Induced Seismicity - Physical Mechanisms and Temporal Trends in Kansas

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KANSAS GEOLOGICAL SURVEY
The University of Kansas

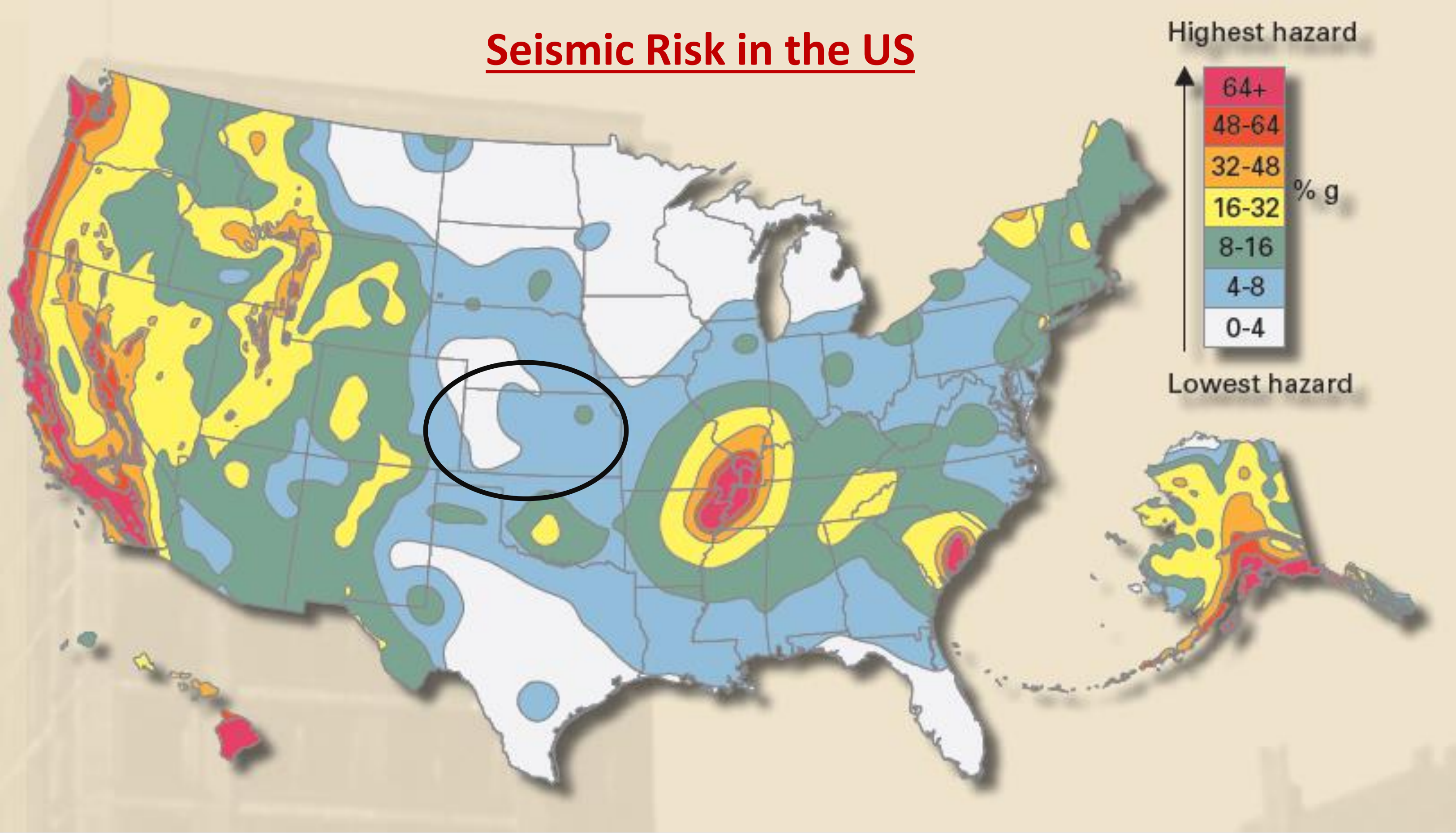
TBirdie Consulting inc

NETL

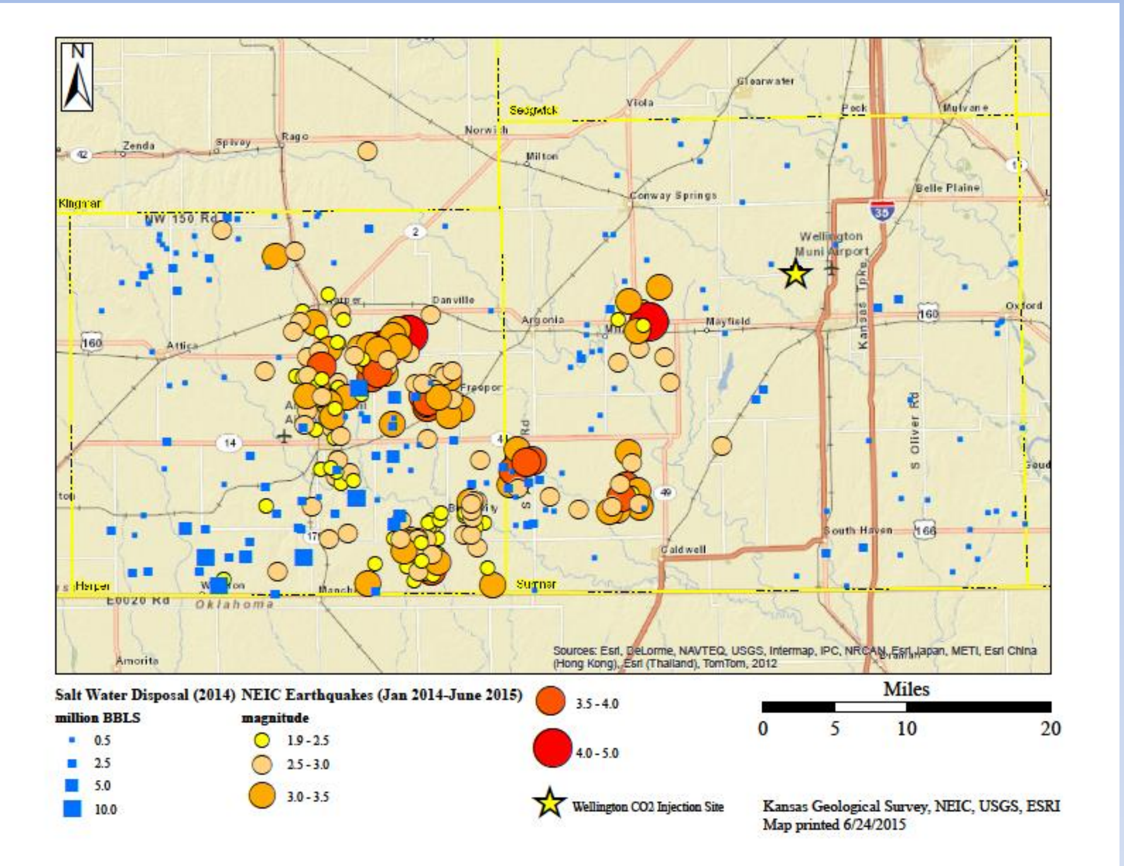
Presentation Outline

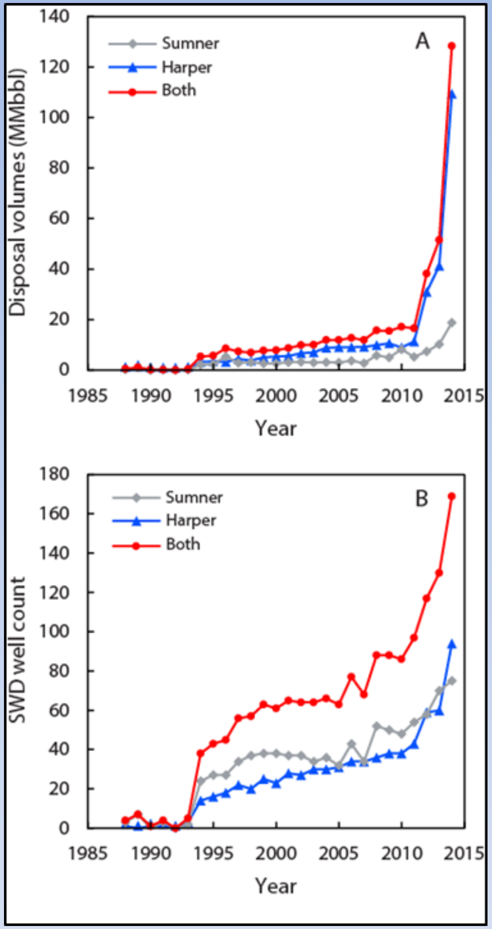
- Seismicity Trends in Kansas
- Geomechanics of faulting
- Relationship between fault characteristics and seismic magnitude
- Estimating Slip Tendency of Faults

Kansas Assumed to Lie in a Seismically Benign Area



Earthquake Trends in Southern Kansas



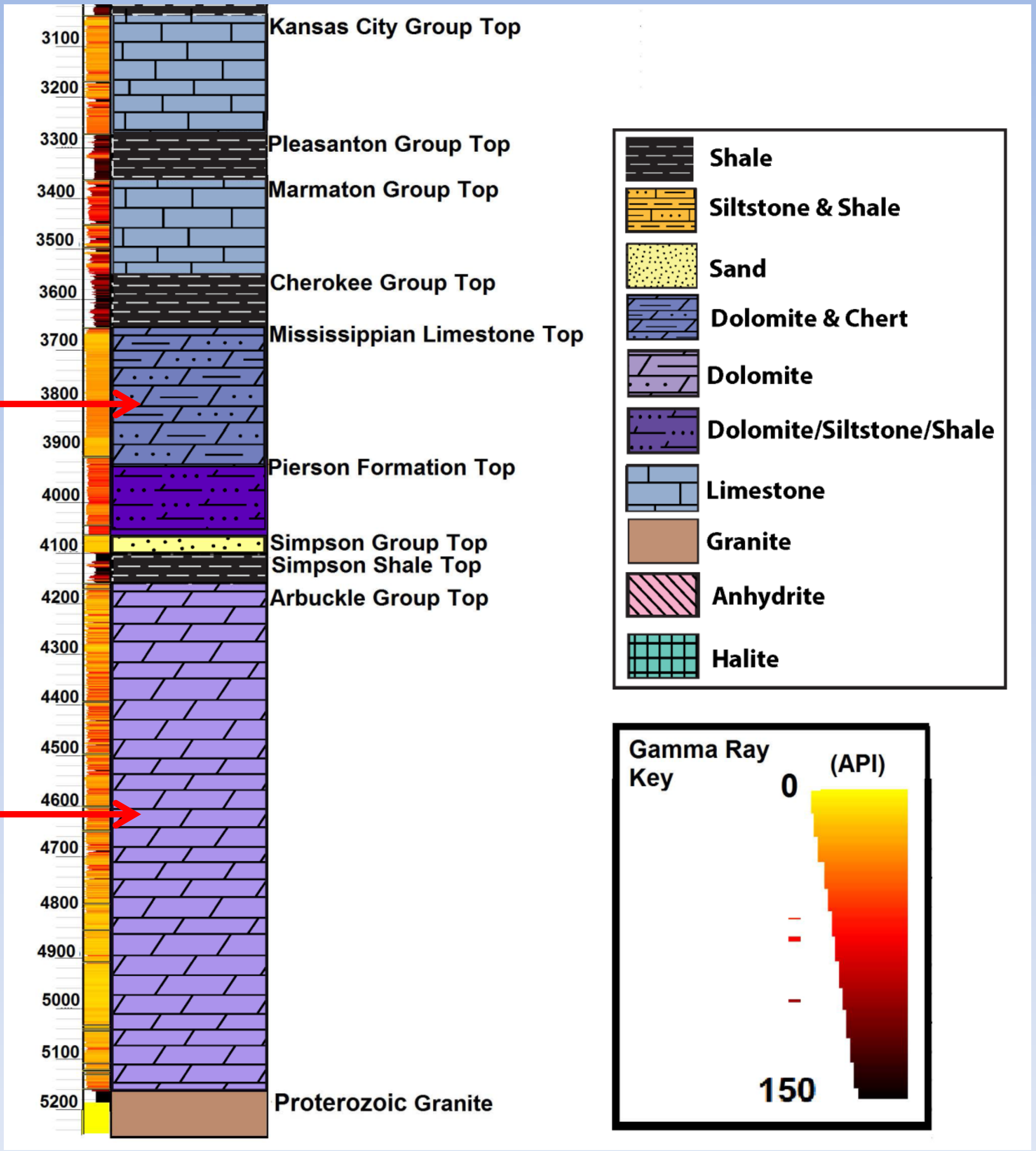


- **Large earthquakes (> M3.8) in past year associated with waste water injection in the Arbuckle saline aquifer**

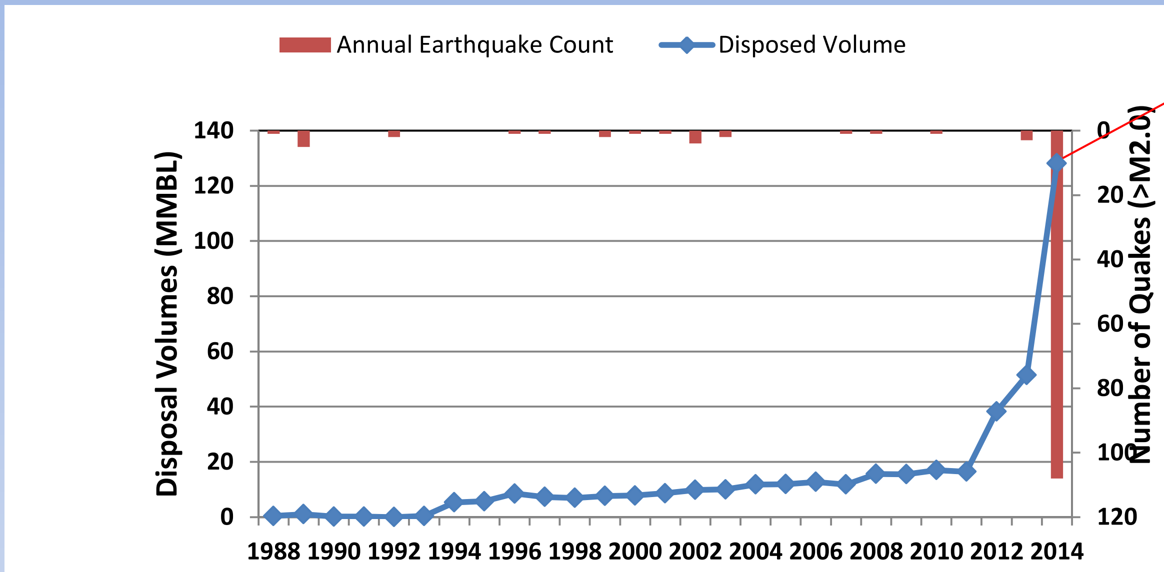
Reservoirs Supporting Oil and Gas Operations

Mississippian Oil and Gas Reservoir

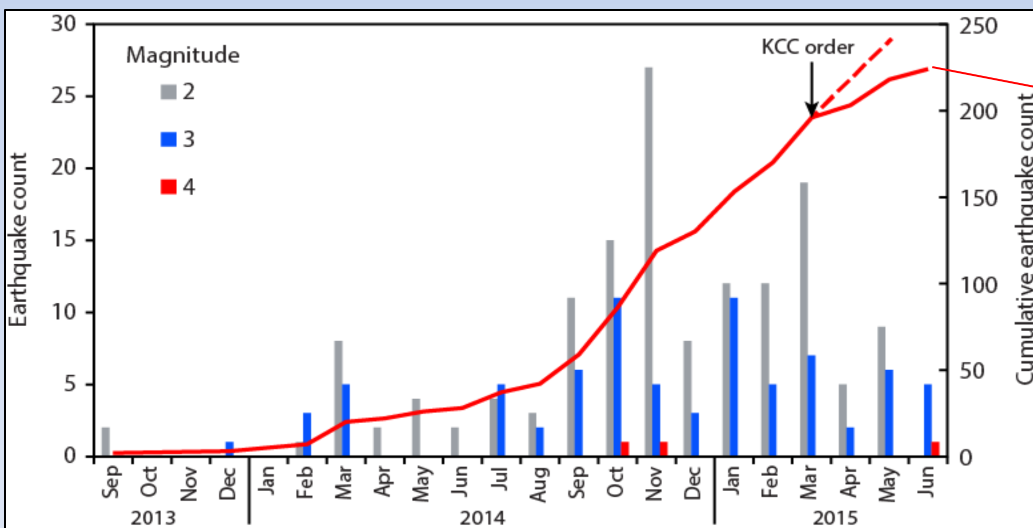
Arbuckle Saline Aquifer
(Waste Disposal)



Seismic Trends in Southern Kansas

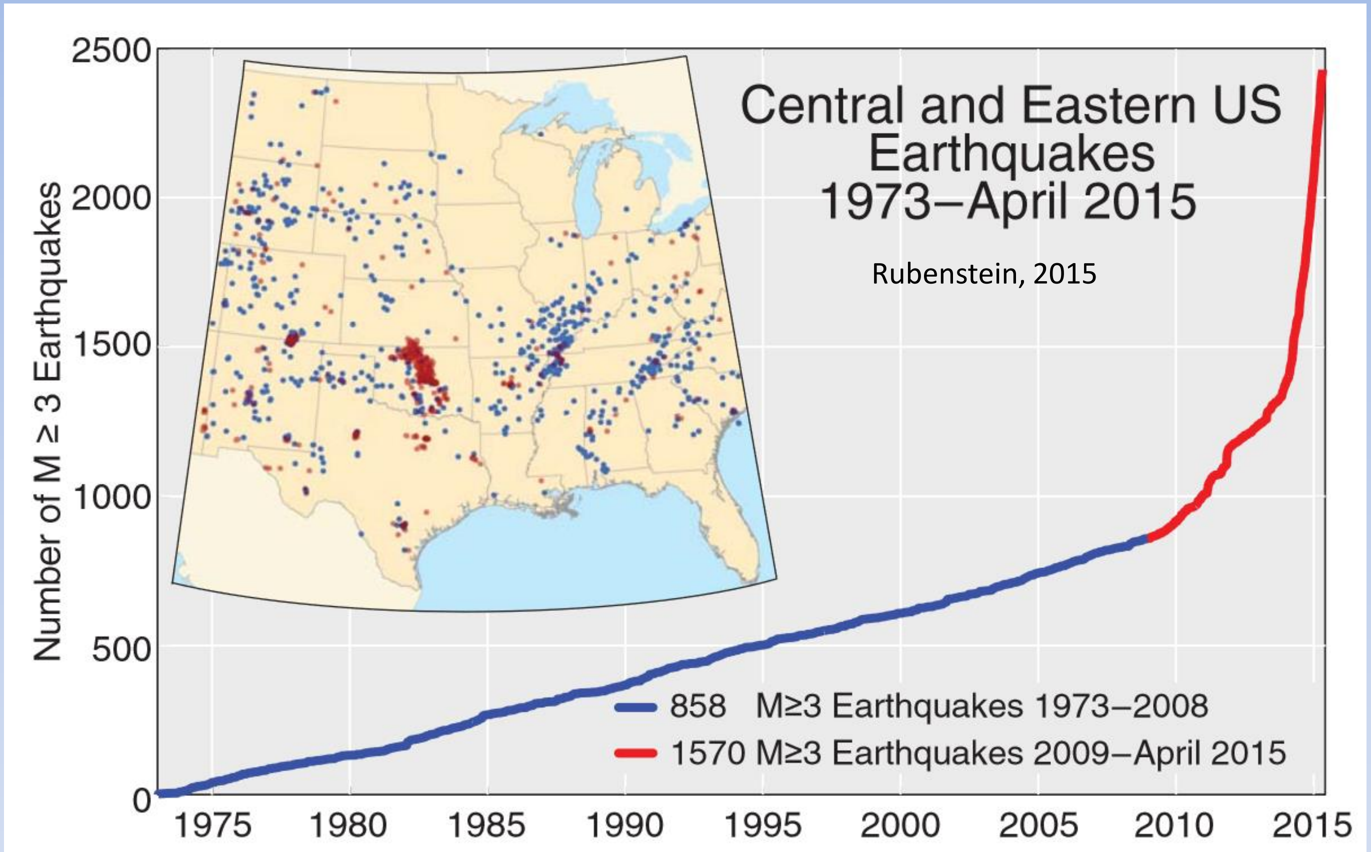


Equivalent to 3,700 Million Gallons



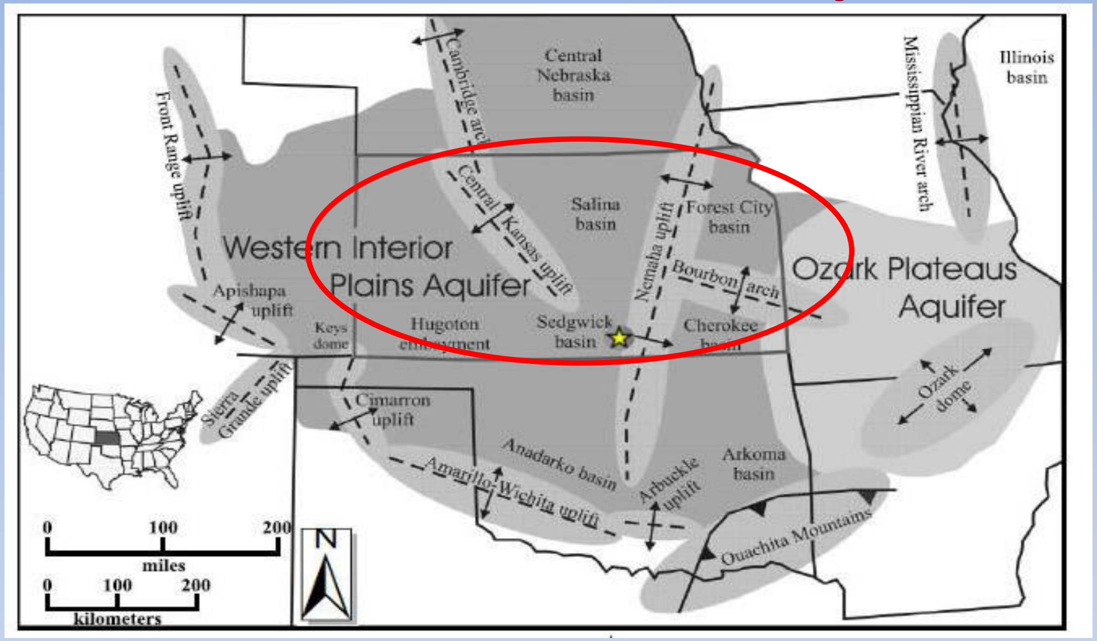
- Some abatement in seismicity following restrictions on injection rates and volumes in Kansas

Earthquake Trends in Central and Eastern US

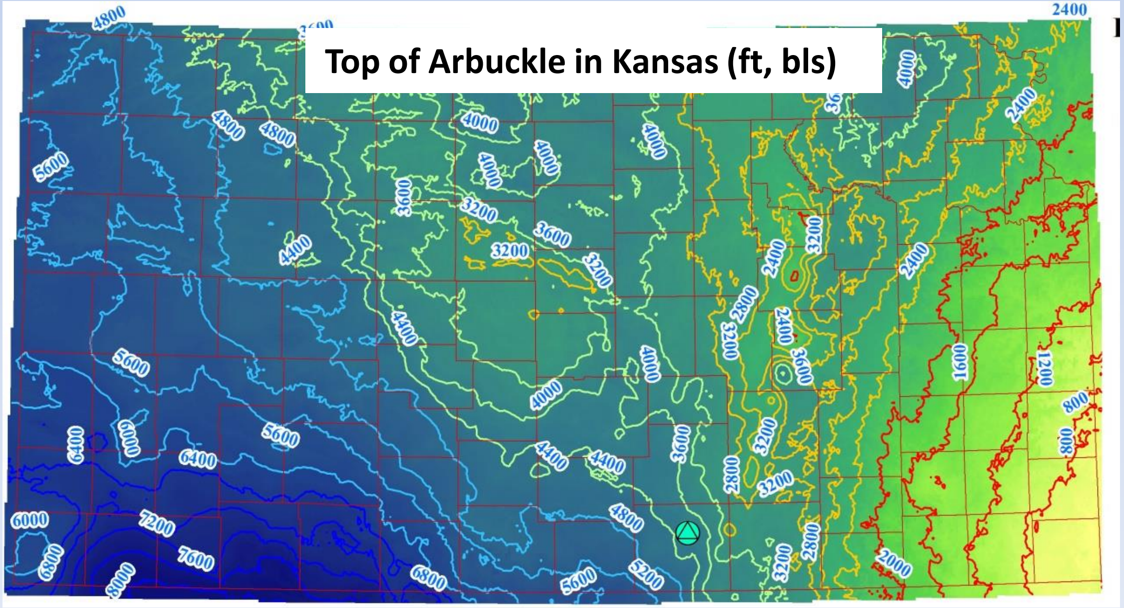


- **Induced seismicity linked to waste disposal in deep saline aquifers and not fracking**

Arbuckle Aquifer in Kansas



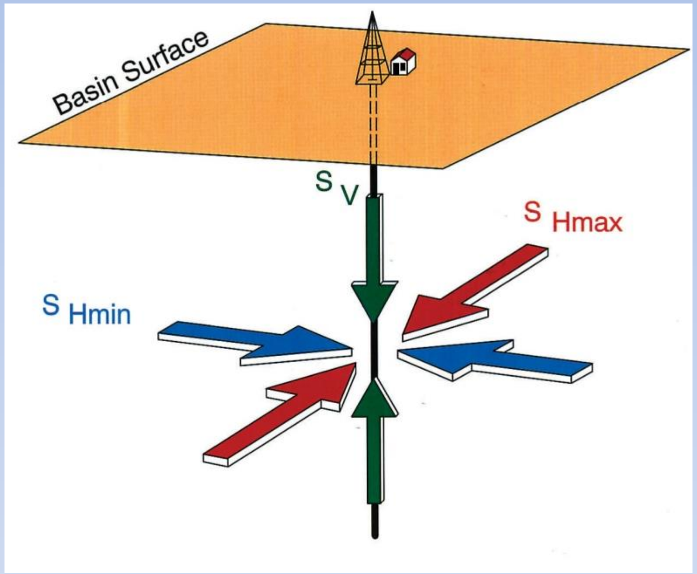
- Cambrian-Ordivician Arbuckle aquifer (Dolomitic)
- 700 million- 1 billion years

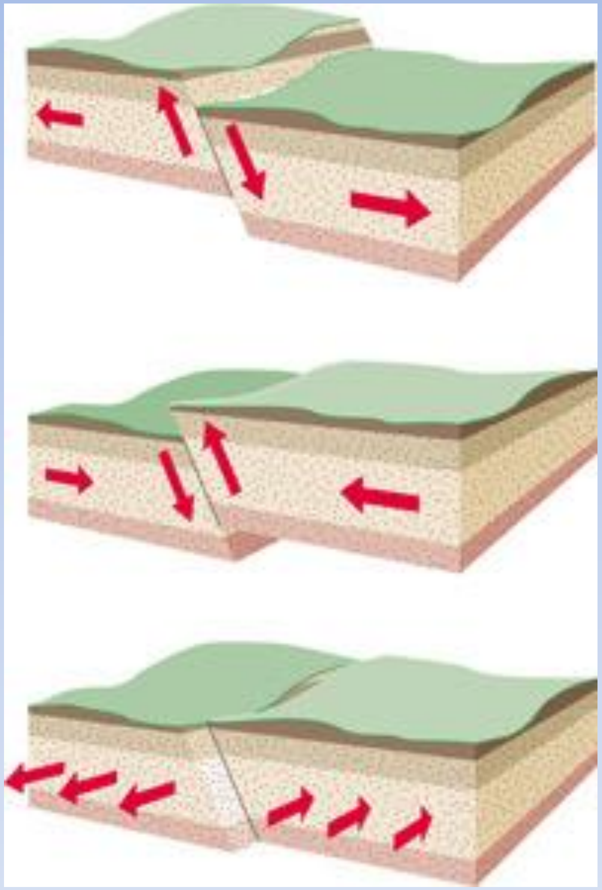


- Arbuckle ~ 1000-ft thick in Kansas

Subsurface Stress Field

Three Principal Stresses





Normal Fault

$S_v > S_{Hmax} > S_{Hmin}$

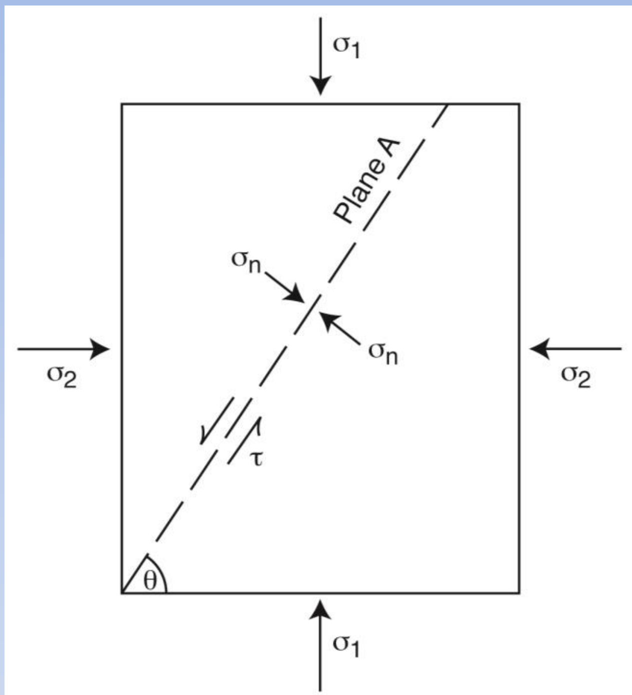
Reverse Fault

$S_{Hmax} > S_{hmin} > S_v$

Strike Slip Fault

$S_{Hmax} > S_v > S_{hmin}$

Failure Plane



Shear Stress (along fault Plane)

$$\tau = \left(\frac{\sigma_1 - \sigma_2}{2}\right) sin2\theta$$

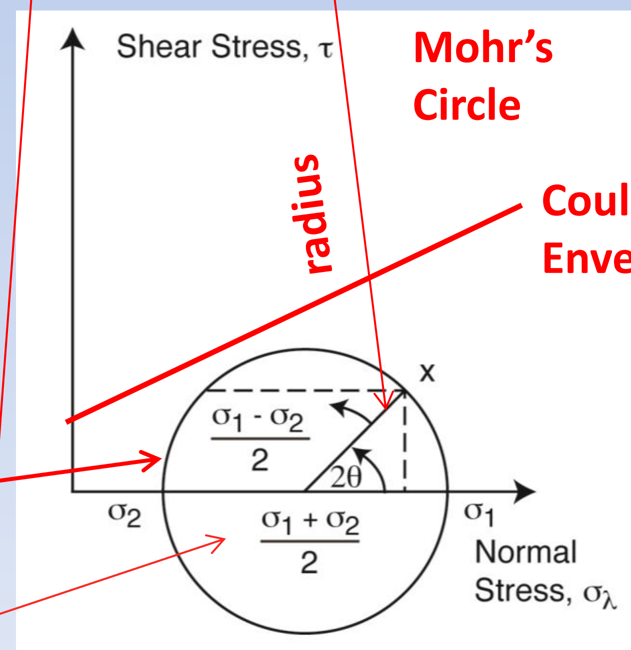
Shear stress a function of <u>difference</u> in principal stresses and not absolute magnitude of stresses

Normal Stress (perpendicular to fault plane)

$$\sigma_n = \frac{\sigma_1 + \sigma_2}{2} + \left(\frac{\sigma_1 - \sigma_2}{2}\right) cos2\theta$$

centroid

radius

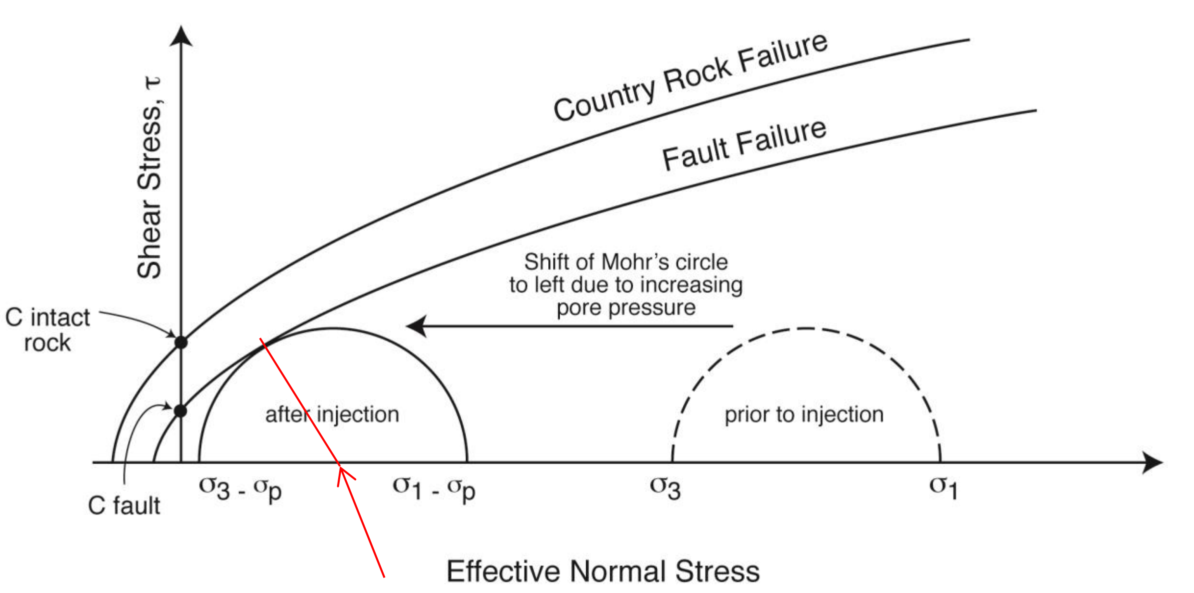


Mohr's Circle

Coulomb Failure Envelope

Fault slips when Mohr's circle touches Coulomb Failure Envelope for <u>critically oriented faults</u>

Effect of Induced Pore Pressure on Fault Slippage

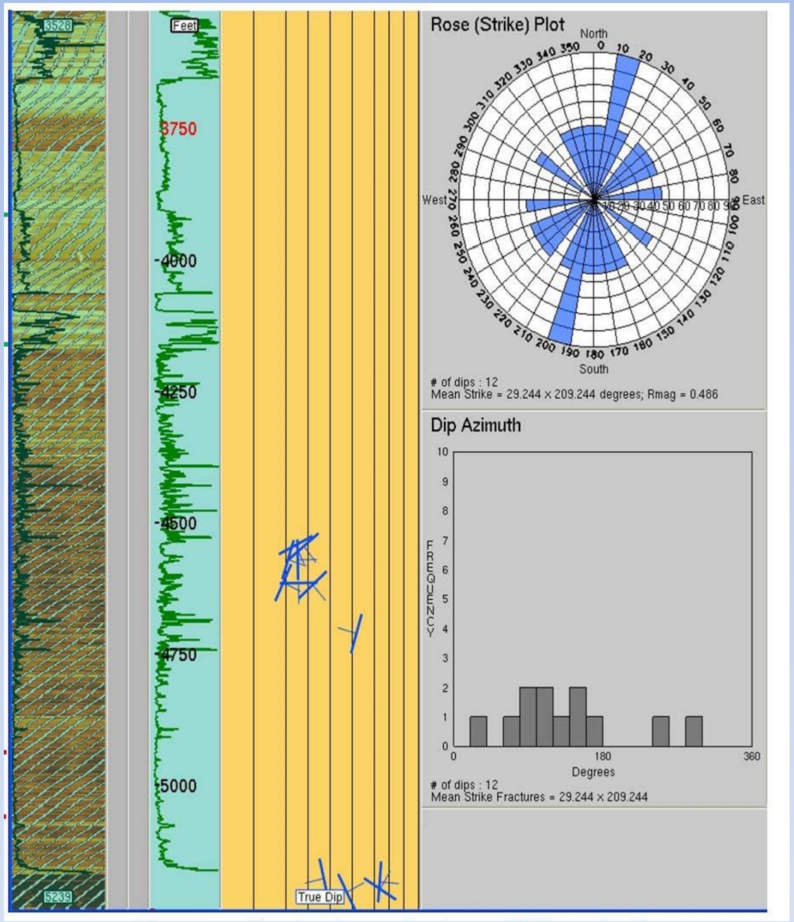


- **Critical fault orientation is typically 120º in Mohr Space; 60º in real space**
- **Non-critically oriented faults require larger pressures to fail**

Data Needed to Predict Earthquake Potential

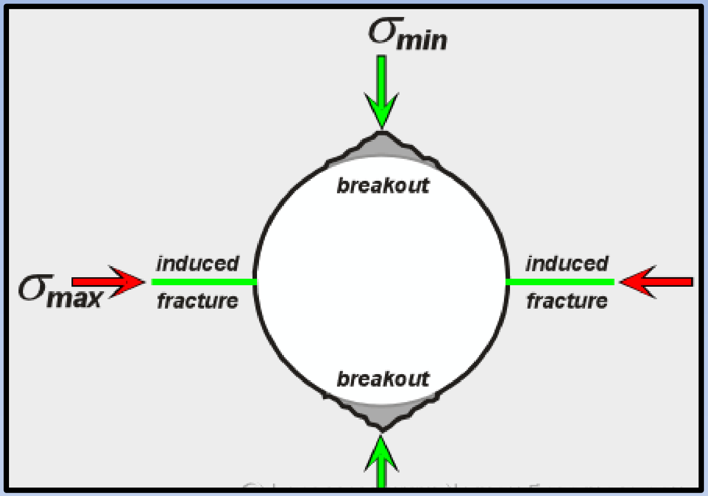
- Principal stresses and direction
- Orientation of faults
- Pore pressures
- Fault length

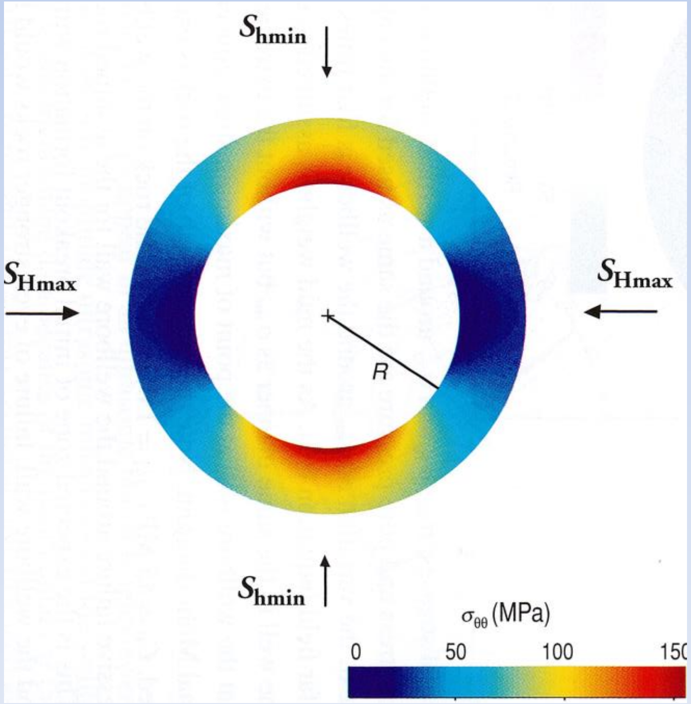
Image Log for Fracture Orientation and Stress Field Direction

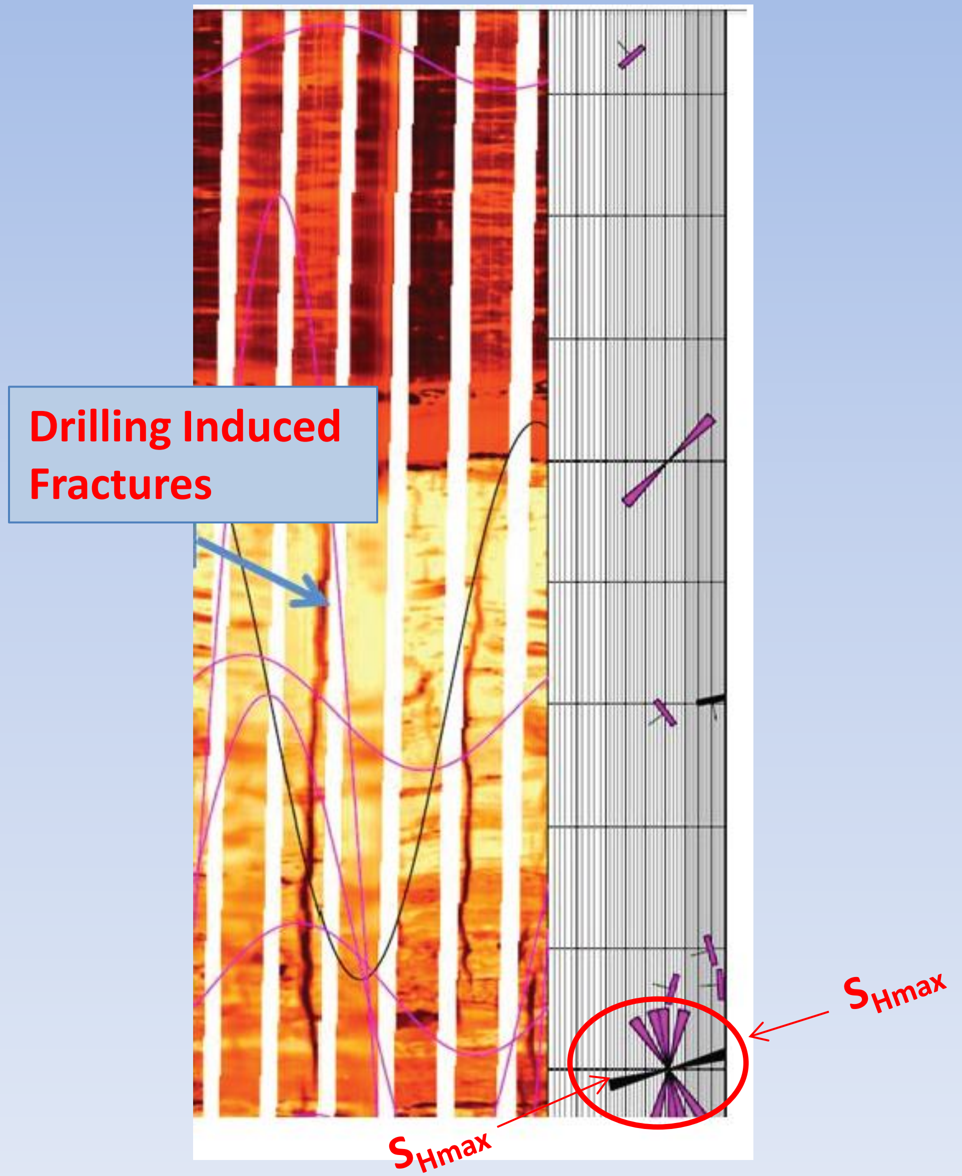


- **Highest strike density in NNE-SSW direction**
- **Present-day stress field ?**
- **Fault orientation ?**

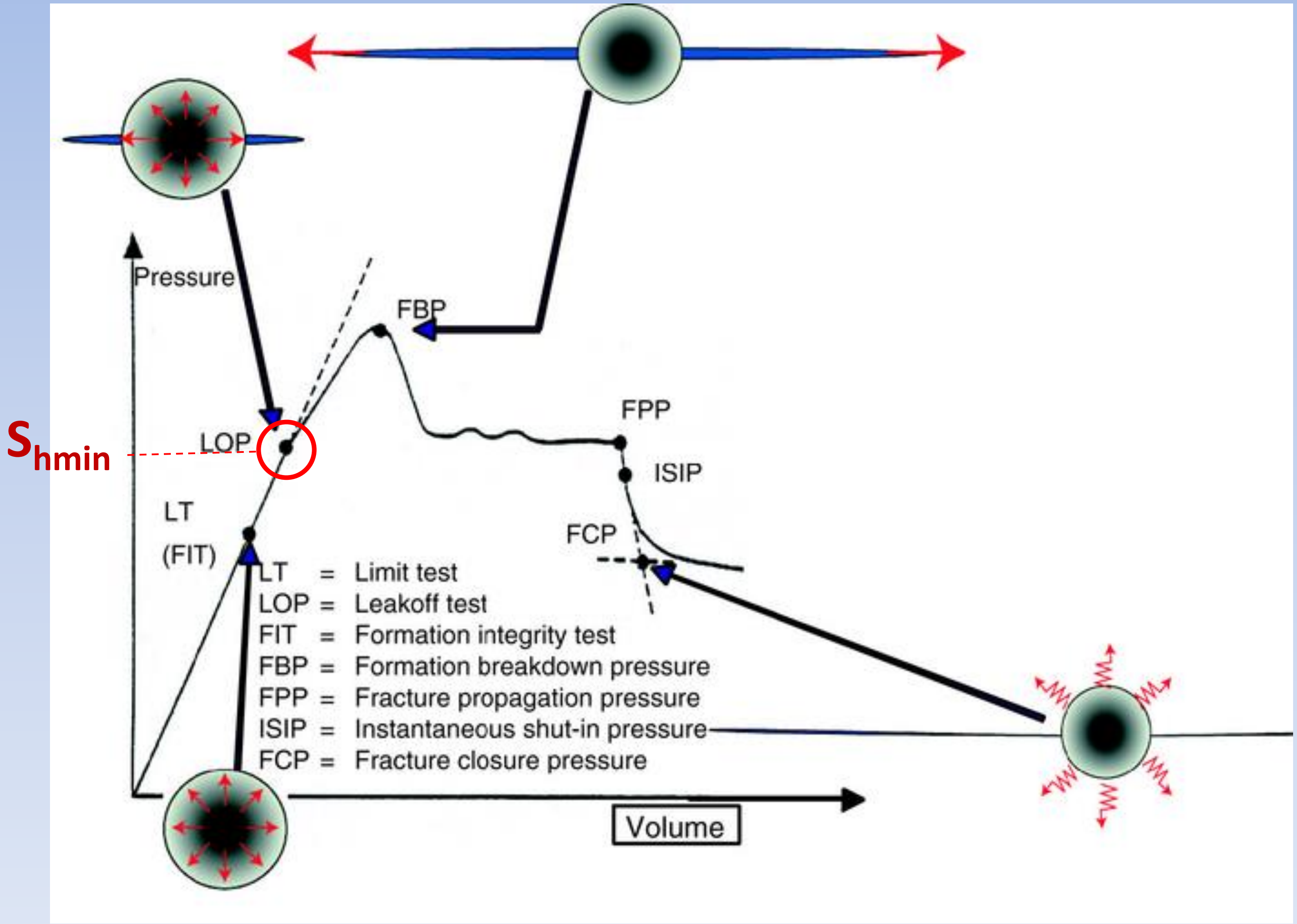
Drilling Induced Fractures to Estimate Present-Day Principal Stress Directions



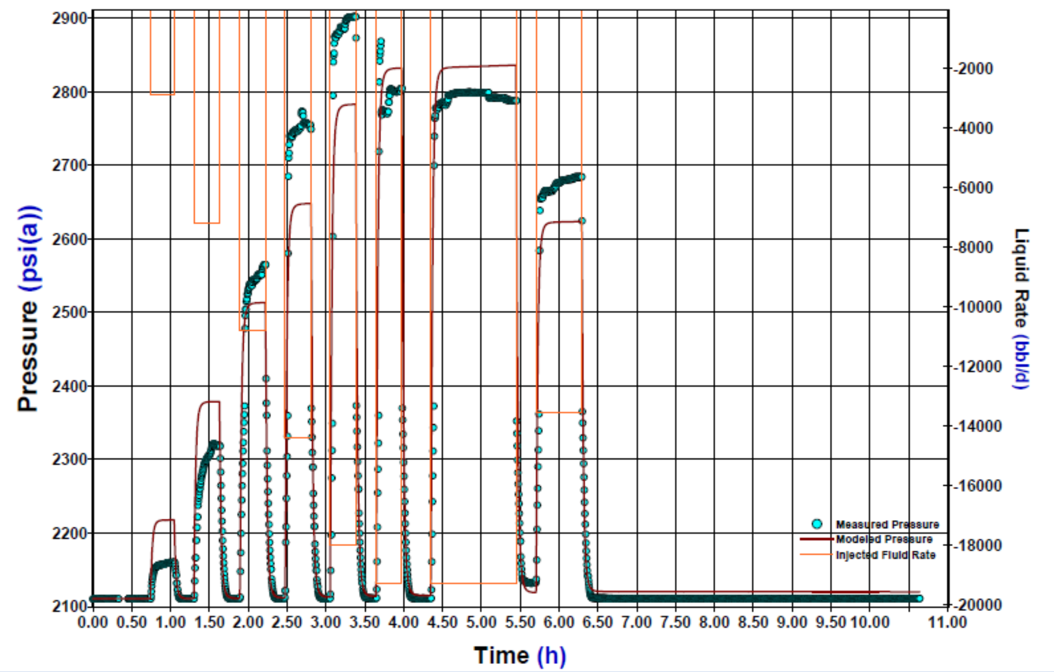




Determining Minimum Horizontal Stress (S_{hmin}) from Leak-off Test



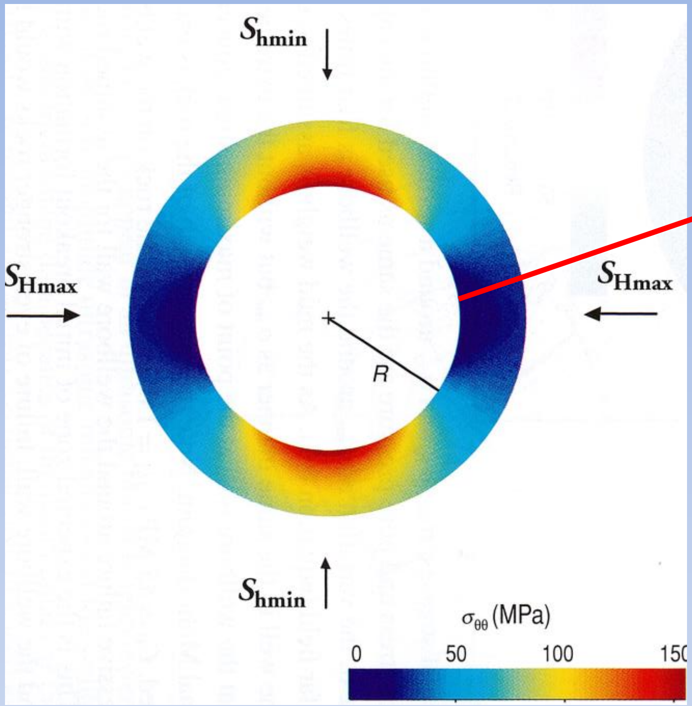
Step Rate Test in Sumner County



- **Leak-Off ~ 2900 psi (5,000 ft below surface)**

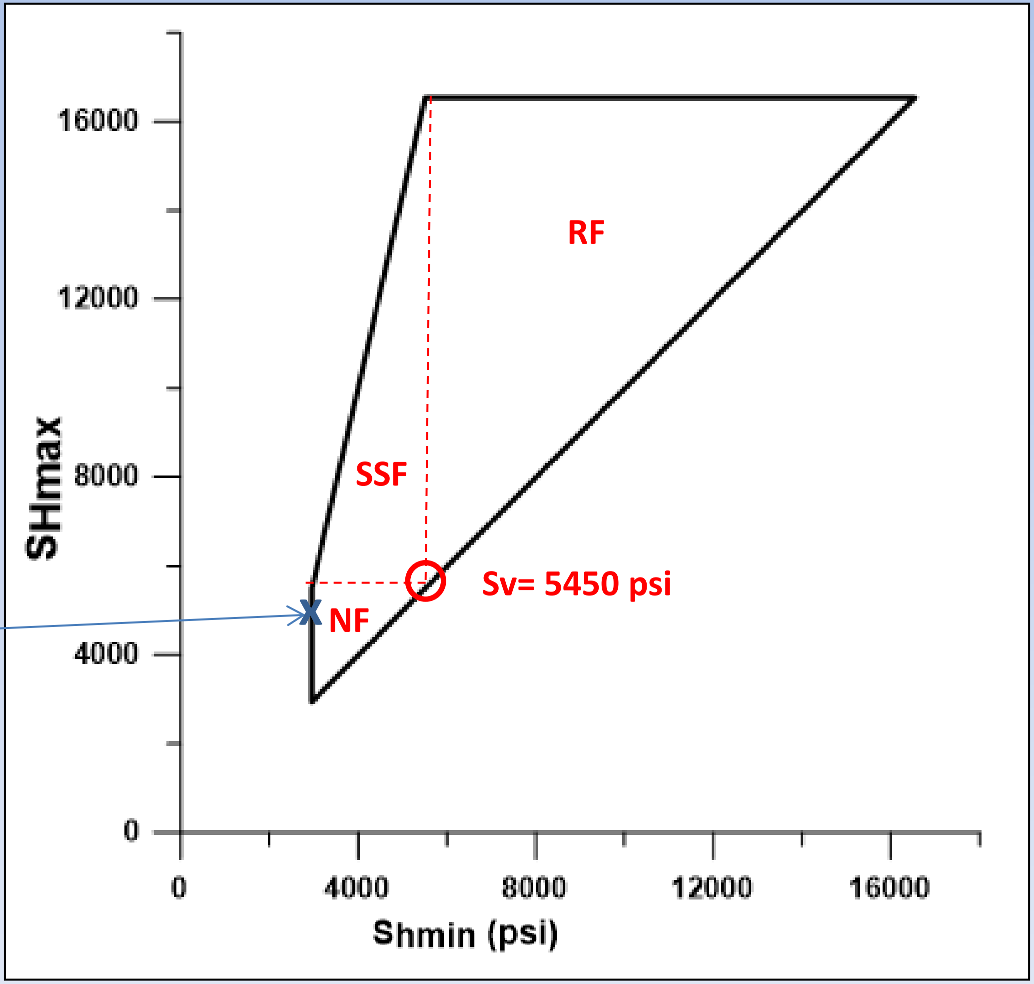
Question: With S_{hmin} known, what is S_{Hmax} ?

Drilling Induced Fractures to Estimate Faulting Environment



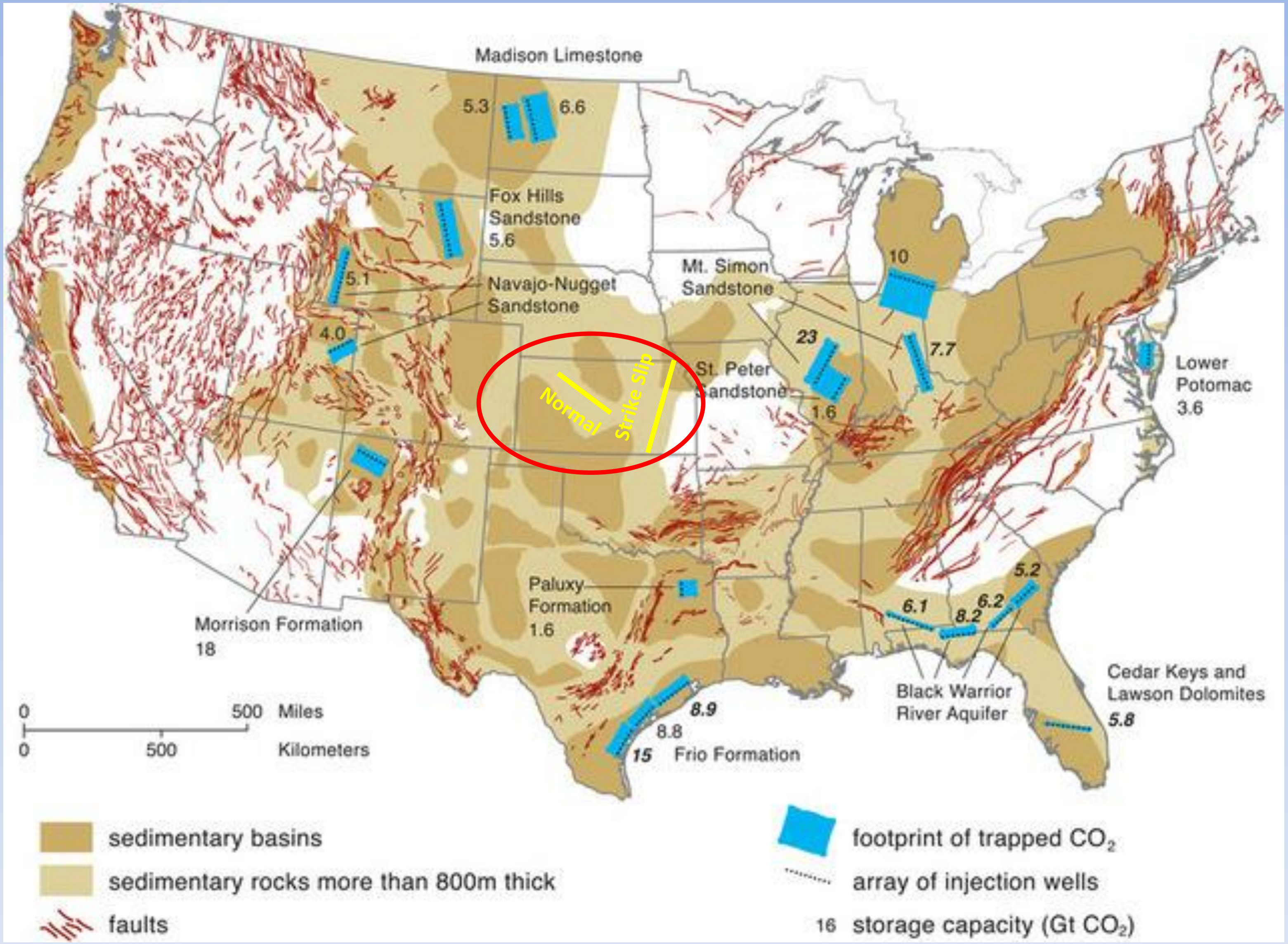
$$S_{Hmax} \sim 3S_{Hmin} - 2P_p + 0.1(S_{hmin} - P_p)$$

= 4,540 psi



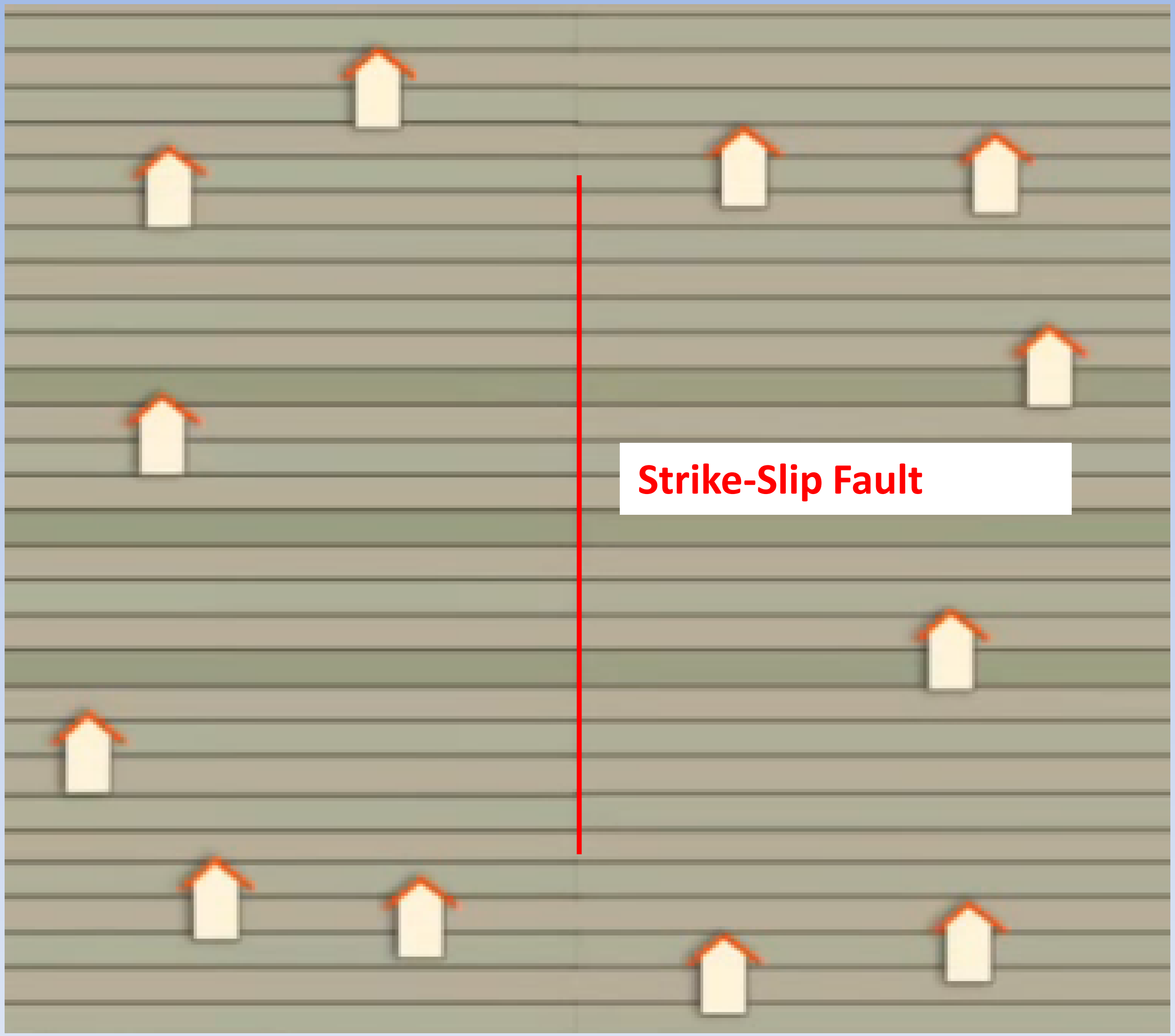
Normal stress environment in southern Kansas

Inadequate Fault Mapping

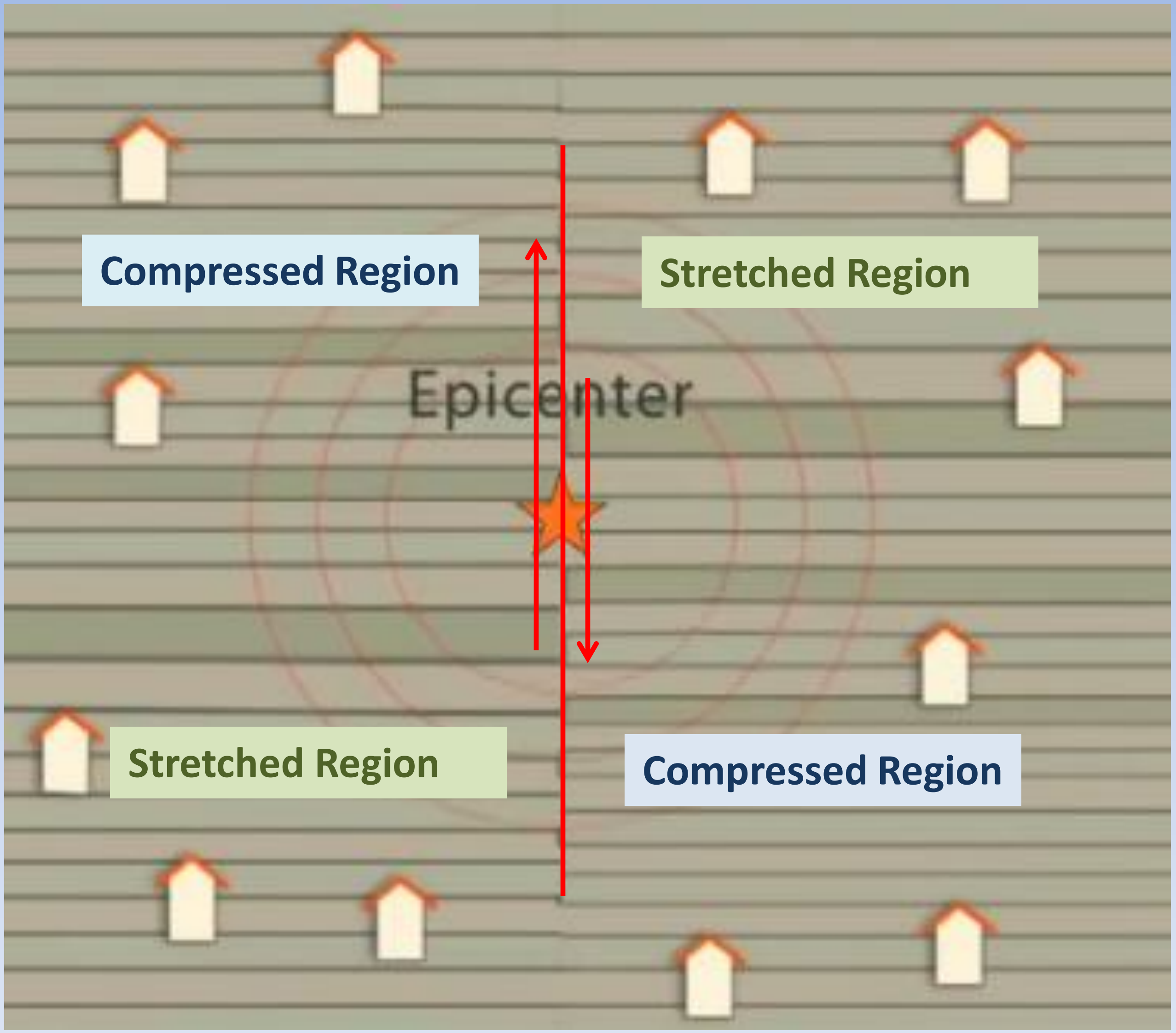


- **Faults in naturally dormant areas not adequately mapped.**

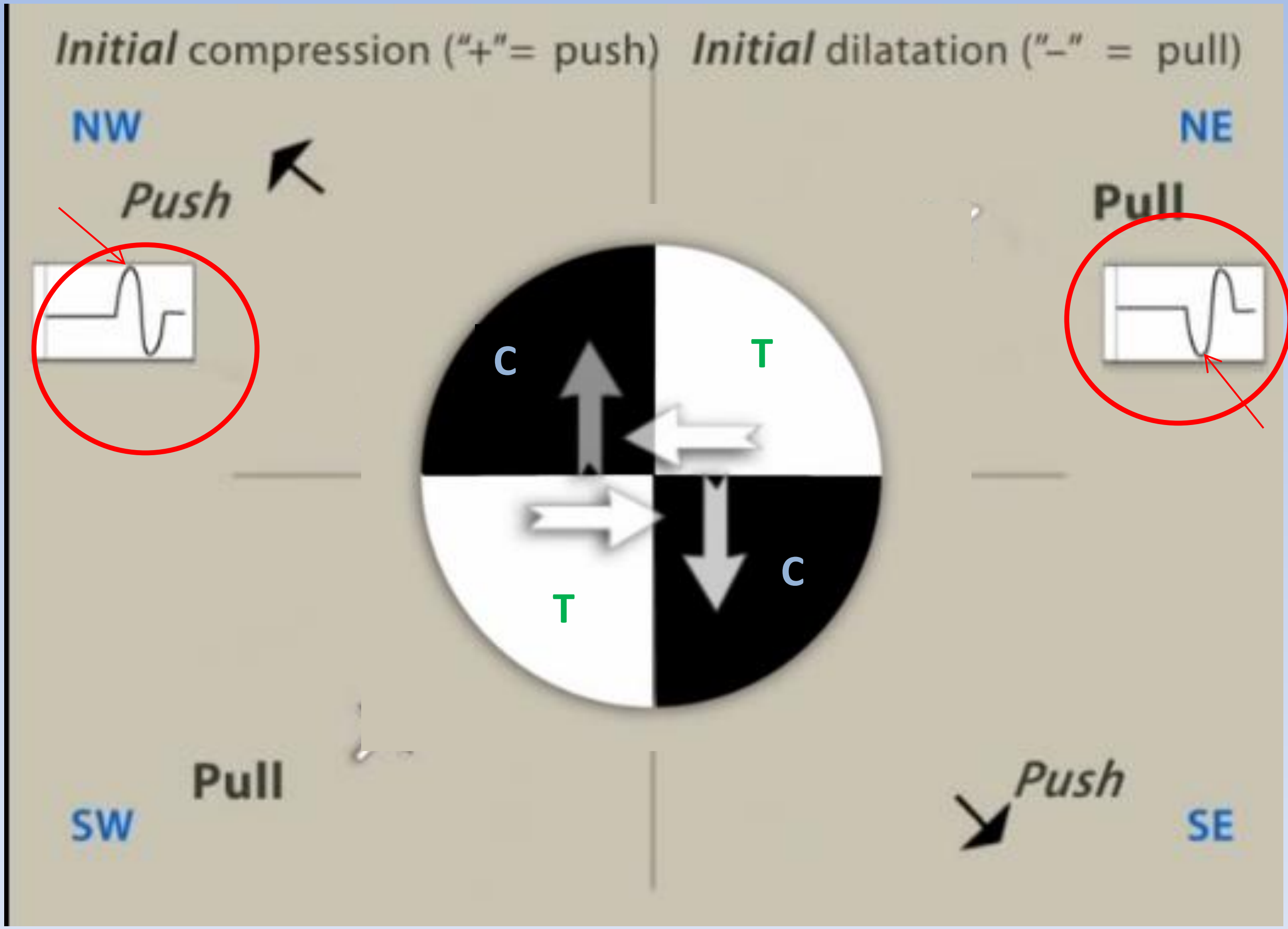
Determining Fault Type from Focal Mechanism



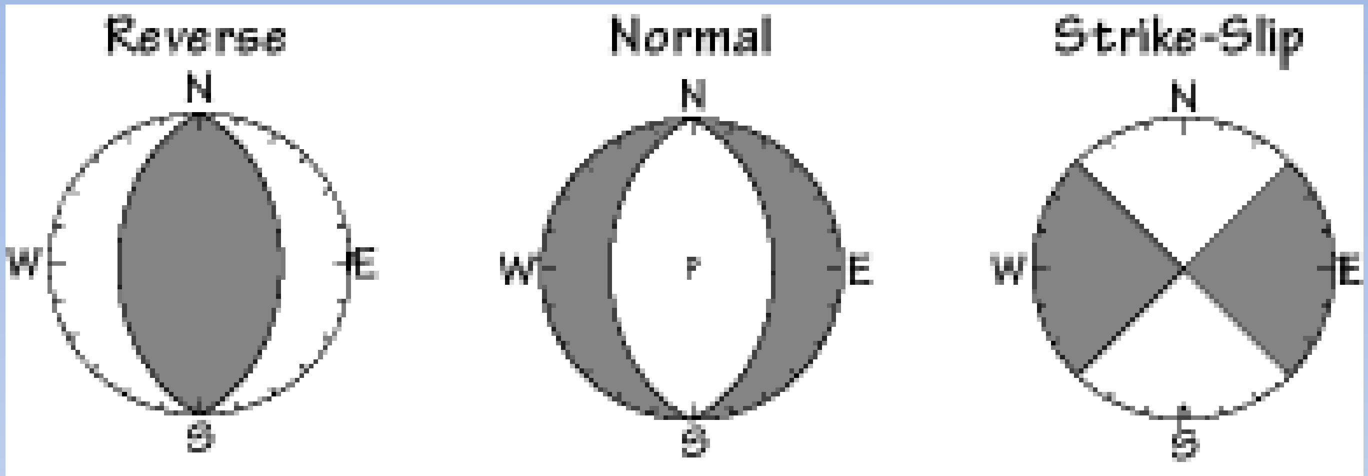
Determining Fault Type from Focal Mechanism

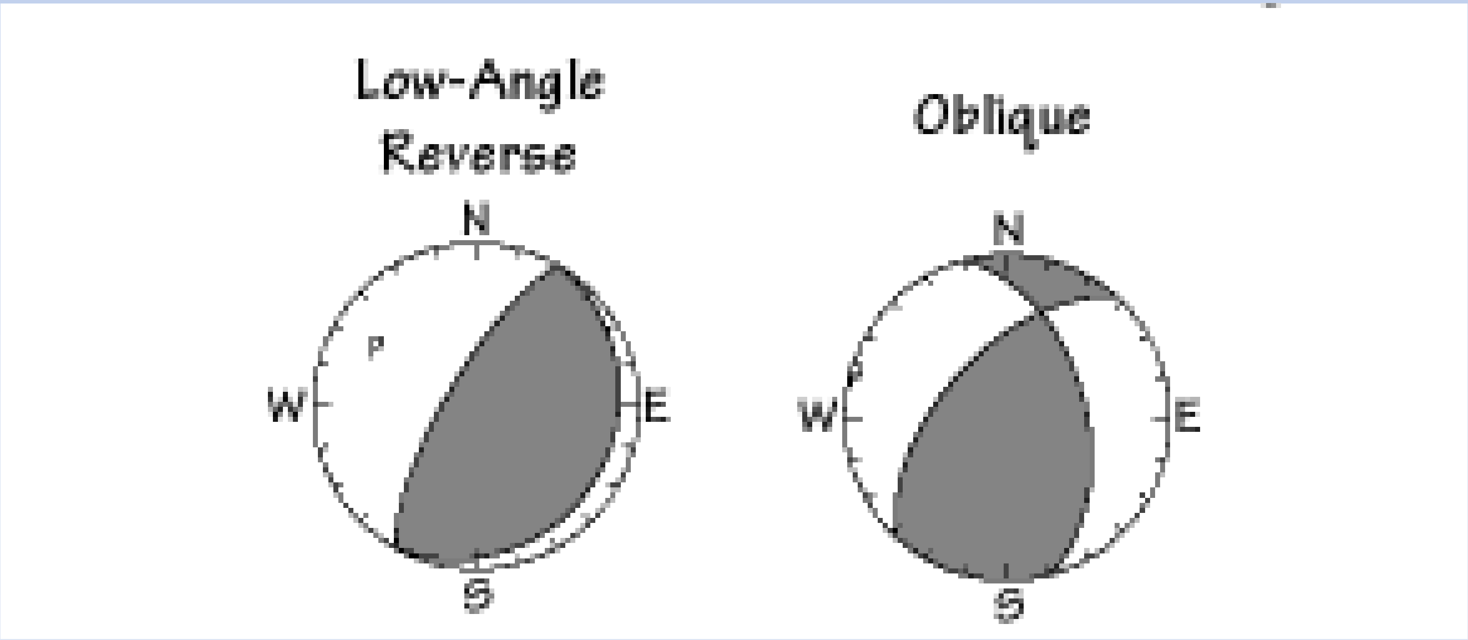


Signal Arrival Time in Compressed and Stressed Regions Assist in Determining Fault Type

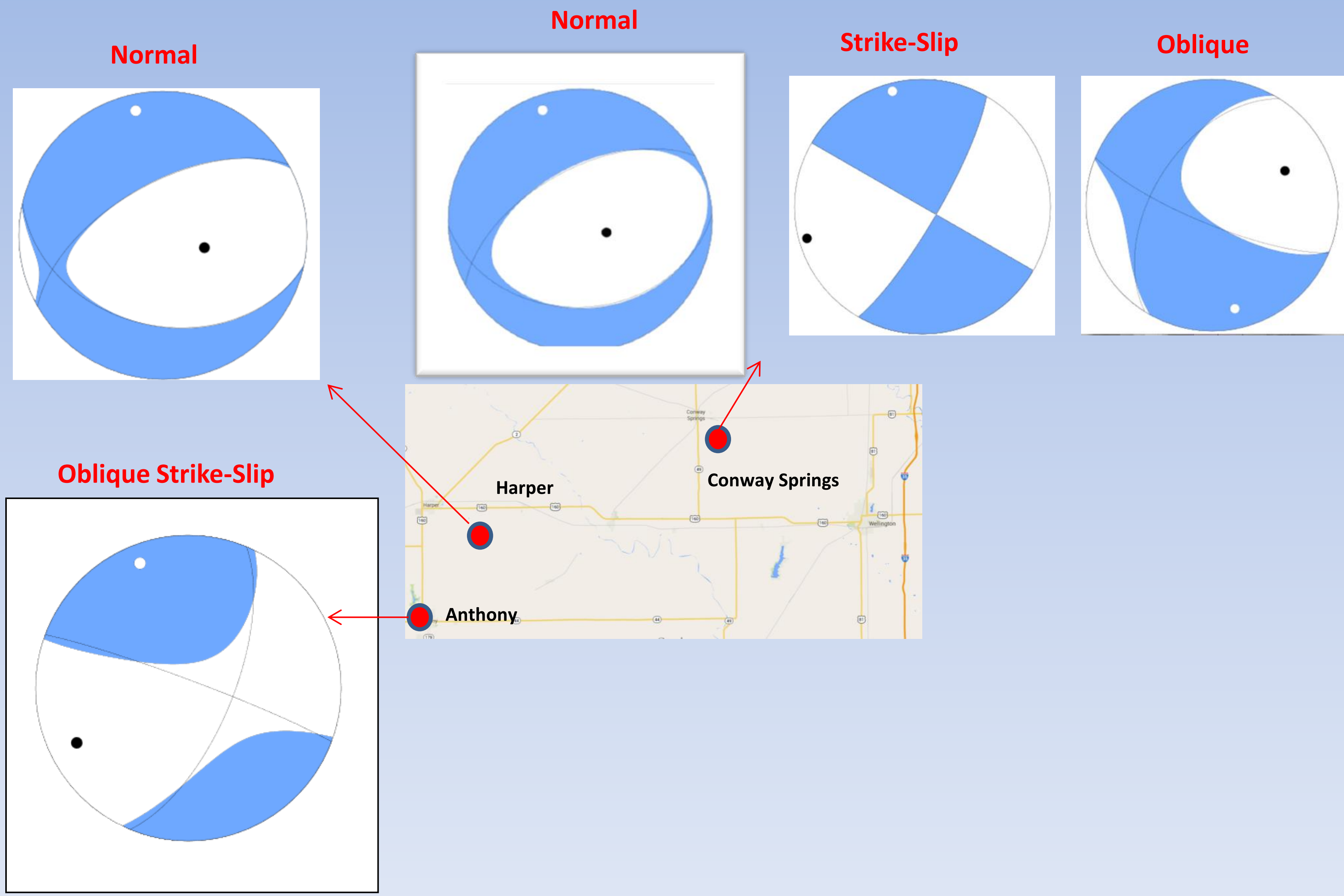


Focal Mechanism Beachballs

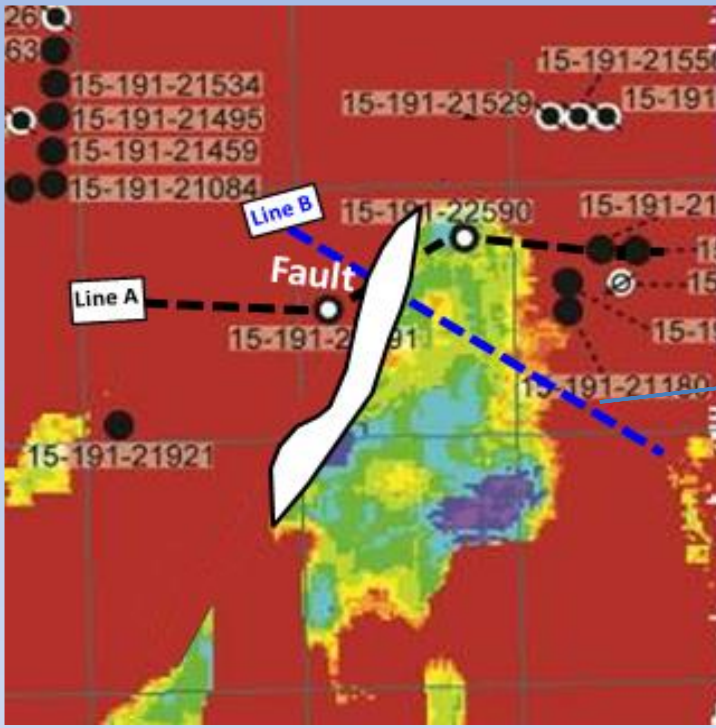




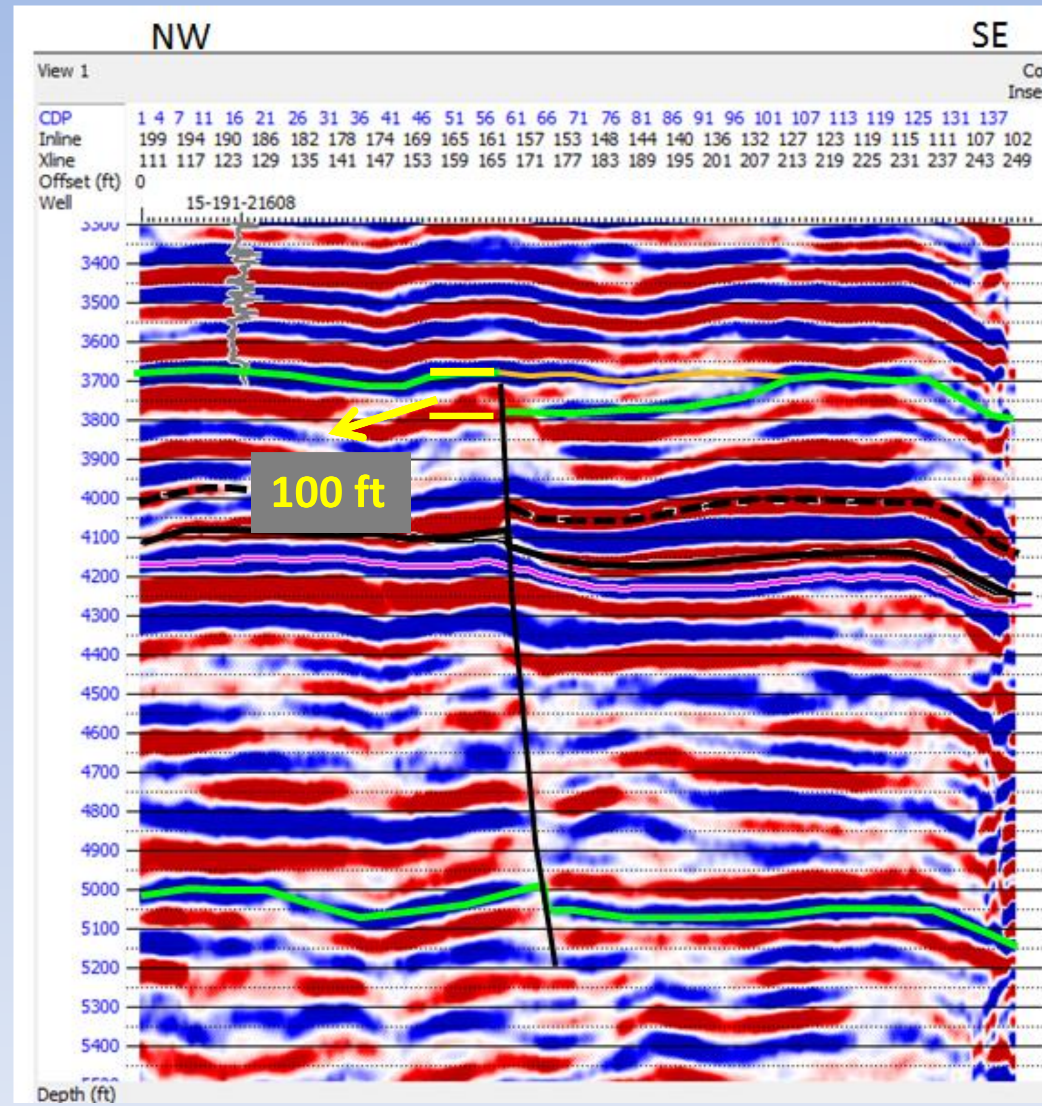
Focal Mechanism of Major Seismic Events in Kansas



Fault Identification Using Seismic Data

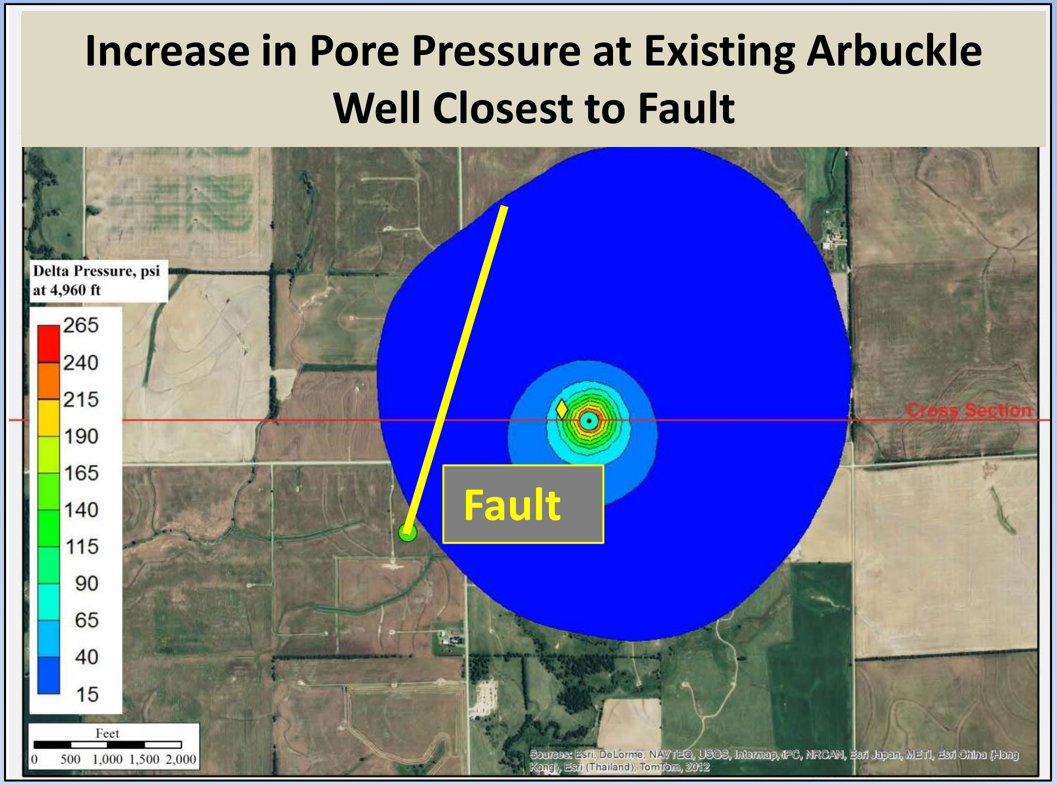


Fault Length ~ 8,000 ft

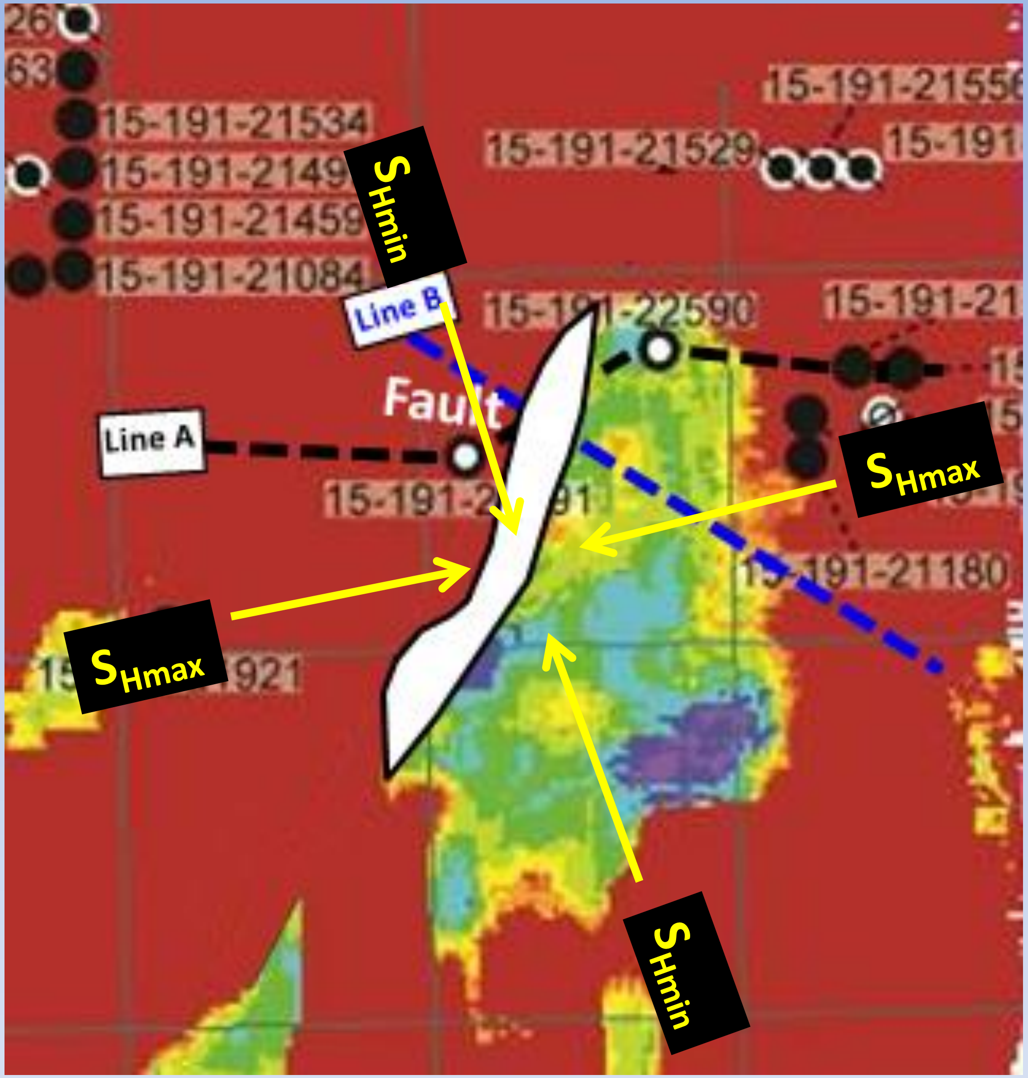


Induced Pressures in Arbuckle

- **Average induced pressure on fault ~15 psi**
- **Overburden pressure (S_{max}) ~ 5,250 psi**
- **Minimum Horizontal pressure (S_{min}) ~ 2,900 psi**

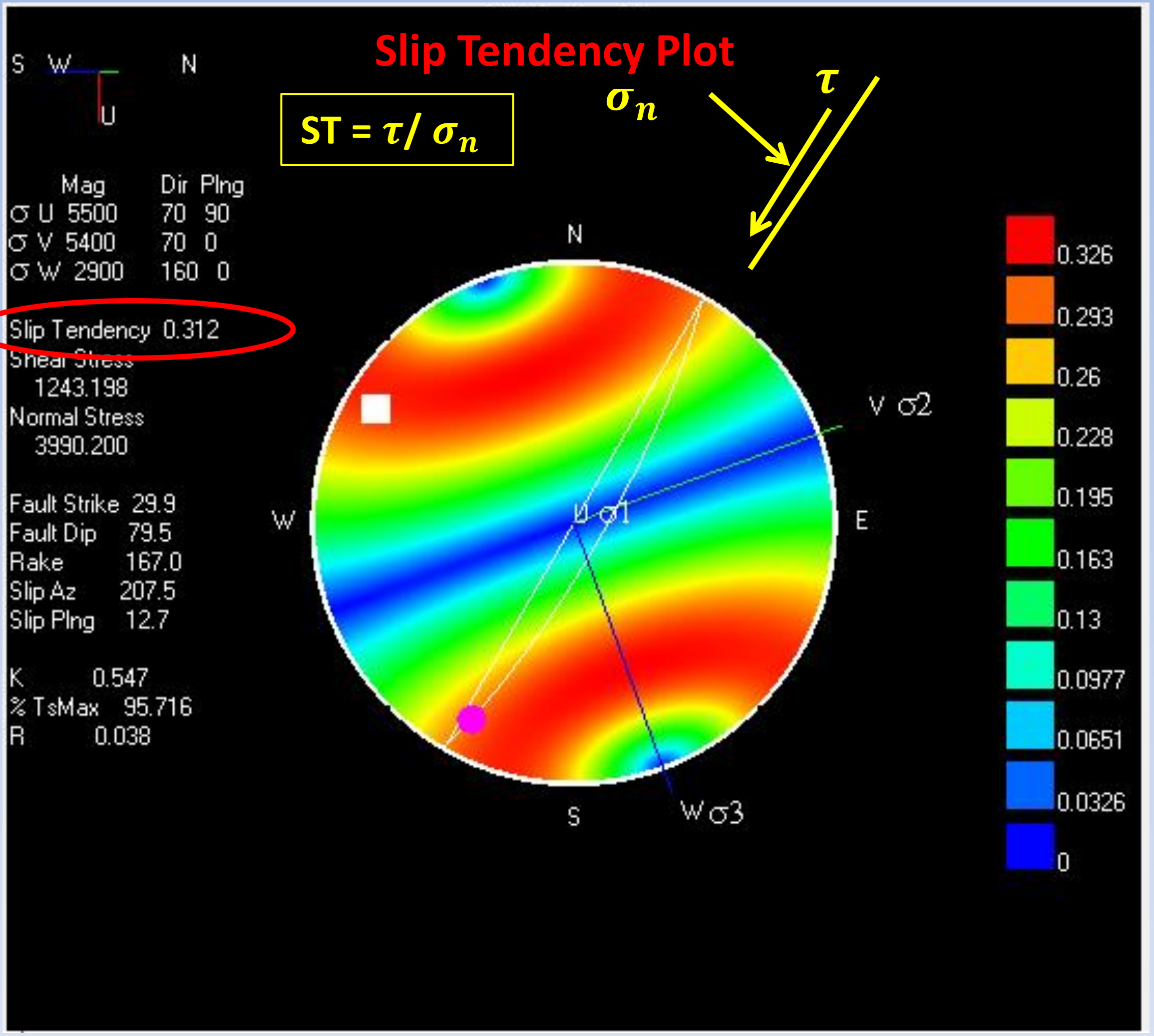


Fault Orientation and Stress Field at Site



- Fault not oriented in principal (minimum and maximum) stress planes
- 3-D analysis required

3D Stress Analysis Using SWRI 3DStress Software

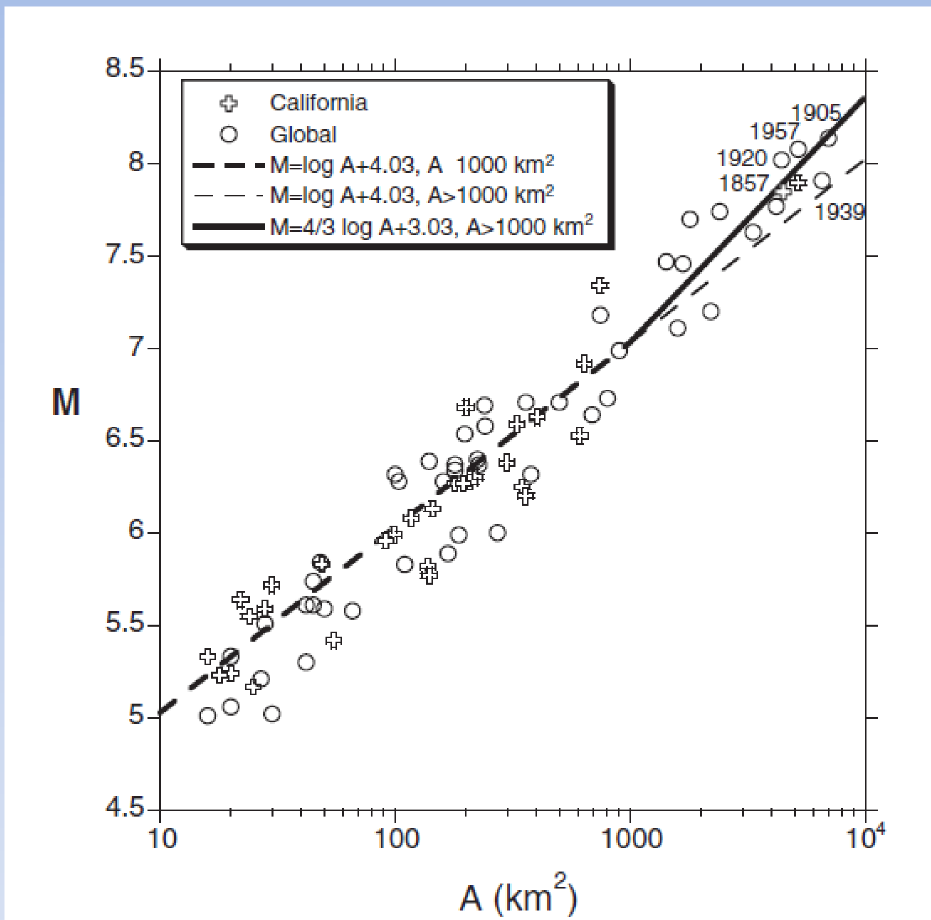


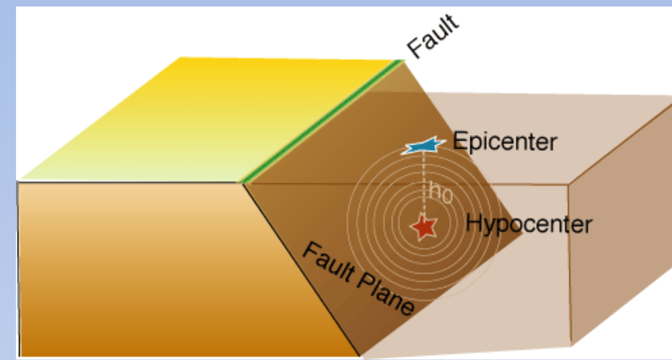
- **Slip Tendency (ST =Shear Stress/ Normal Stress)** is used to estimate potential for fault slippage
- ST= 0.3 (lower than of 0.5; typically assumed). Conducting sensitivity studies to assess Slip Tendency to key parameters

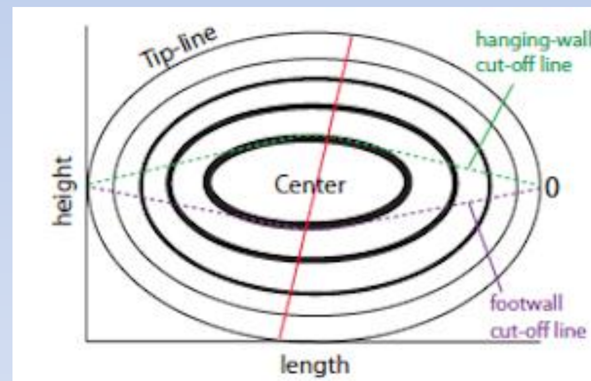
Relationship Between Earthquake Magnitude and Infrastructure Damage

Richter Magnitudes	Description	Earthquake Effects	Frequency of Occurrence
Less than 2.0	Micro	Micro-earthquakes, not felt.	About 8,000 per day
2.0-2.9	Minor	Generally not felt, but recorded.	About 1,000 per day
3.0-3.9	Minor	Often felt, but rarely causes damage.	49,000 per year (est.)
4.0-4.9	Light	Noticeable shaking of indoor items, rattling noises. Significant damage unlikely.	6,200 per year (est.)
5.0-5.9	Moderate	Can cause major damage to poorly constructed buildings over small regions. At most slight damage to well-designed buildings.	800 per year
6.0-6.9	Strong	Can be destructive in areas up to about 160 kilometres (100 mi) across in populated areas.	120 per year
7.0-7.9	Major	Can cause serious damage over larger areas.	18 per year
8.0-8.9	Great	Can cause serious damage in areas several hundred miles across.	1 per year
9.0-9.9	Great	Devastating in areas several thousand miles across.	1 per 20 years
10.0+	Epic	Never recorded; see below for equivalent seismic energy yield.	Extremely rare (Unknown)

Relationship Between Fault Plane Area and Earthquake Magnitude



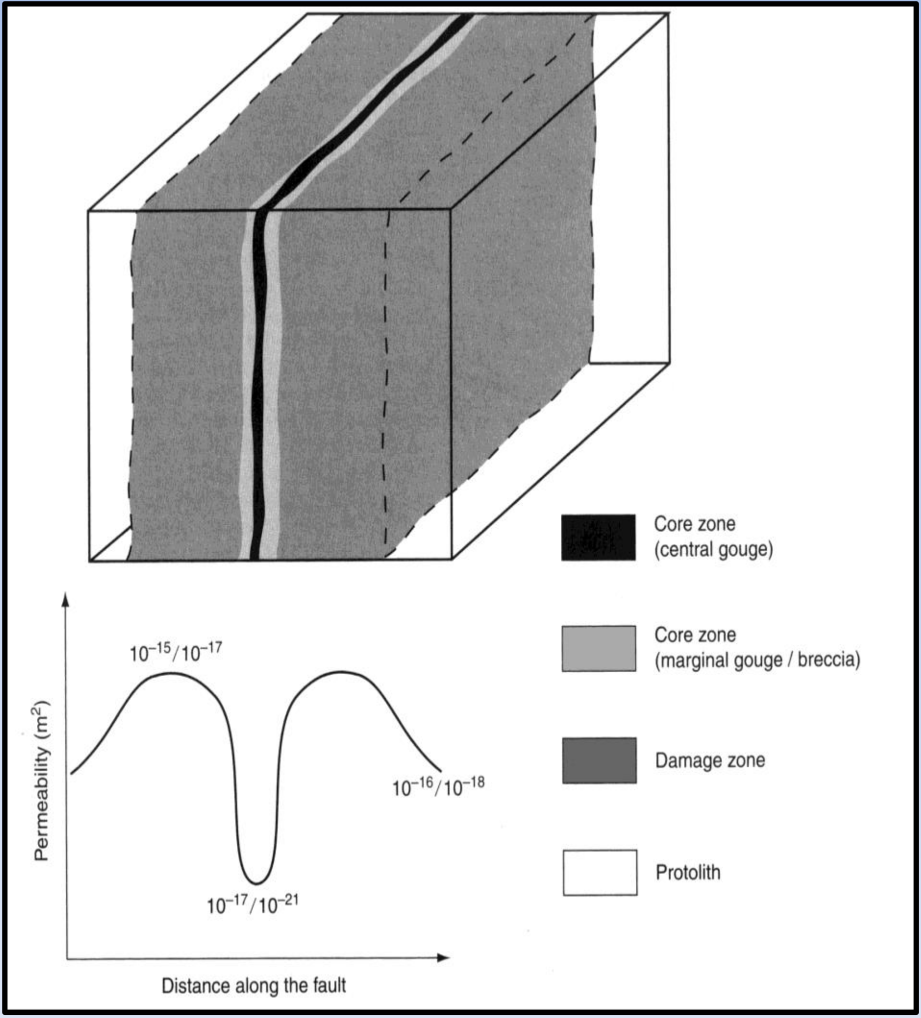




Faults are approximately as long as deep

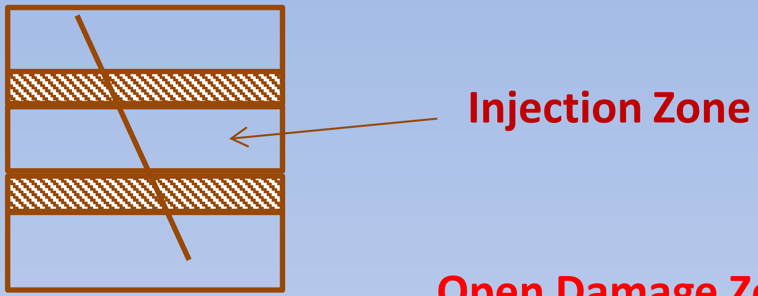
- **Faults less than 3.5 km (2.3 mi) long are not likely to cause severe damage even if they slip**
- **Fault at site is ~ 1.3 mi long – not a significant siesmic risk**

Fault Zone Architecture and Flow Properties

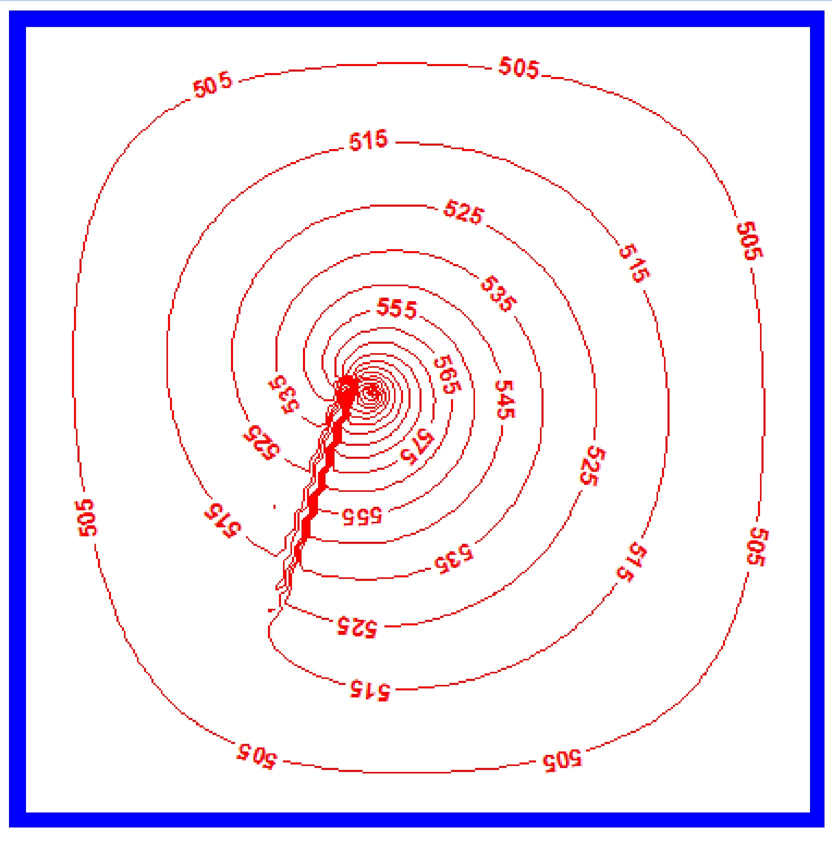


Usukidani Fault, Japan

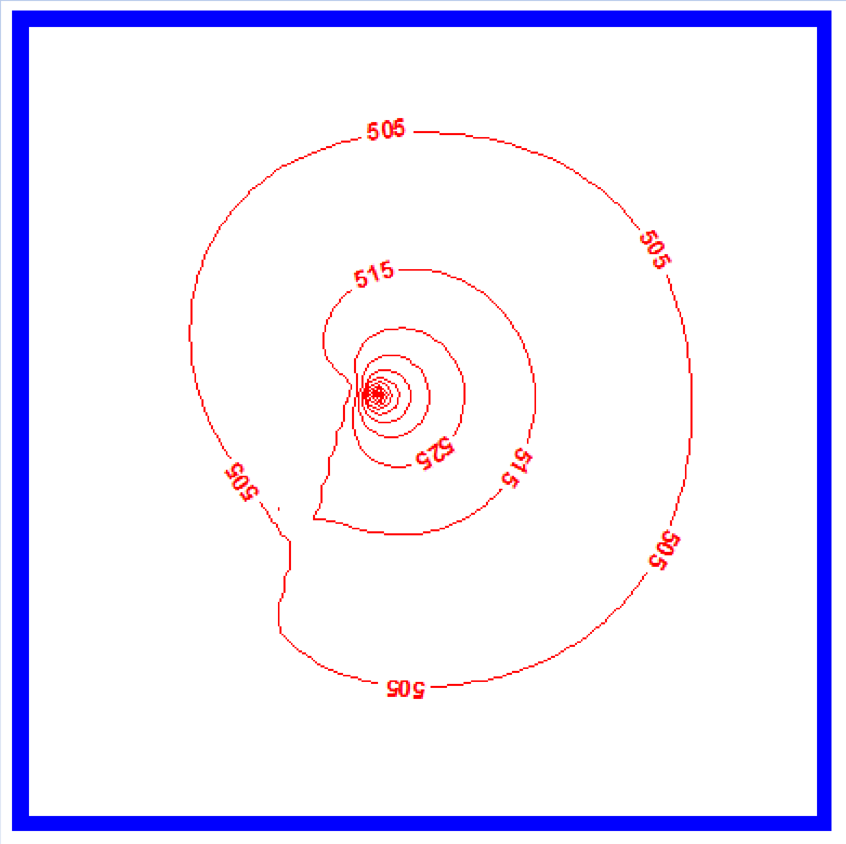
Sensitivity of Flow and Induced Pressures to Fault Zone Architecture



Healed Damage Zone
(Pressure Buildup)



Open Damage Zone
(Pressure Dissipation)



Summary

- **A combination of field tests, geophysical logs, and seismic data can be used to estimate:**
    - **Stress field and orientation**
    - **Fault types that caused earthquakes**
    - **Presence of faults**
- **The stress field and fault data can be used to determine Slip Tendency of faults**
- **Fault architecture, which influences flow properties, is necessary to properly estimate induced pressure on faults**