Assessing Induced Seismicity Risk at the Wellington Geologic Sequestration Site

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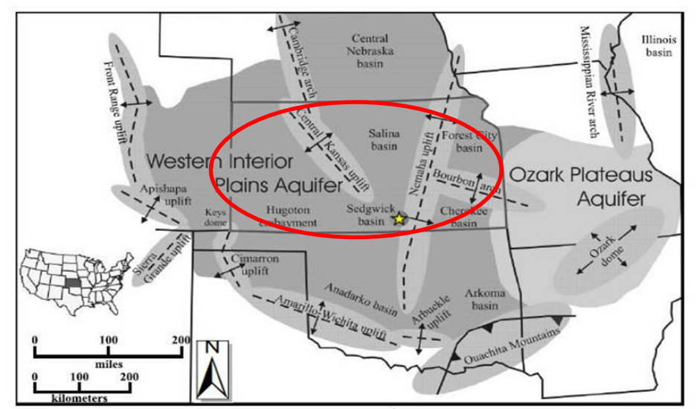
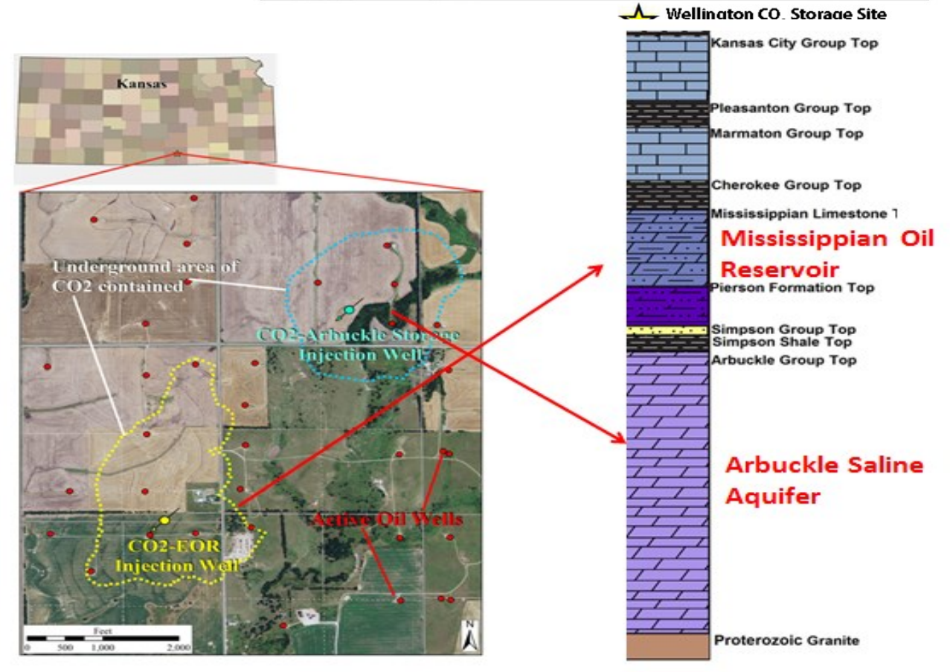
Introduction



The cambro-ordovician age Arbuckle aquifer in Kansas has been targeted for CO_2 geologic sequestration. The aquifer exists at depths exceeding 4,000 feet in the southwestern parts of the state, where it is also greater than 1,00 feet thick.

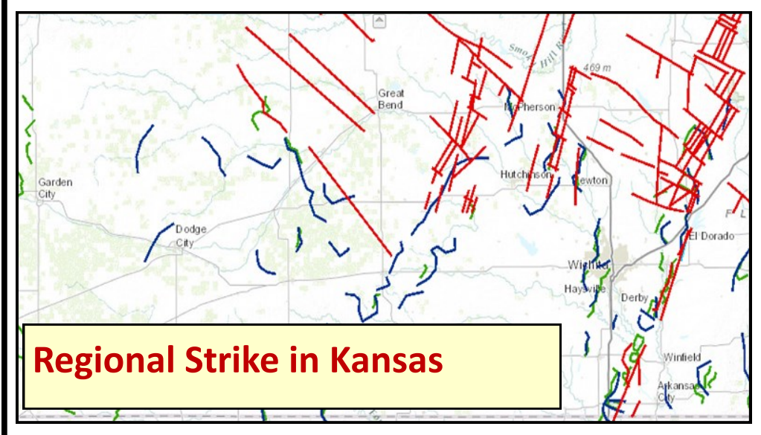


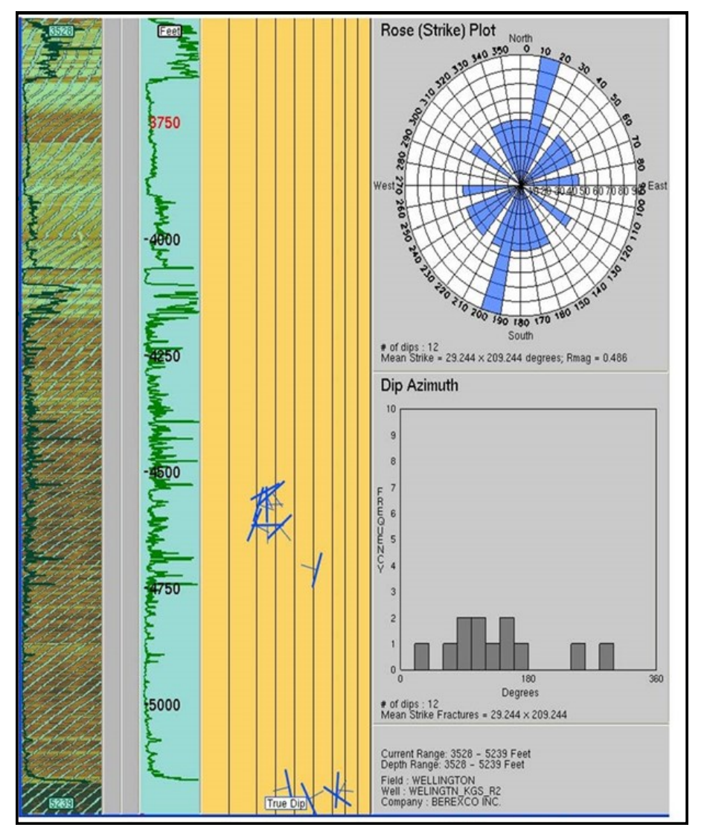
In order to test the ability of the Arbuckle to safely store CO2, a (DOE sponsored) 26 KTon pilot scale project is underway at the Wellington site in south-central Kansas. The goal of the study is to demonstrate the ability of the aquifer to safely sequester the CO2, to evaluate innovative technologies for monitoring the plume and pore pressures, and to demonstrate the ability to track the plume and pressure fronts with simulation models.

Determination of Principal Stress Directions

Historical Stress Field

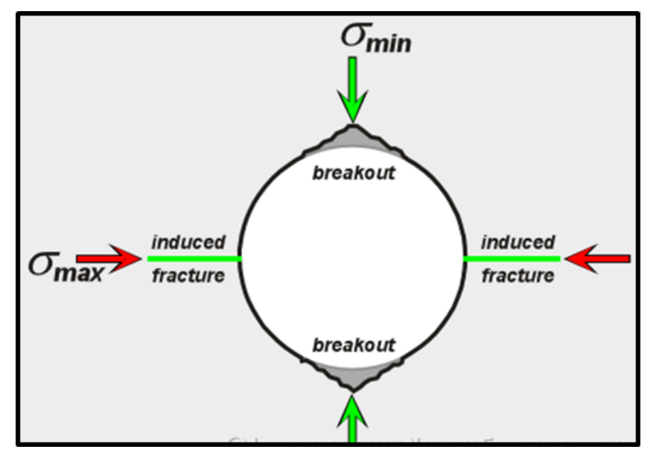
X-tended Range Micro Imager (XRMI) log acquired at the CO2 injection well along with the Rose Plot of fracture strike suggests that the dominant strike direction is north-east. This is in accordance with the regional strike map. However, we cannot infer the present-day stress field with certainty from fractures in the XRMI logs, as these fracture could be formed under an older stress field, and not reflect present-day conditions.

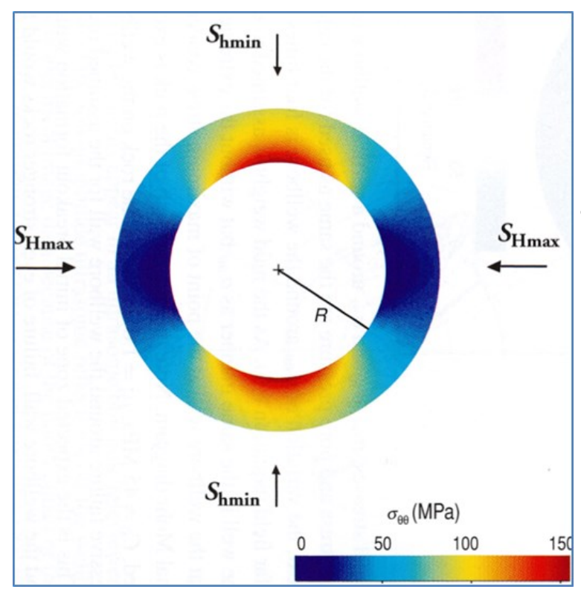




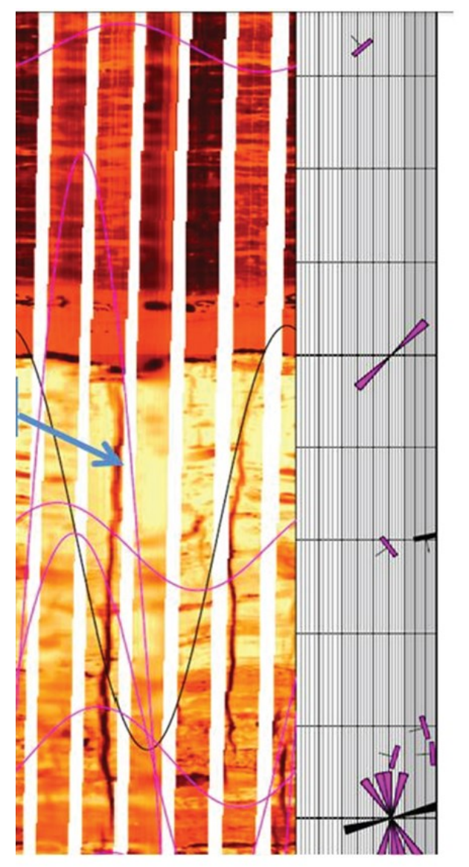
Present-Day Stress Field

The orientation of the present-day stress field however can be determined if fractures are induced during drilling. These fractures are easily identified on image logs as they occur 180 degrees apart and extend in the vertical direction. Drilling induced fractures occur when there is a sufficiently large difference in the minimum and maximum horizontal stress, which causes the tangential stress along the borehole to go into tension along the direction of the minimum horizontal principal stress direction. Since rocks have negligible tensile strength, fractures are formed along the axis of the borehole if the minimum tangential stress is close to zero.



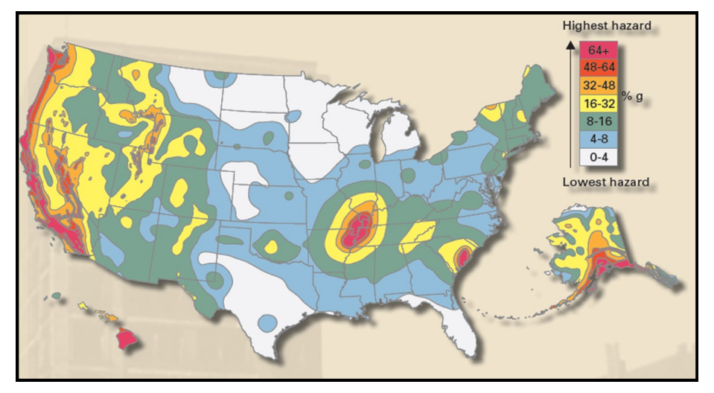


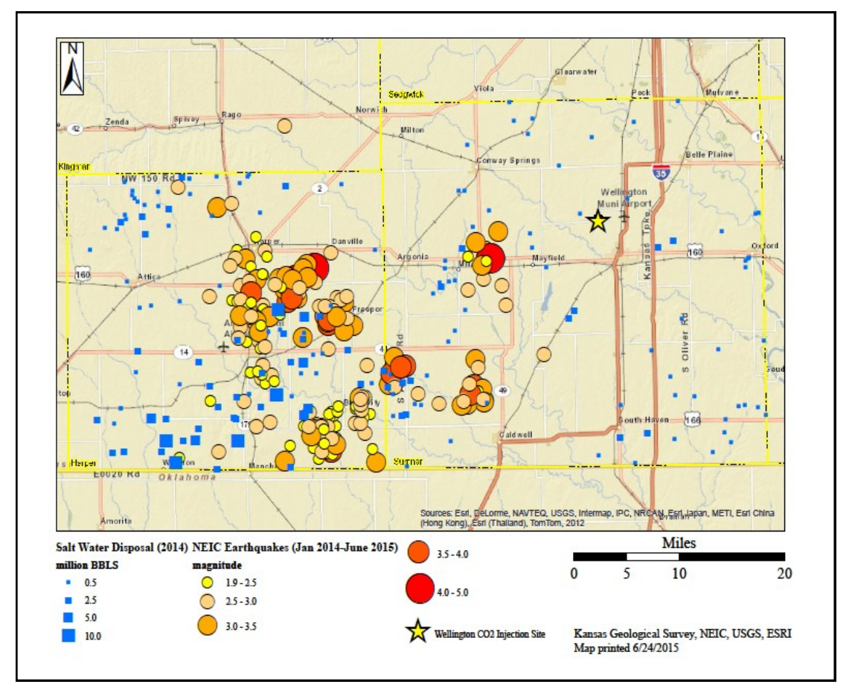
Drilling induced fractures were identified from well logs at the Wellington site (black vertical fractures). These are formed at an angle of approximately 20° E-W. Therefore, the maximum principal direction is along the EEN direction, and the minimum principal stress is in the NNW direction.

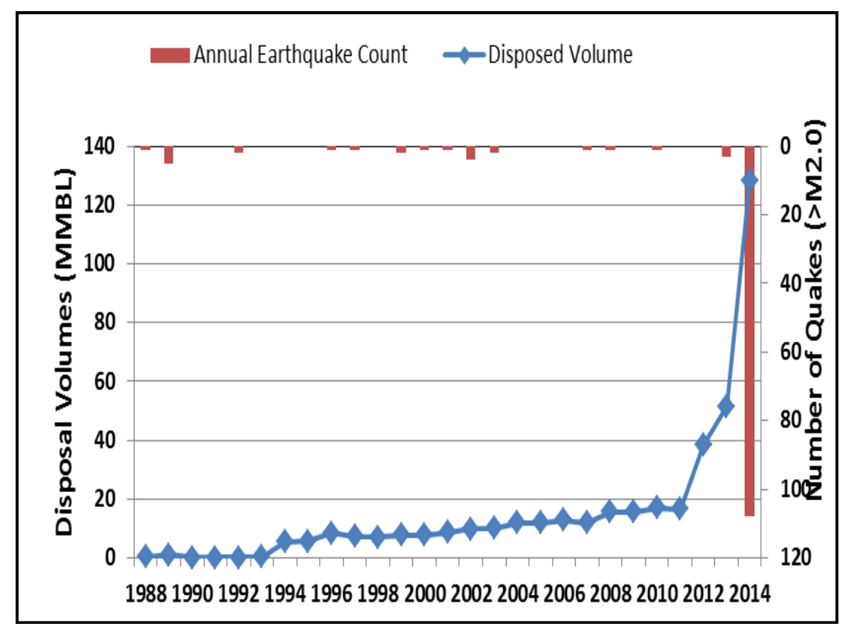


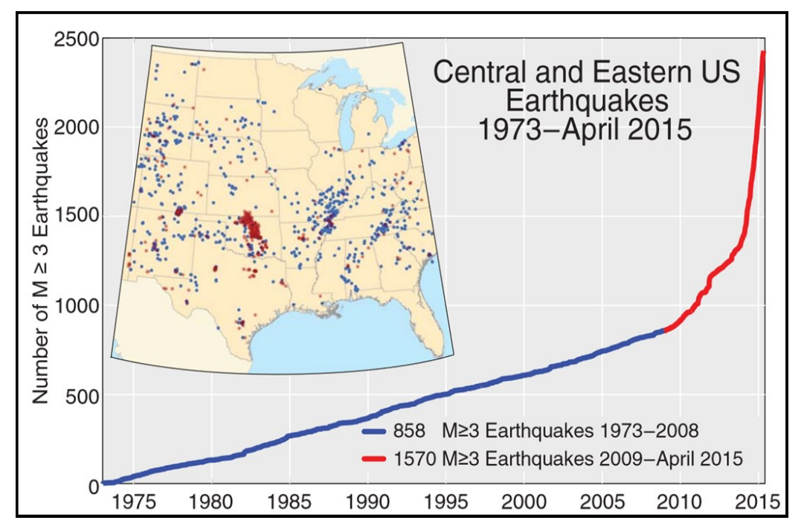
Earthquakes in Kansas

Kansas has historically resided in a seismically benign area. The state however experienced a large number of earthquakes commencing in fall 2014. These have been attributed to disposal of increasing amounts of waste disposal in the Arbuckle aquifer related to oil and gas operations in the region.

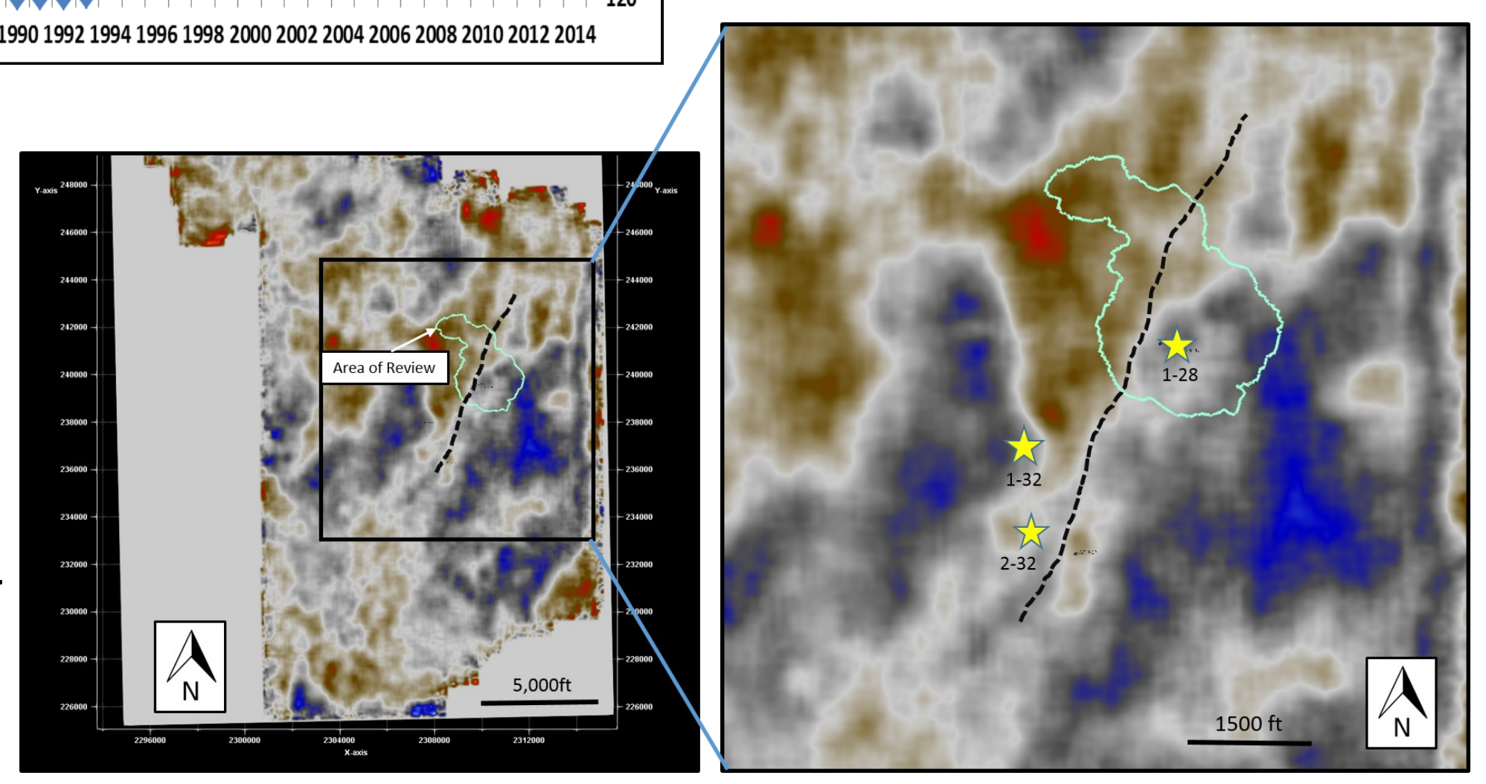








In order to proceed with CO_2 injection at the Wellington site, the US EPA, as part of the permitting process, required a demonstration that the proposed injection will not cause an earthquake. The issued gained urgency with the discovery of an 8,000 feet (2.5 km) long fault immediately west of the proposed injection well. The approach implemented to address the likelihood of inducing earthquakes at the Wellington site is described.



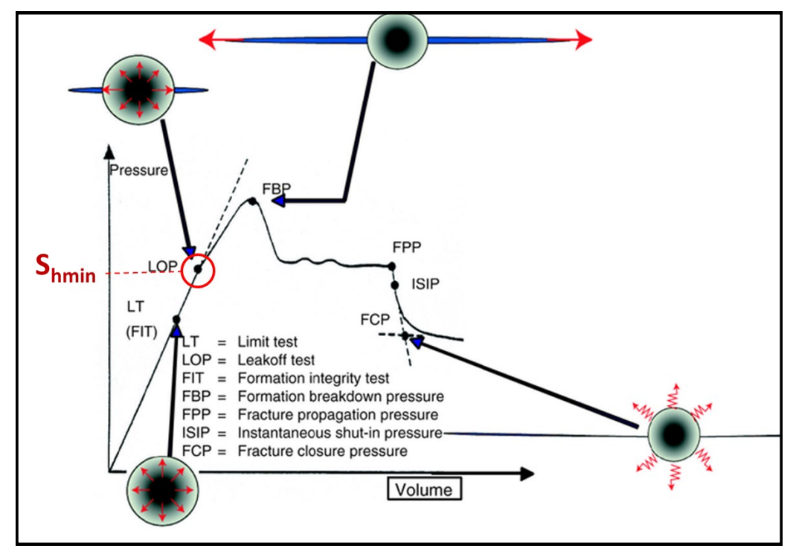
Principal Stress Magnitudes

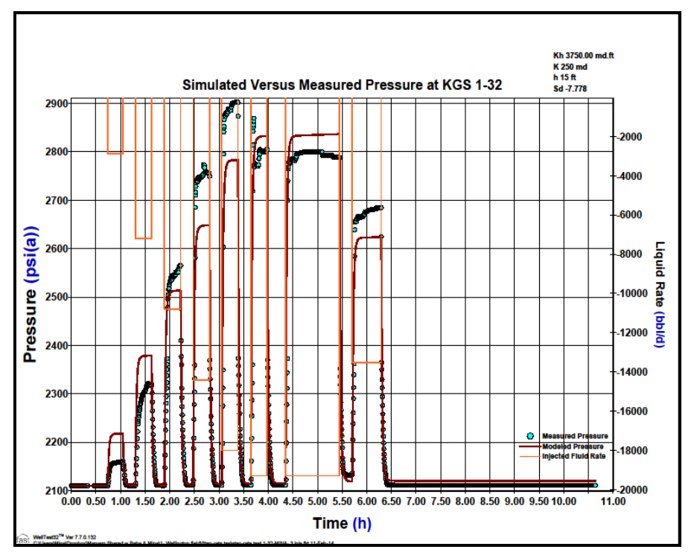
Principal Vertical Stress (S_V)

The principal vertical stress is equivalent to the weight of the rock, and is equal to 5,577 psi at the injection depth of 4,980 ft

Minimum Principal Horizontal Stress (S_{hmin})

The minimum principal horizontal stress is equivalent to the stress at the leak-off point. A pulse test, which is a variant of a leak-off test, was conducted from which a parting pressure of approximately 2,887 psi was estimated as the minimum principal stress at the proposed injection depth.





Maximum Principal Horizontal Stress (S_{hmax})

The formation of drilling induced fractures is dependent on the relative magnitude of the two principal horizontal stresses.

The minimum (tangential) hoop stress occurs in the direction of the maximum principal horizontal stress along the borehole and is given by:

$$\sigma_{\theta\theta}^{min} = 3S_{hmin} - S_{Hmax} - 2P_p - \Delta P - \sigma^{\Delta T}$$

The last two terms are associated with stresses due to mud weight and differential temperatures. Neglecting these two terms and assuming negligible tensile strength of carbonate rocks, the maximum principal horizontal stress along the borehole is given by:

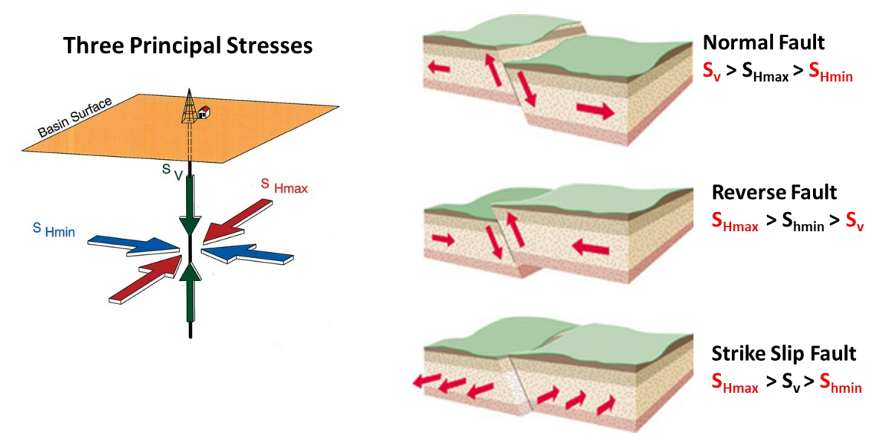
$$S_{Hmax} = 3S_{hmin} - 2P_p$$

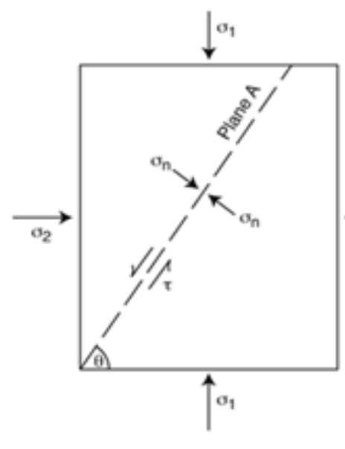
Estimated Principal Stresses at Wellington Site

Principal Stress	Magnitude (psi)
Vertical	5,577
Minimum Horizontal	2,887
Maximum Horizontal	4,501

Geomechanics of Faulting

The subsurface is subject to 3 orthogonal principal stresses. Depending on the direction of the maximum and minimum principal stresses, three different types of faults can develop.

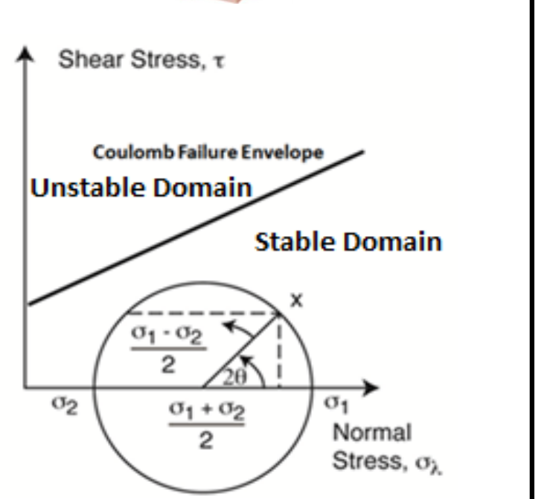




The normal stress, σ_n , and shear stresses ,τ, acting on an arbitrary fault plane at an angle, θ, and subject to the maximum and minimum compressive stresses, σ_1 and σ_2, are calculated as:

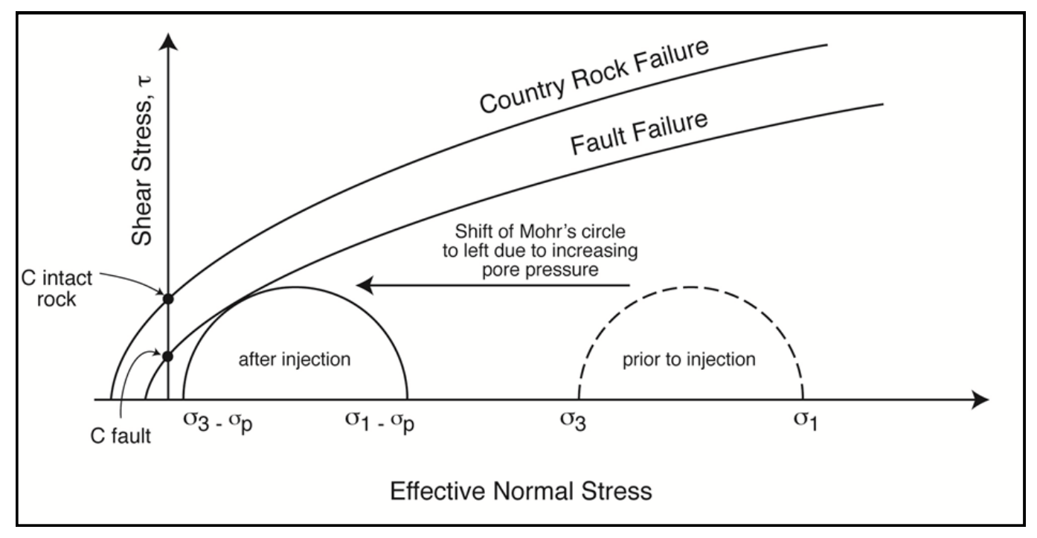
$$\sigma_n = \frac{\sigma_1 + \sigma_2}{2} + \left(\frac{\sigma_1 - \sigma_2}{2}\right)\cos 2\theta \qquad \& \qquad \tau = \frac{(\sigma_1 - \sigma_2)}{2}\sin 2\theta$$

and depicted graphically on a Mohr's Circle. The Coulomb Failure Envelope is a "strength" line representing a certain ratio of shear and normal stress at which a particular fault will slip. If the stresses acting on a fault are such that the Mohr's Circle touches the Coulomb Failure Envelope, then critically oriented faults will slip.



Increasing the fluid pressure reduces the effective normal stress and shifts the Mohr circle towards the failure envelope. The failure criterion for a fault may therefore be written in a general form as :

$$\tau_{sliding} = C_{fault} + \mu(\sigma_n - P_{fluid})$$



Information Needed to Determine Slip Potential of Wellington Fault

Fault: Length, orientation, coefficient of friction, and cohesive strength

Stress Field: The orientation and magnitude of the three Principal Stresses

Pore Pressures: Injection based pore pressure along fault

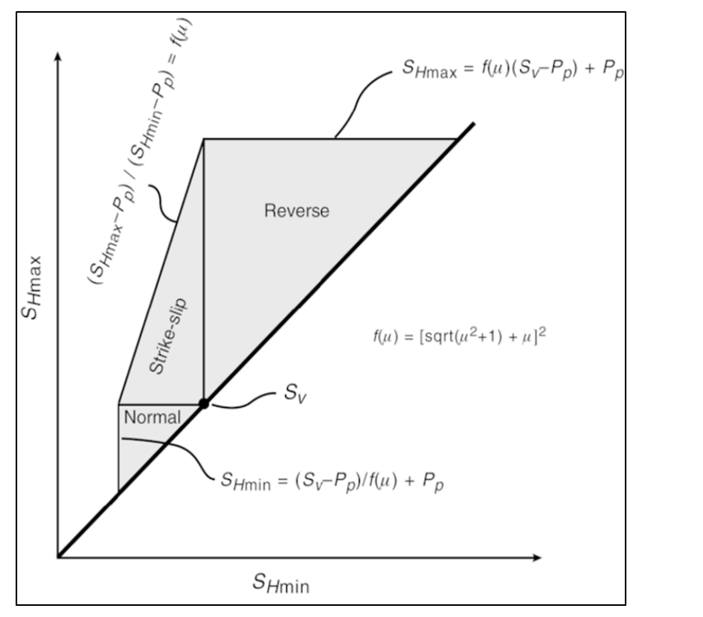
Validation of the Derived Stress Field and Faulting Environment

The derived principal stresses can be validated by ensuring that the values reside within the Stress Envelope. The stress envelope defines the failure limits and thereby provides the range of stresses (i.e., bounds) that can exist at any depth for a known or assumed coefficient of friction. The envelope is constructed by considering the following three limiting equations for each of the three faulting modes, along with the constraint that the maximum principal stress is equal to or greater than the minimum principal stress.

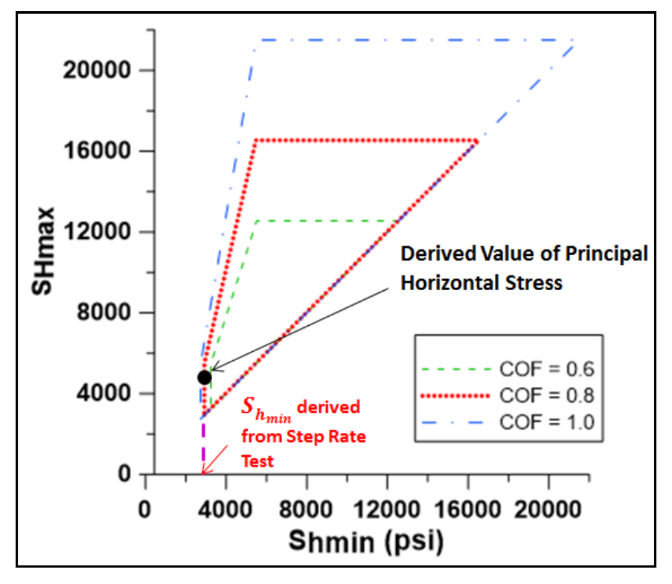
Normal Faulting Environment —> $\frac{S_v - P_p}{S_{hmin} - P_p} \le [(\mu^2 + 1)^{1/2} + \mu]^2$

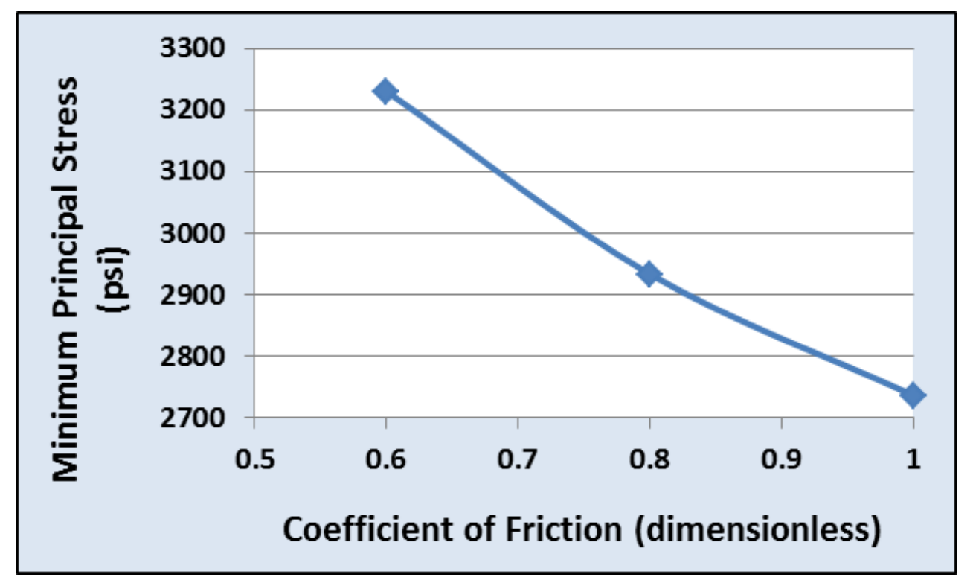
Reverse Faulting Environment —> $\frac{S_{Hmax} - P_p}{S_{hmin} - P_p} \le [(\mu^2 + 1)^{1/2} + \mu]^2$

Strike-Slip Faulting Environment —> $\frac{S_{Hmax} - P_p}{S_v - P_p} \le [(\mu^2 + 1)^{1/2} + \mu]^2$



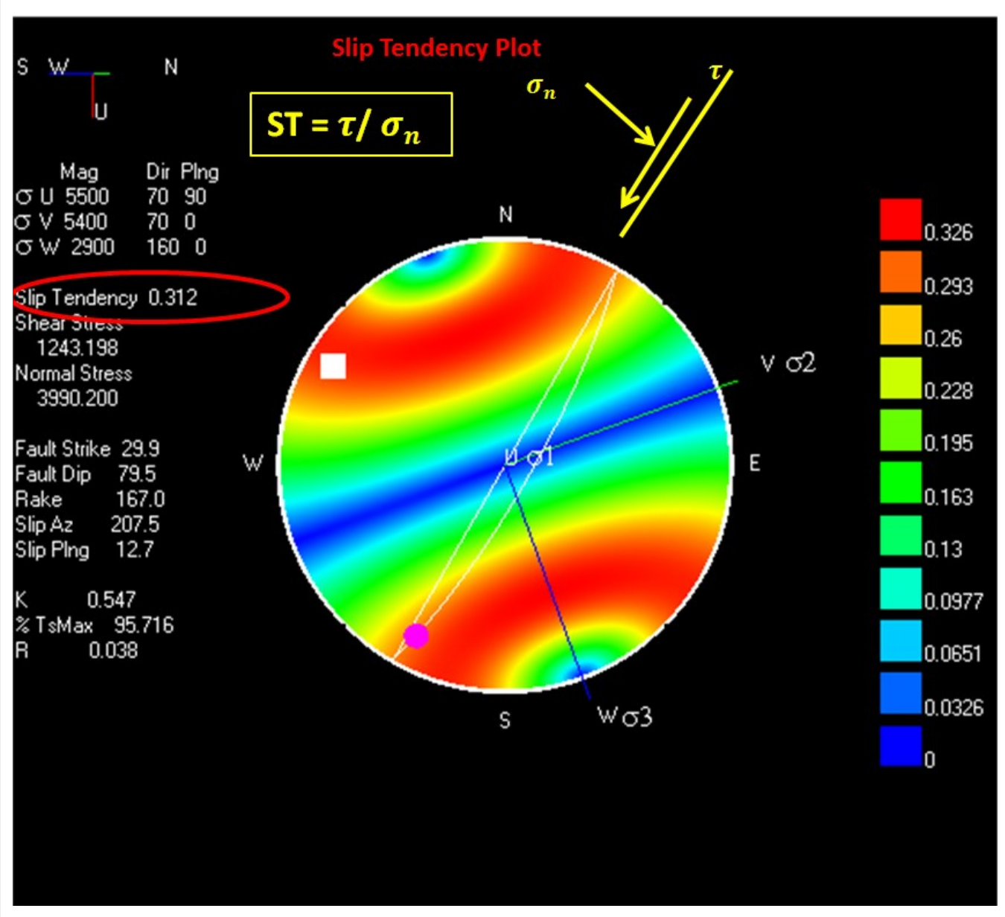
Stress Envelope at Injection Depth for Various Coefficient of Friction



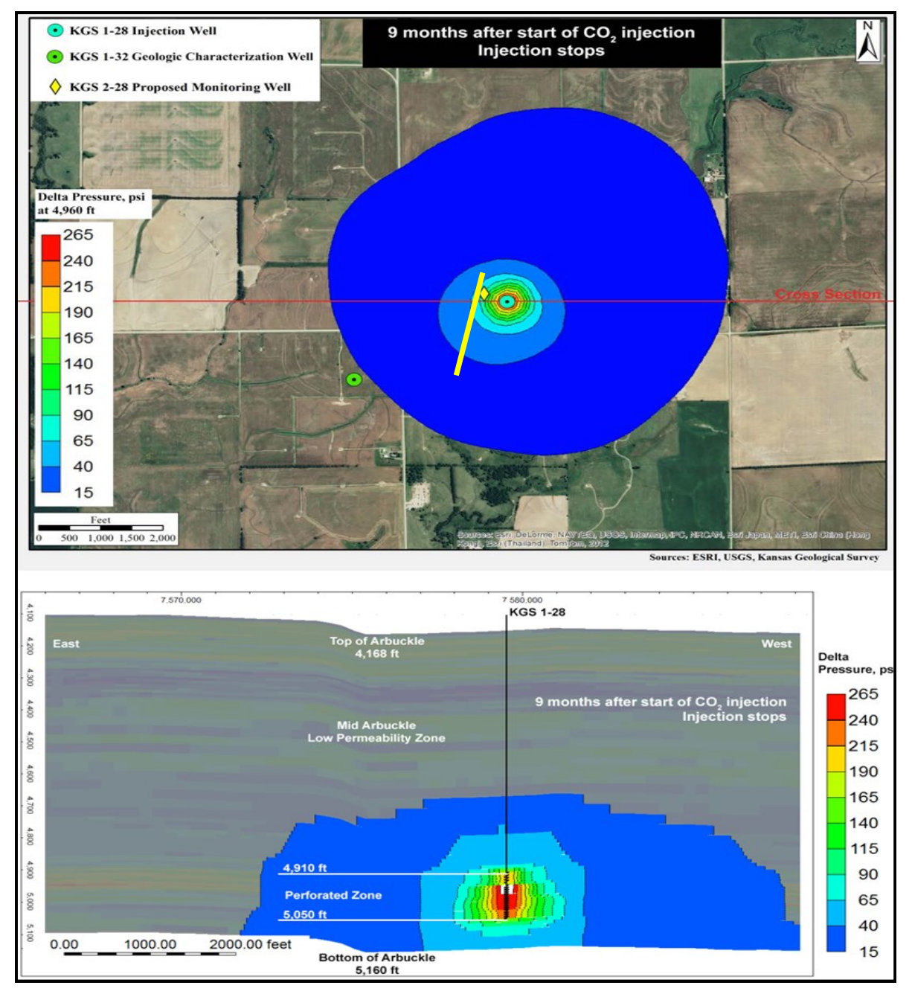


- The derived horizontal stress field lies within the stress envelope for a coefficient of friction of approximately 0.8, which is a reasonable value for dolomite rock.

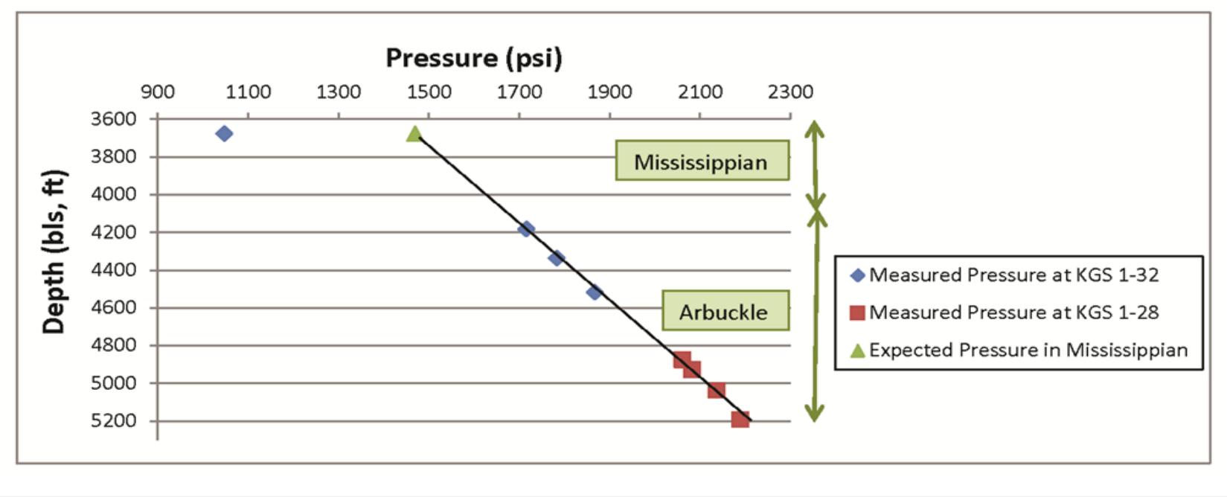
Calculating Slip Tendency



Since the fault is not oriented in the principal stress plane, it is necessary to conduct 3-D stress analysis to determine the Slip Tendency. This was accomplished using Southwest Research Institute's 3-dimensional stress analysis software 3DStress. This program determines the Slip Tendency, ST (Shear Stress/Normal Stress) of a fault given the 3D stress field and the fault strike and dip. Simulations were conducted with the CMG multiphase brine- CO_2 simulator to estimate the increase in pore pressure due to injection of 40,000 tons of CO_2 over a 9-month period The Slip Tendency stereonet for the stress tensor at Wellington is shown on the left. For the fault at Wellington, a very low Slip Tendency of 0.31 was calculated by STRESS3D. This is well below the coefficient of friction of 0.45-0.75 derived from laboratory testing of samples representing cohesionless carbonate faults. Therefore, it can be concluded that the induced stress field due to CO2 injection is insufficient to cause the fault at the Wellington site to slip.

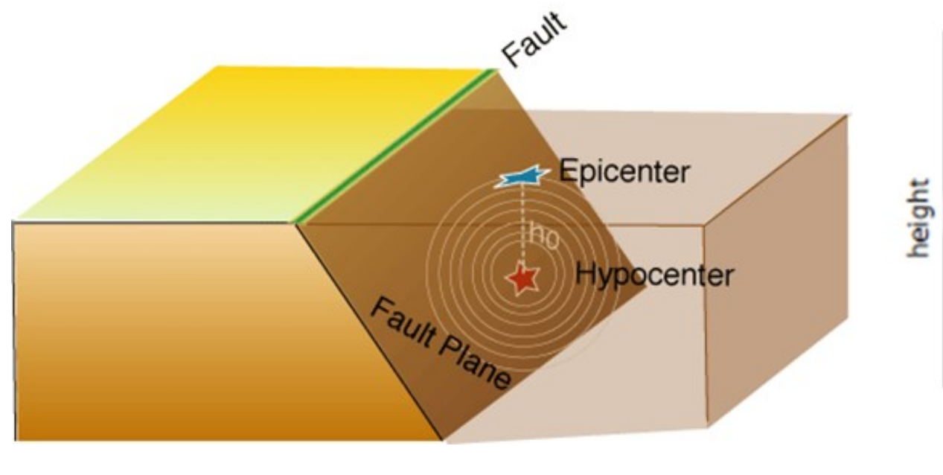


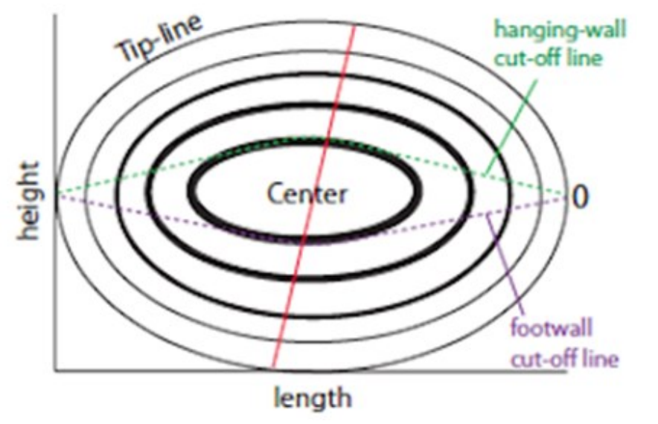
It is worth noting that the coefficient of friction for the Arbuckle dolomite derived from the stress envelope is approximately 0.8, indicating a strong rock. Also, the fault at Wellington is very likely healed because of the large pressure differential noted for the fluids in the Arbuckle aquifer and overlying Mississippian reservoir. This would suggest a dormant and healed fault at the Wellington site, which would have a high cohesive strength and coefficient of friction, more representative of country rock than an active slipping fault.

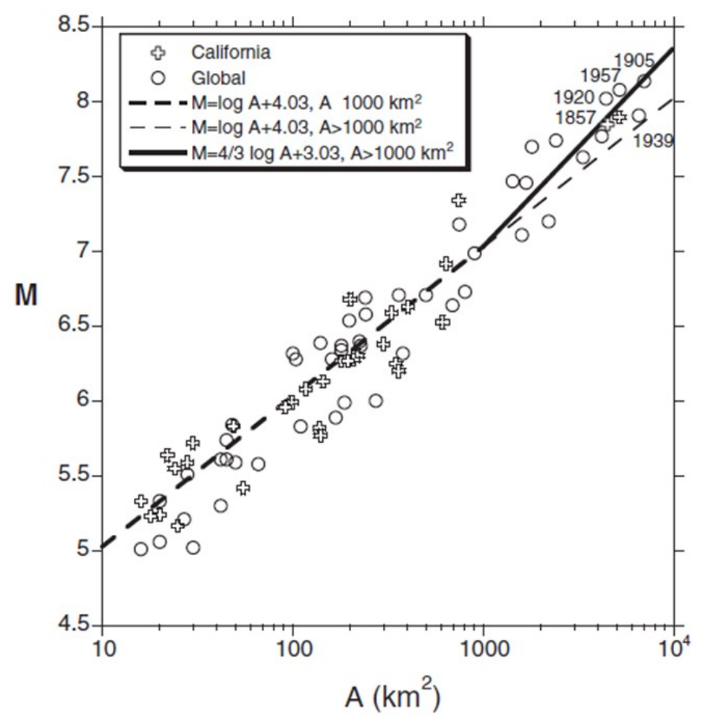


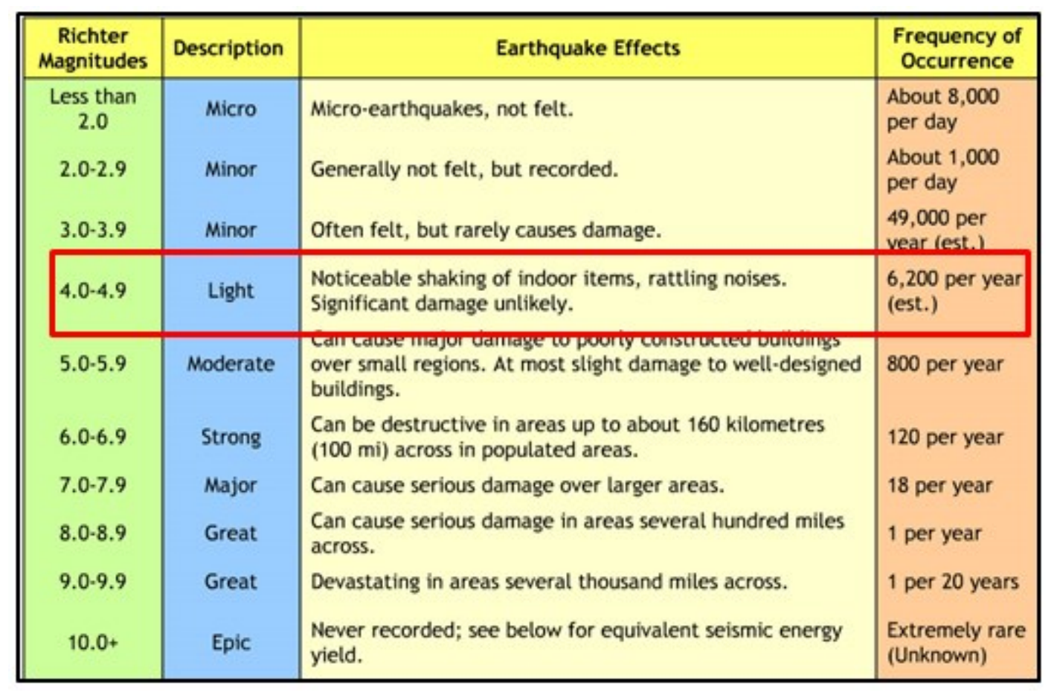
Relationship Between Fault Size and Earthquake Magnitude

While the fault at Wellington is unlikely to slip, it is worth considering the impact of slippage were it to occur. Faults are typically oval shaped, and therefore as a first approximation, it can be assumed that they are as deep as long. Therefore, for the 2.5 km long Wellington fault, the fault plane can be assumed to have a cross-sectional area of approximately 6.26 Km^2. The relationship between the fault area and the magnitude of earthquake at failure is shown in the figure below. Based on this scaling relationship, if the Wellington fault were it to slip, it could potentially cause an earthquake of maximum magnitude of approximately M4.75. As shown in the accompanying chart, an earthquake of such magnitude is unlikely to cause catastrophic 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)

Faults in the mid-continent were historically not of importance, and therefore inadequately mapped. For large scale CO_2 geologic sequestration, it may necessary however to expend effort to map faults in the mid-plain states.