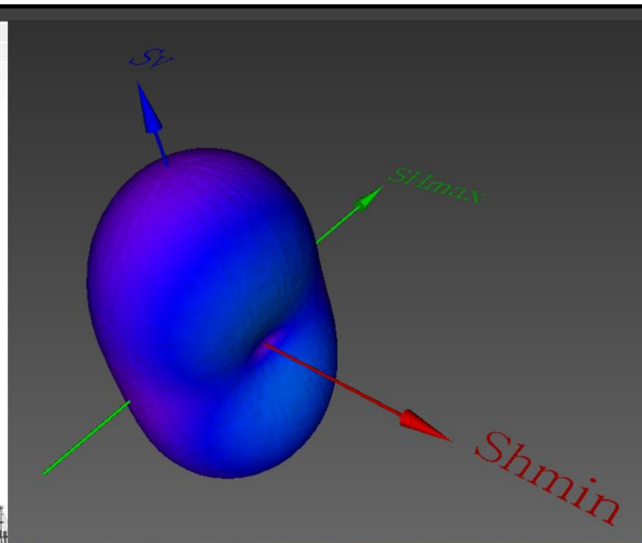
$$\sigma = \sigma_x\,Cos^2\theta + 2\tau_{xy}\,Sin\,\theta\,Cos\,\theta + \sigma_y\,Sin^2\theta$$

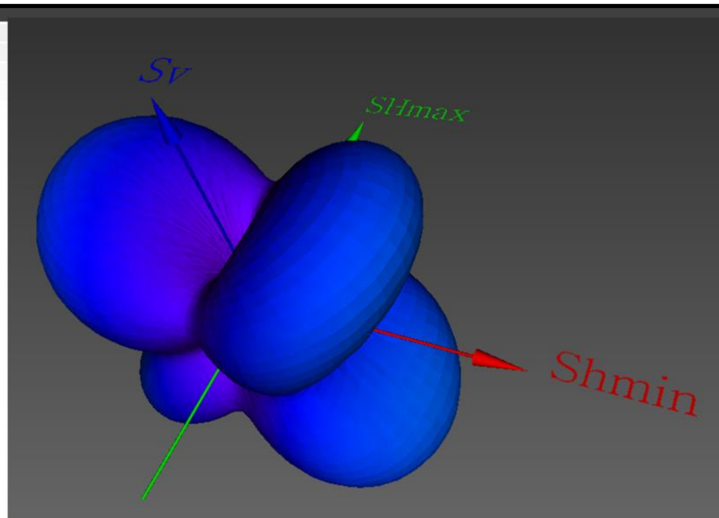
Shear stress acting on the plane:

$$\tau = \tfrac{1}{2}(\sigma_y - \sigma_x)\,Sin\ 2\theta + \tau_{xy}\,Cos\ 2\theta$$

Principal stresses (acting normal to a plane where τ = 0):

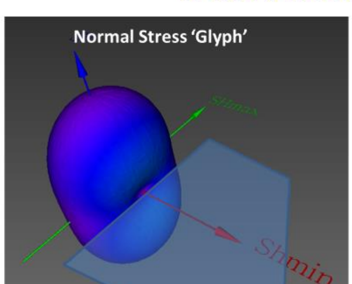
$$\sigma_{1,2} = \tfrac{1}{2}(\sigma_x + \sigma_y) \pm \sqrt{\tau_{xy}^2 + \tfrac{1}{4}(\sigma_x - \sigma_y)^2}$$

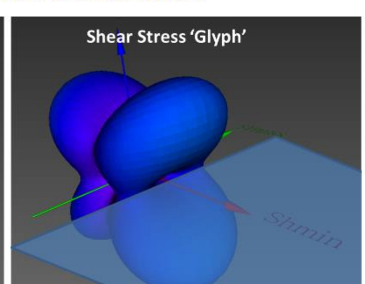




Stresses On Vertical Faults

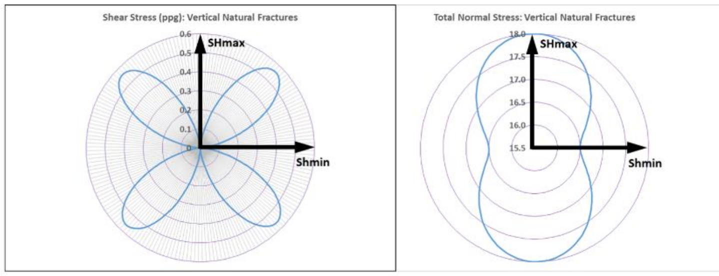
Assume: Sv=20ppg; SHmax=18ppg; Shmin=16.5ppg
What are the total normal and shear stresses as a function of fault azimuth for vertical faults?





Stresses On Vertical Faults

Assume: Sv=20ppg; SHmax=18ppg; Shmin=16.5ppg
What are the total normal and shear stresses as a function of fault dip direction (SHmax_Az=0°)?



Dip Direction

STRESS & PRESSURE

Poroelasticity

- *Largely, the concepts just presented assume that the material is homogeneous and solid. Rock, however, is inhomogeneous and filled with fluids.*
- *Pore fluids can, and do, play a major role in the constitutive behavior of rock.*
- *"Poroelasticity", the elastic behavior of porous material, is based upon the work of Maurice Biot.*
- *In addition, Karl Terzaghi developed the concept of "effective stress".*

Effective Stress

- Terzaghi realized that, for soils, it was not the total stress that soils responded to but the stress acting on the soil particles themselves:

$$Effective\ Stress,\ \sigma'_{ij} = \sigma_{ij} - p_o \delta_{ij}$$

where p_o is pore pressure, δ is the Kronecker delta, and i and j are axes designations.

- For rocks, this has been simplified to:

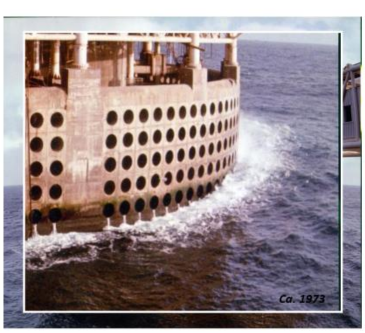
$$\sigma'_{ij} = \sigma_{ij} - \alpha p_o$$

where α is Biot's constant and is ~ 1 (and is related to the ratio of the frame modulus to the solid modulus).

Effective Stress

- The practical consequence of the effective stress principle is that rock behavior is governed not only by the total stresses acting, but also the fluid pressures acting.
- *Further, this suggests that in situations where we do not change the total stresses (say, deep in the earth) but do change pore pressure, we can cause a significant behavioral response from the rock and even failure.*

North Sea Subsidence

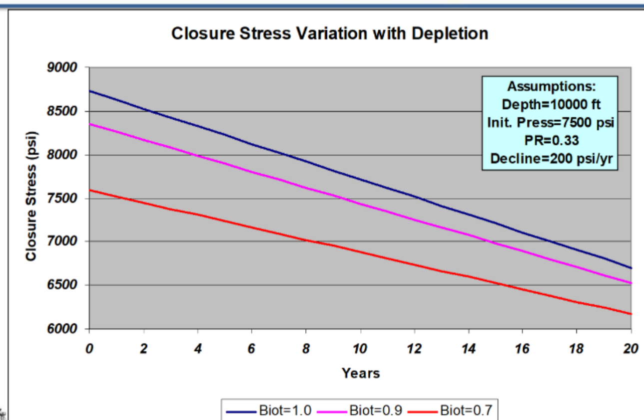


Closure Stress or Frac Gradient

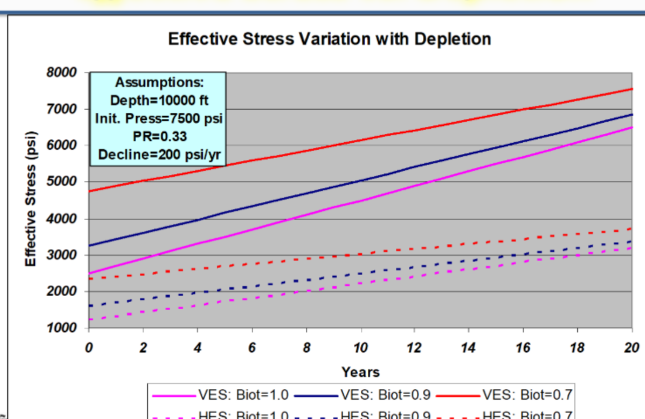
- **Closure Stress or FG, which is taken to be the stress at which a fracture closes (or opens, actually), is, ideally, the far field total minimum horizontal stress, Shmin (i.e., the sum of the effective stress and pore pressure).**

- ***What happens as the formation pressure changes over time? Does the Shmin stress change? Increase? Decrease?***

Closure Stress vs. Depletion

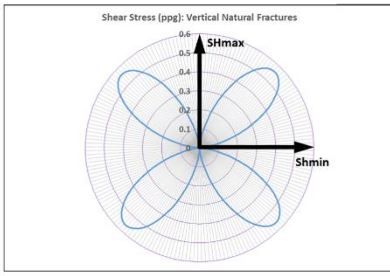


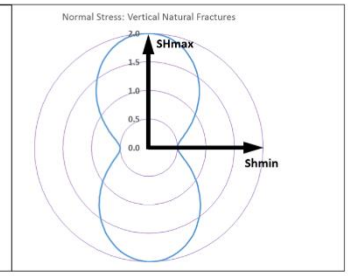
Effective Stress vs. Depletion



Stresses On Vertical Faults w/Pressure

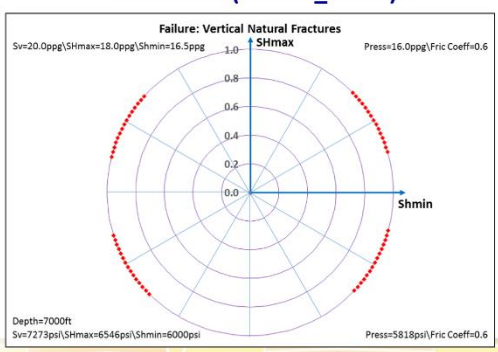
Assume: Sv=20ppg; SHmax=18ppg; Shmin=16.5ppg; Pp=16.0 ppg. What are the normal and shear stresses as a function of fault dip direction (SHmax_Az=0°)?





Stresses On Vertical Faults

Assume: Sv=20ppg; SHmax=18ppg; Shmin=16.5ppg; Pp=16.0 ppg. What orientation of faults are at shear conditions (SHmax_Az=0°)?



Conditions for Fault Slip (EQs!!)

Normal Effective Stress x Friction Coefficient < Shear Stress

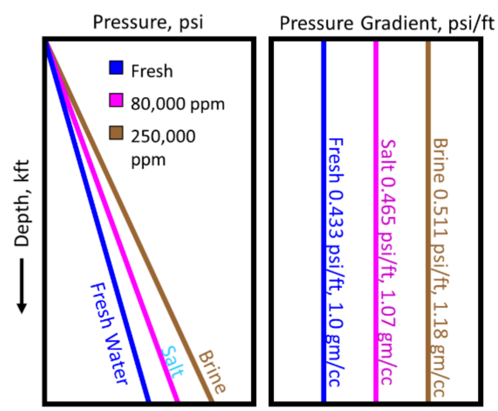
$$(\sigma_{Tn} - P_p) \times \tan(\phi) < \tau$$

σ_{Tn} =Total normal stress on fault;
P_p = Pressure on fault plane;
Φ = Friction angle; and
τ = Shear stress on fault plane.

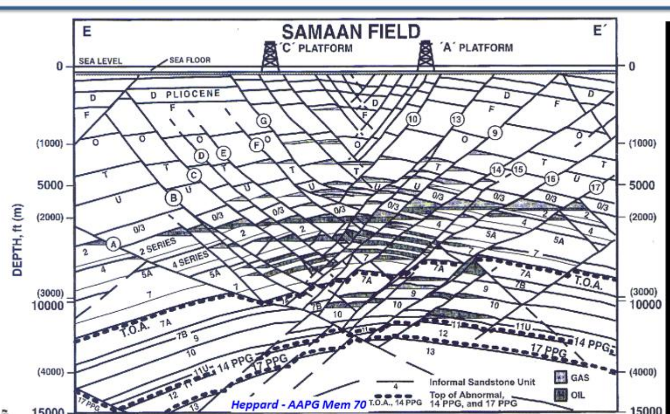
Normal and Abnormal Pressure

- Normal pressure is defined as the condition where the fluid pressure equals the hydrostatic pressure of seawater (open system).
- Abnormal pressure is a condition where the fluid pressure is greater than the hydrostatic fluid pressure for seawater (closed system).
- Subnormal pressure is the condition where the fluid pressure is less than the hydrostatic pressure for seawater (how might this occur?).

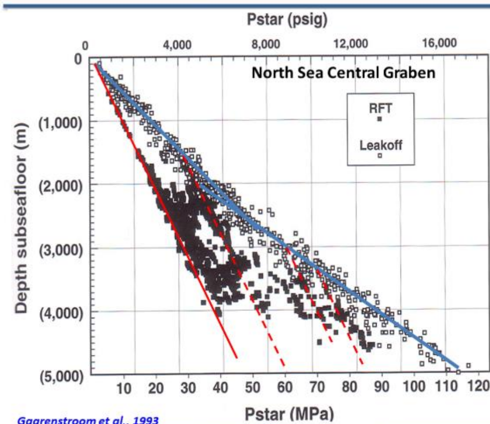
Normal Pressure



Examples: Samaan Field, Trinidad



Examples: Pressure vs. Depth



Gaarenstroom et al., 1993

In many petroleum basins, it is observed that at shallower depths pore pressures are mostly hydrostatic. Why?

Deeper in the basin, high overpressures may occur. Why might this be?

At intermediate depths overpressure development is more variable. Why could this be?

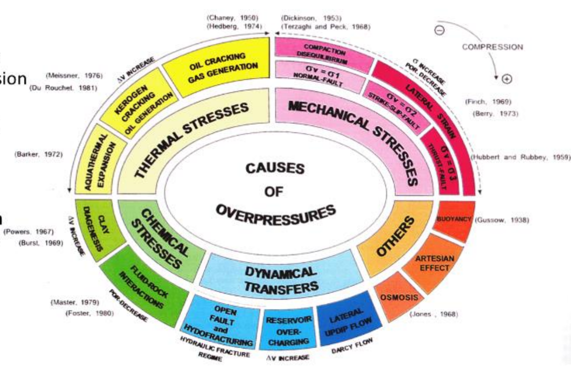
Overpressure appears to be limited by the fracture pressure as represented by the LOT's. Why?

Overpress. Generation Mechanisms

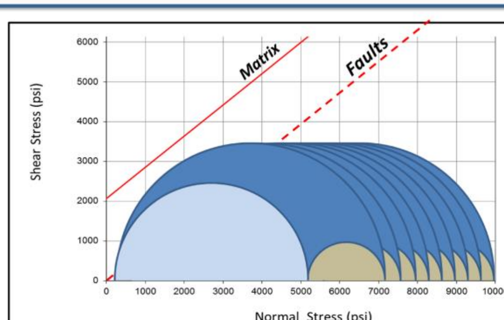
Stress Generated
- Undercompaction
- Tectonic compression

Thermally Generated
- Aquathermal
- Diagenetic

Fluid Redistribution in Permeable Zones
- Buoyancy
- Centroid
- Lateral transfer
- Hydraulic head
- Osmosis

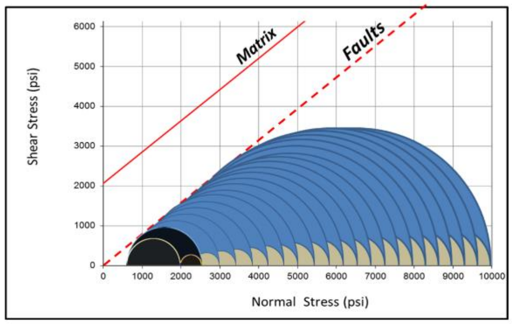


Influence of Pore Pressure on Stress



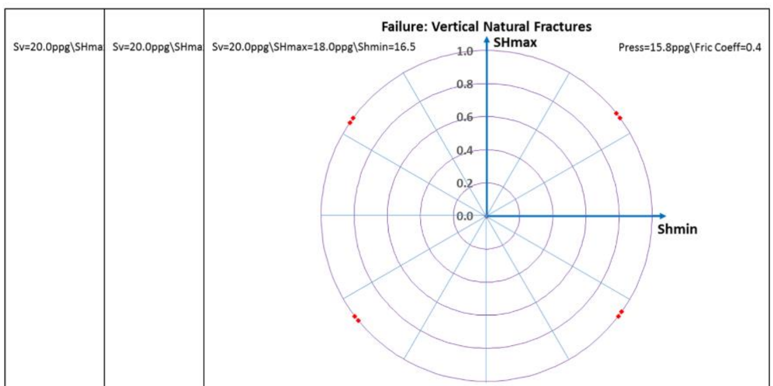
Increasing pressure pushes the rock toward failure...

Influence of Pore Pressure on Stress

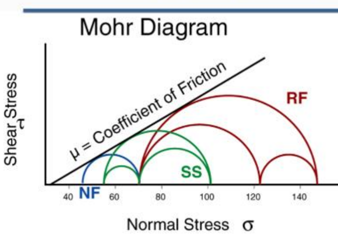


To prevent failure, the maximum stress difference greatly declines...

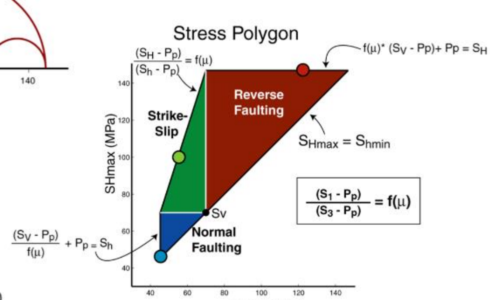
Vertical Faults: Shear Conditions



Stress Limits: Frictional Limit



$$f(\mu) = \left(\sqrt{\mu^2 + 1} + \mu\right)^2$$



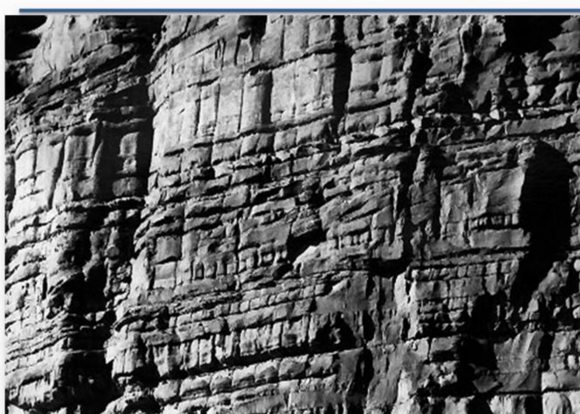
Zoback (1990)

FAULTS & FRACTURES

Rock Irrefutable Realities…

1. All rocks have fractures…
2. Fractures are created/reactivated by stresses…
3. We can never know exactly how many fractures, where are they and how they look…but…

All Rocks have Faults/Fractures



Variable fracture density within layers

Properties of Faults/Fractures

The hydro-mechanical behavior of the joint is controlled primarily by the roughness of the surface

Using the words favored by Professor Neville Cook:

" Natural joints in rock can be described as two rough surfaces in partial contact"

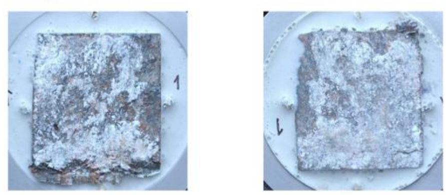
The roughness of the joint surfaces depends on many factors:
rock type and the geological conditions to which the joint has been subjected.

All surfaces are rough on some scale and that the contact between two rough surfaces affects most physical properties, including electrical and thermal conductance, stiffness, strength, and hydraulic conductivity.

Mechanical Properties- Dilation

Before mechanical test

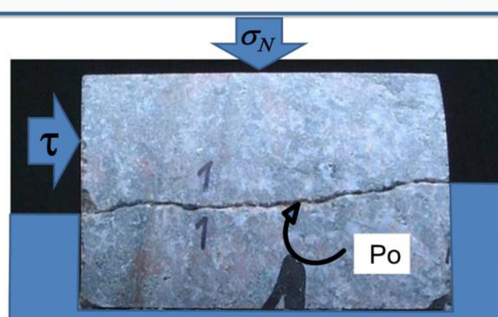
After mechanical test



Samples from TASQ tunnel at Äspö HRL
Normal loading and shear tests on joints

Lars Jacobsson, Mathias Flansbjer
SP Swedish National Testing and Research Institute
Borås, Sweden

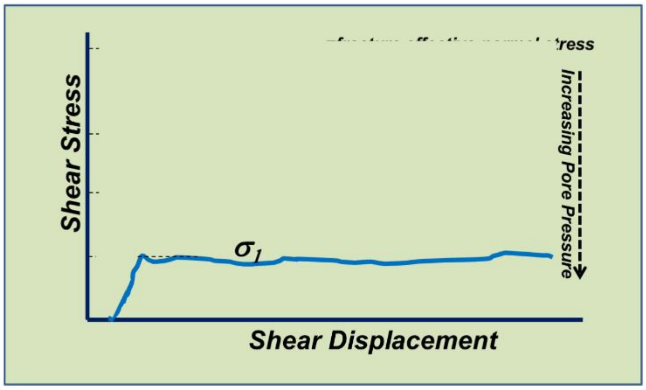
Natural Fracture Mechanical Behavior



Effective stress=σ'
Total stress=σ_N
Pore pressure=Po

$$\sigma' = \sigma_N - p_o$$

Natural Fracture Mechanical Behavior



What Are Common Characteristics?

- Very non-linear mechanical behavior.
- Shearing damage.
- Normal stiffness dependence on normal stress; and
- Decrease in dilation angle with plastic shear displacement.

Flow and Deformation of Fractures

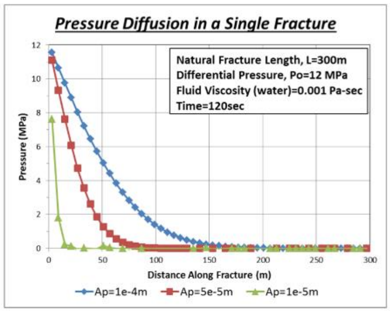
The direct relationship between fluid flow and fracture aperture has been established from experimental, theoretical, and numerical investigations of fluid flow through a fracture.

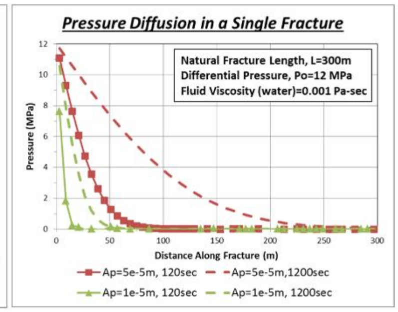
The cubic law: $$Q = \frac{\gamma_w}{12\mu} G a^3 \Delta h$$

Aperture	Flow
100%	100%
90%	73%
70%	34%
50%	13%

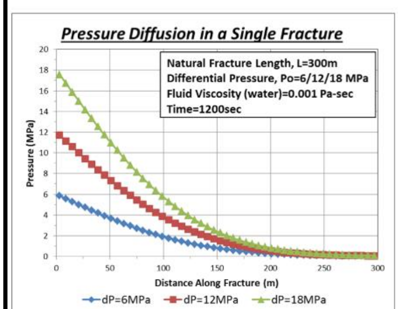
This relationship is the Reynolds equation for viscous flow between parallel plates and is often referred to as the cubic law.

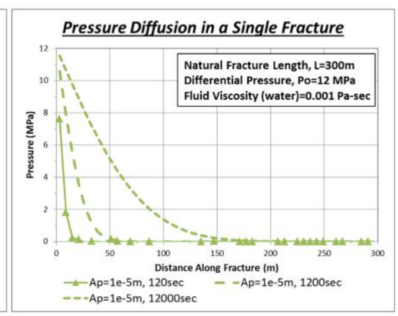
Consideration of Fault/Fracture Pressure Diffusion

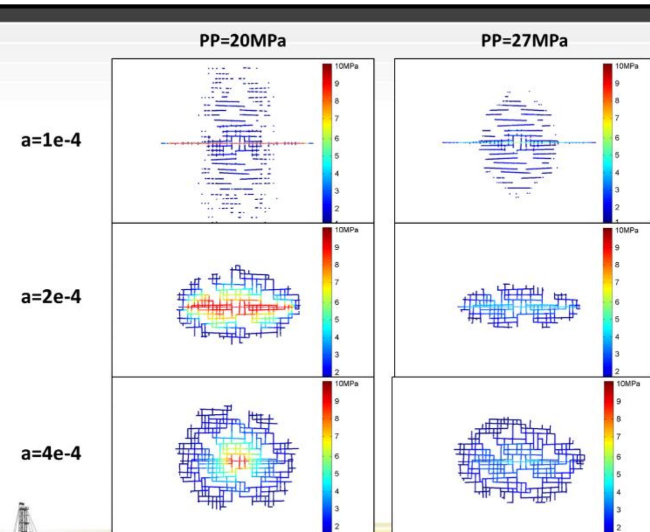




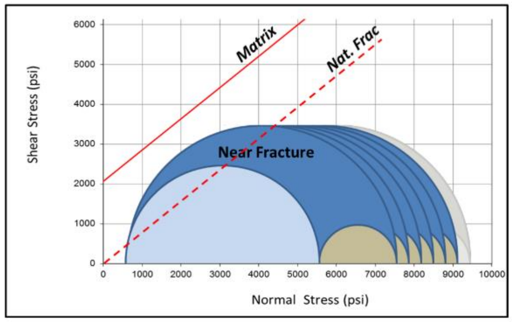
Consideration of Natural Fracture Pressure Diffusion



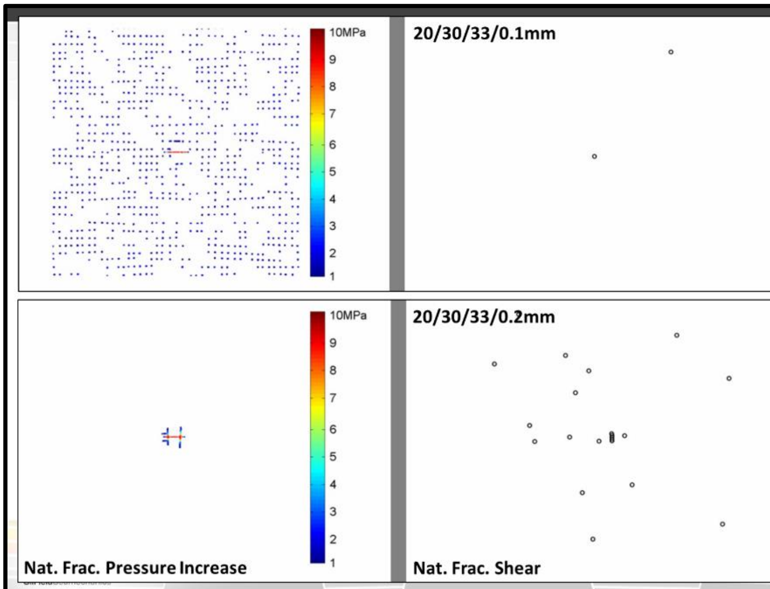




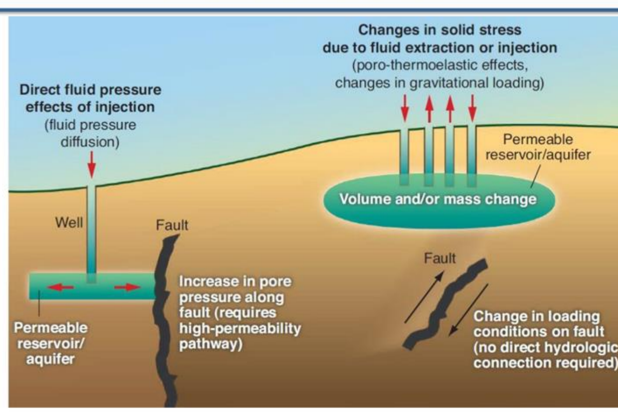
Stress Change Due to Increasing Pressure in Faults/Fractures



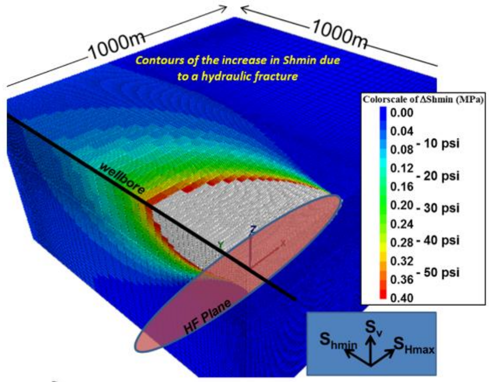
Increasing pressure pushes the rock toward failure...



Induced Stresses



Induced Stresses



The generation of fracture width causes a change in the stress field. Here, the simulated increase in the minimum horizontal stress (ΔShmin) – often called the "Stress Shadow" – is shown in cutaway view.

KEY ISSUES

Base Data:

1. *Initial stress field – magnitude, orientation, ranking*
2. *Initial pressure field – over/under/normal pressure*
3. *Fault/fracture structure – dip, dip direction, length, connectivity*
4. *Fault/fracture mechanical properties – friction, cohesion, aperture, permeability*

Operational Effects:

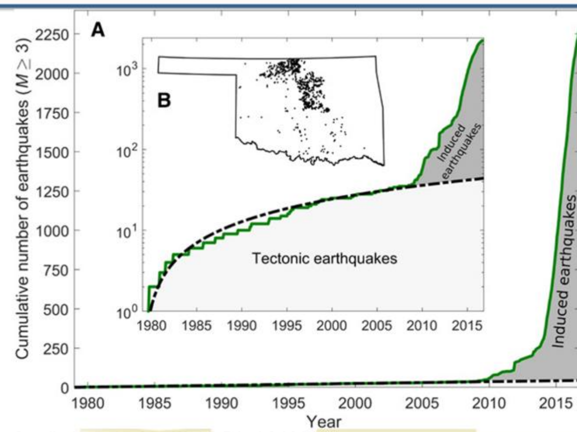
1. *Induced pressure changes – injection, poro-elastic*
2. *Induced stress changes – loads, deformations, pressures*

Injection Parameters:

1. *Injection parameters – location*
2. *Injection parameters – rate, volumes (short and long-term), pressures*

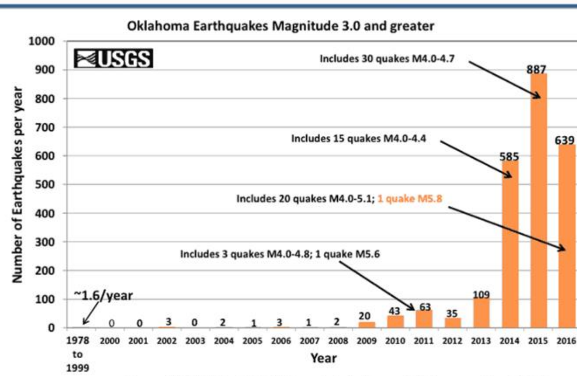
OKLAHOMA CASE HISTORY

M>3 Oklahoma EQs: 1979 – 09/2016



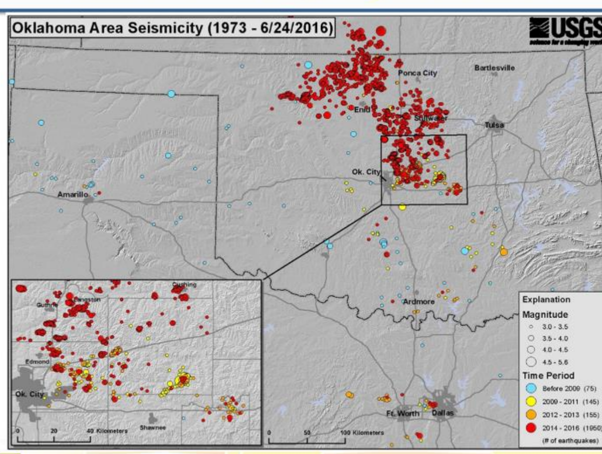
Cornelius Langenbruch, and Mark D. Zoback Sci Adv 2016;2:e1601542

Oklahoma EQs by Year



Source: USGS-NEIC ComCat & Oklahoma Geological Survey; Preliminary as of Dec. 31, 2016

Oklahoma EQs by Location



Government Response

News from the **Oklahoma Corporation Commission**

Matt Skinner, Public Information Director
Phone: (405) 521-4180
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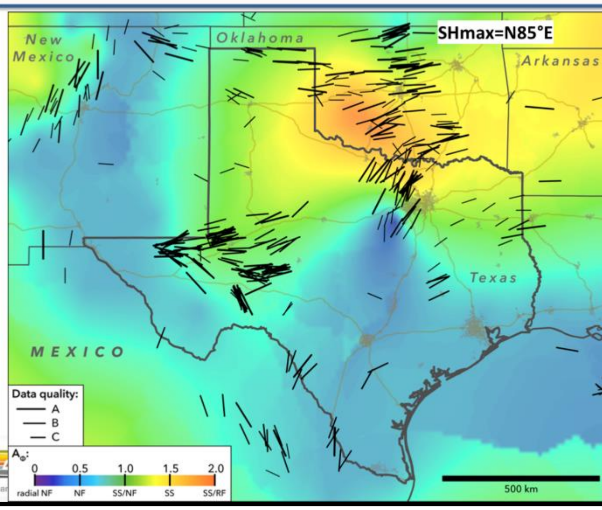
MEDIA ADVISORY – LATEST ACTION REGARDING PAWNEE AREA

Based on new data, the Oklahoma Corporation Commission's Oil and Gas Division (OGCD) is taking further action in the area of the 5.8 earthquake that occurred in the Pawnee area on September 3, 2016. Key points:

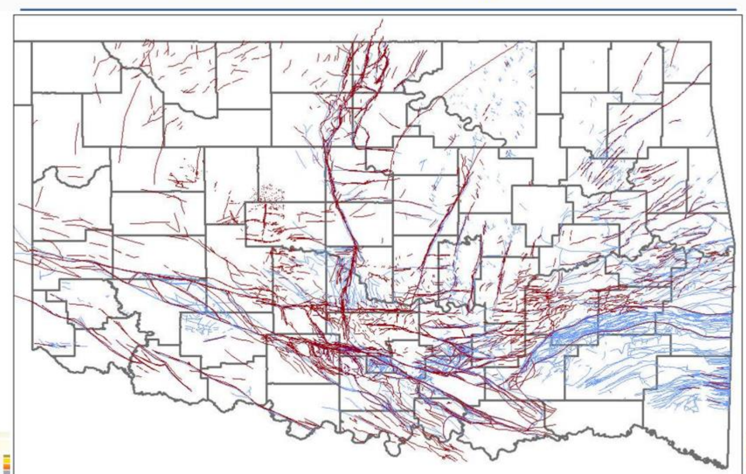
- This action is a collaborative effort involving the OGCD and the Environmental Protection Agency, as it involves Osage county, which is under EPA jurisdiction.
- The new data is the result of work by the Oklahoma Geological Survey and the United States Geological Survey.
- Total size of action area (Area of Interest, or AOI): 1,116 square miles
- Number of wells in AOI: 48 Arbuckle disposal wells within OCC jurisdiction, 19 Arbuckle disposal wells within EPA jurisdiction. Total: 67 Arbuckle disposal wells.
- Number of wells to cease operations: 32 (27 in OGCD jurisdiction, 5 in EPA jurisdiction).
- Total volume reduction: 40 thousand barrels a day (OCC jurisdiction only).
- Reason for action: New fault data
- The action is an evolution of the directive issued on September 03, 2016. As such, the latest directive is taken under the OCC's emergency authority** and is mandatory.

**Approved by the Oklahoma Legislature last session at OCC request.

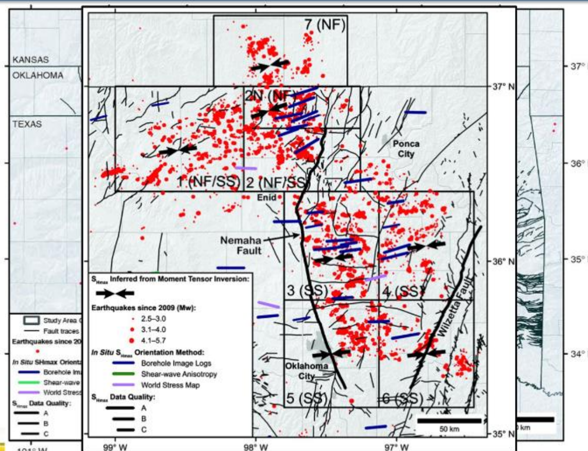
Oklahoma/Texas Stress Field



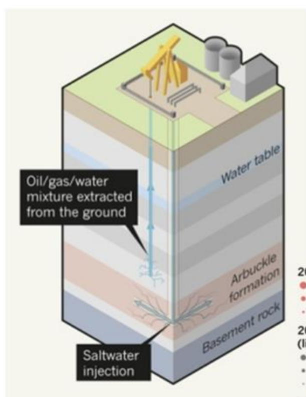
Oklahoma Fault System

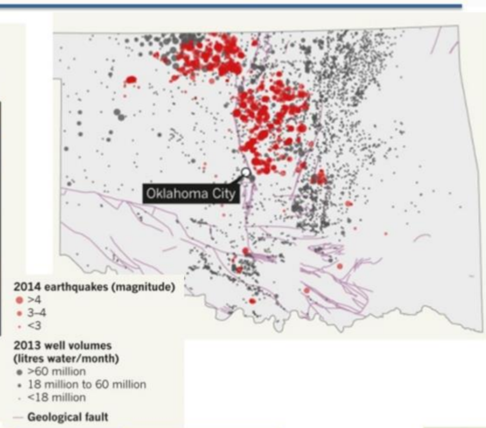


Oklahoma Faults and Earthquakes



SW Injectors vs. Earthquakes





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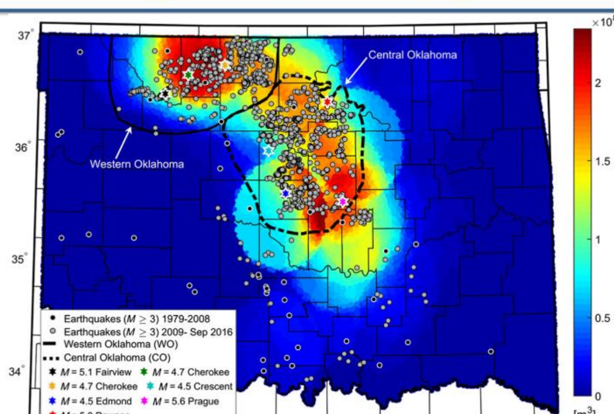

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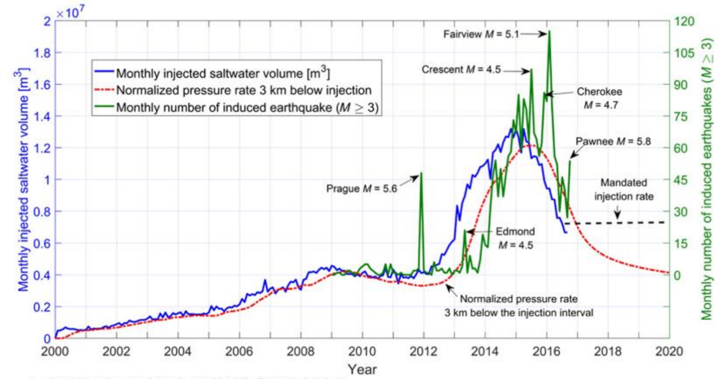

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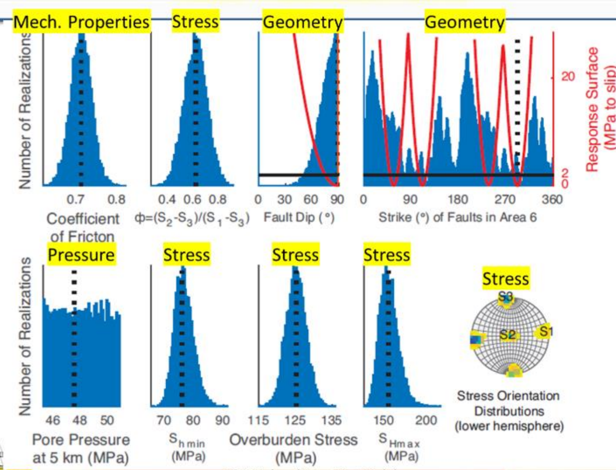
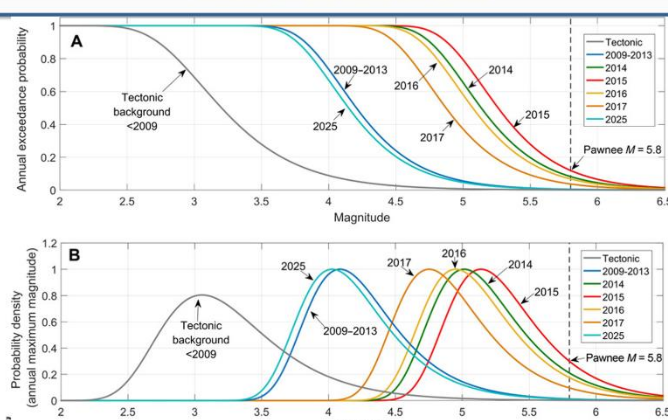
Risk Assessment



Risk Assessment



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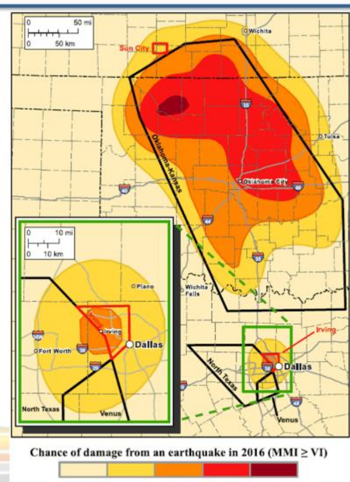

Evaluation

Saltwater Disposal Operational Factors	Formation Characteristics	Injection Operations	Operating Experience
Significant	Injection horizon likely incommunication with basement, underpressured injection interval	High cumulative injection volumes and rates	Limited injection experience in region, past earthquakes clearly or ambiguously correlated with operations
Moderate	Injection horizon potentially in communication with base-ment, slightly underpressured injection interval	Moderate cumulative injection volumes and rates	Moderate injection experience in region with no surface felt ground shaking
Minor	Injection horizon not in communication with basement	Low cumulative injection volumes and rates	Extensive injection experience in region with no surface felt ground shaking

TABLE G.1. *After R.J. Walters et al.: Factors related to saltwater disposal operations that contribute to the level of risk at an injection site. Source: SCITS 2015.*

On the Geomechanics of Induced Seismicity

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