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Coupled hydro-mechanical modeling of injection-induced seismicity in the multiphase flow system

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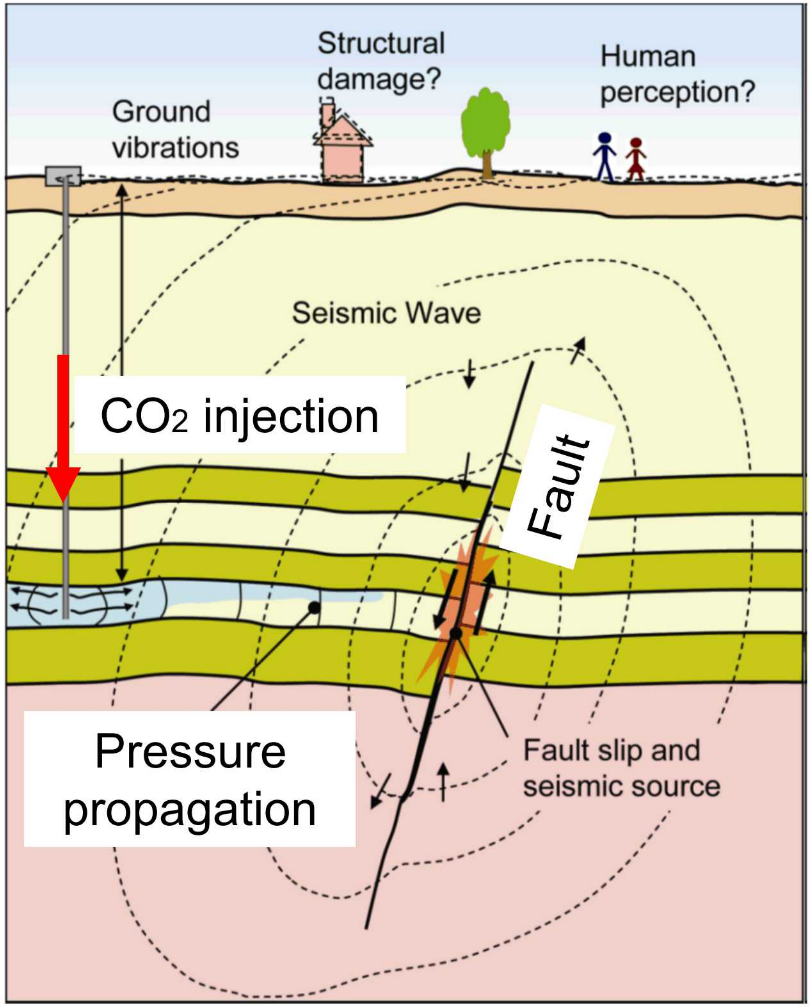
Physical mechanisms



(Rutqvist et al., 2014)

1. Pressure propagation

- Stress perturbation along the fault

Poroelastic coupling

2. CO_2 plume migration

- CO_2-accumulation along or -penetration into the fault

Multiphase flow system

Governing equations

- Two-phase flow in a capillary porous medium

$$\frac{\partial(\rho_w \phi S_w)}{\partial \mathrm{t}} = \nabla \cdot \left[\rho_w \frac{k k_{rw}}{\mu_w} (\nabla p_w - \rho_w \mathrm{g})\right] + Q_w$$

$$\frac{\partial\left(\rho_g \phi S_g\right)}{\partial \mathrm{t}} = \nabla \cdot \left[\rho_g \frac{k k_{rg}}{\mu_g} \left(\nabla \mathrm{p_w} + \nabla p_c - \rho_g \mathrm{g}\right)\right] + Q_g$$

- Relative permeability (k_{ri}) and capillary pressure (p_c) are defined by the van Genuchten functions.

Governing equations

- Two-phase flow in a capillary porous medium

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- Quasi-static linear momentum

$$\nabla \cdot \sigma + \rho \mathrm{g} = 0$$

- Effective stress in fluid-saturated porous media

$$\sigma^{eff} = \sigma + \alpha \mathrm{I} p$$

p = Saturation-weighted average of the phase pressures

- Stress-strain constitutive model

$$\sigma^{eff} = \lambda\, trace(\epsilon)\mathbf{I} + 2G\epsilon$$

Governing equations

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- Two-phase flow in a capillary porous medium

$$\frac{\partial(\rho_w \phi S_w)}{\partial \mathrm{t}} = \nabla \cdot \left[\rho_w \frac{k k_{rw}}{\mu_w} (\nabla p_w - \rho_w \mathrm{g})\right] + Q_w$$

$$\frac{\partial(\rho_g \phi S_g)}{\partial \mathrm{t}} = \nabla \cdot \left[\rho_g \frac{k k_{rg}}{\mu_g} (\nabla \mathrm{p_w} + \nabla p_c - \rho_g \mathrm{g})\right] + Q_g$$

- Stress equilibrium

$$\nabla \cdot [G \nabla u] + \nabla \left[\frac{G}{1 - 2\nu}\right] \nabla \cdot u - \alpha \nabla p + f = 0$$

p = Saturation-weighted average of the phase pressures

Pore pressure change ⇄ Rock deformation

Coulomb stress change

$$\Delta\tau = \Delta\tau_s + f\underbrace{(\Delta\sigma_n + \Delta p)}_{\text{Effective stress}}$$

(+) for tension

Effective stress

$\Delta\tau_s$ = shear stress change

$\Delta\sigma_n$ = normal stress change

Δp = pore pressure change

f = failure friction coefficient

- (+) values of each quantity imply that the fault plane is moved closer to failure

Coulomb stress change

$$\Delta\tau = (\Delta\tau_s + f\Delta\sigma_n) + f\Delta p$$

(+) for tension

Poroelastic stress — $(\Delta\tau_s + f\Delta\sigma_n)$

Pore pressure — $f\Delta p$

$\Delta\tau_s$ = shear stress change

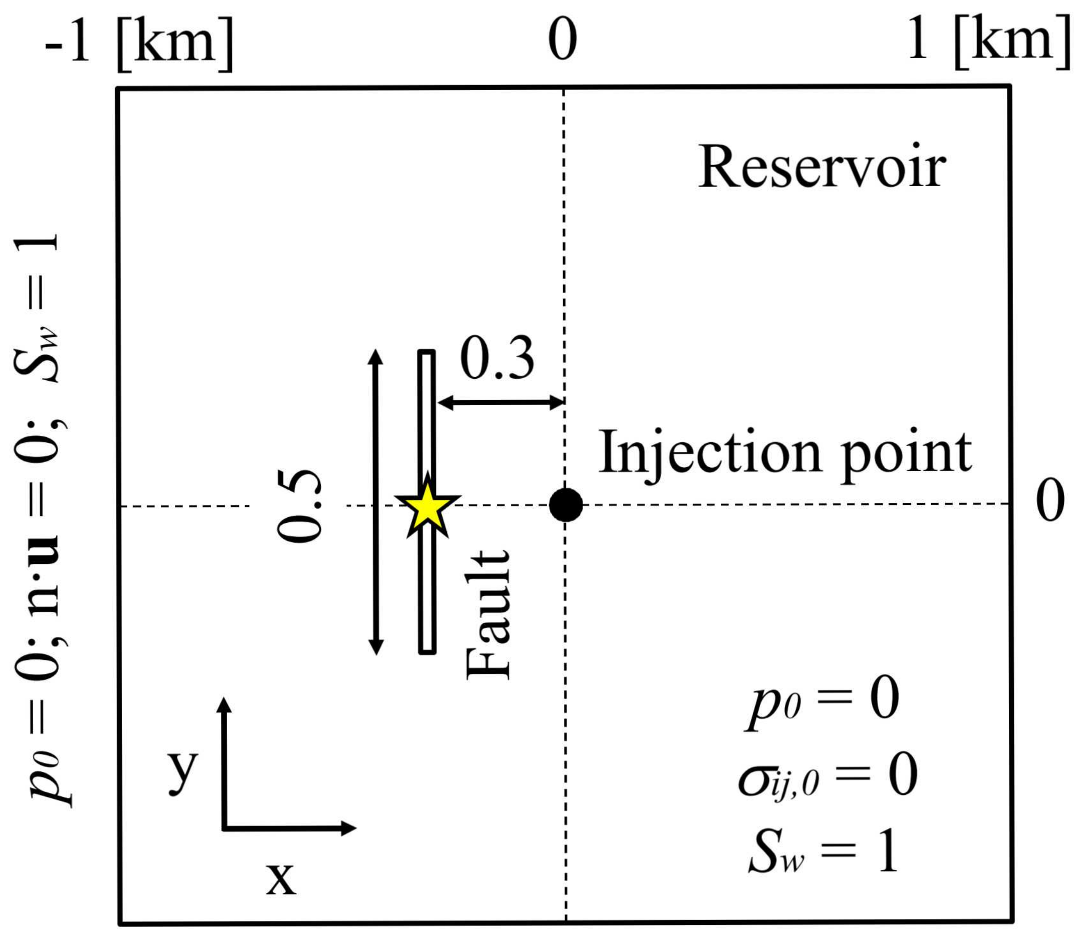
$\Delta\sigma_n$ = normal stress change

Δp = pore pressure change

f = failure friction coefficient

- In the uncoupled system, poroelastic stress term goes to zero (neglecting mechanical behaviors)

Model scheme

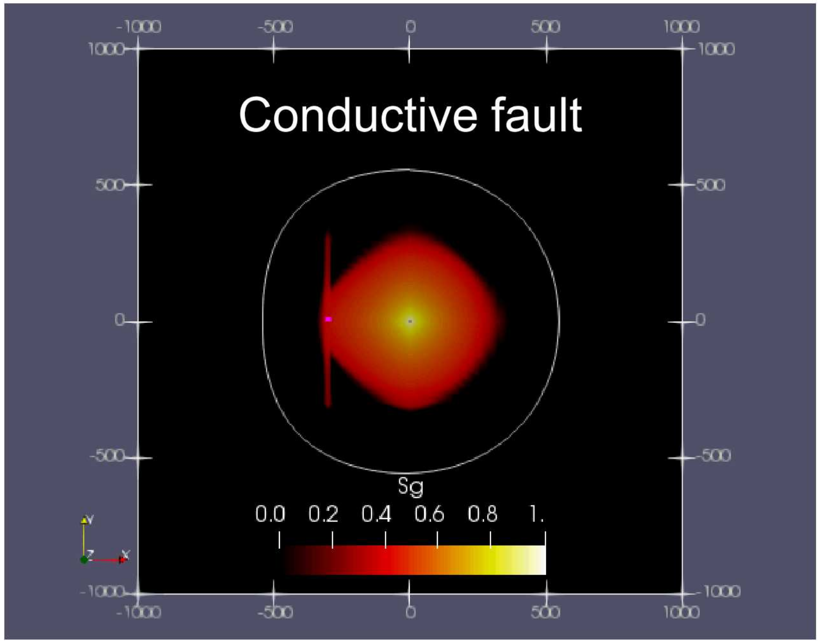


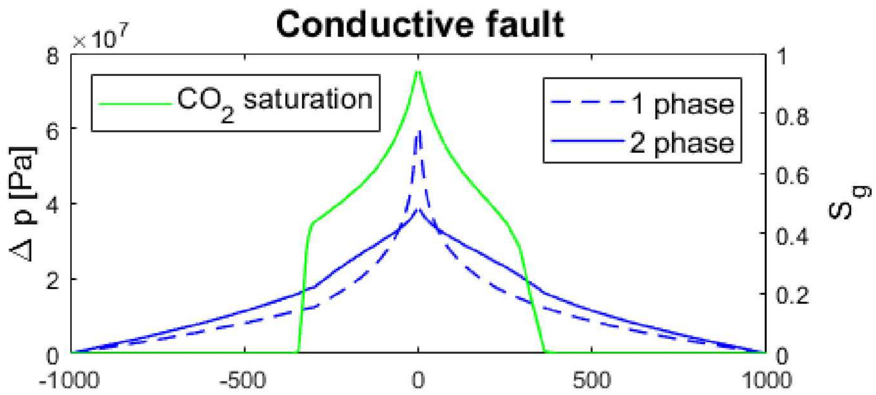
- 2-D aerial view
- Immiscible brine-CO_2 flow system
- Injection for 25 years with the rate of 0.1 [kg/m/s]
- Comparative studies
  - Conductive vs. sealing

$$k_{f,cond} = 1 \times 10^{-12}\ m^2$$
$$k_{f,seal} = 1 \times 10^{-21}\ m^2$$

  - Single- vs. two-phase

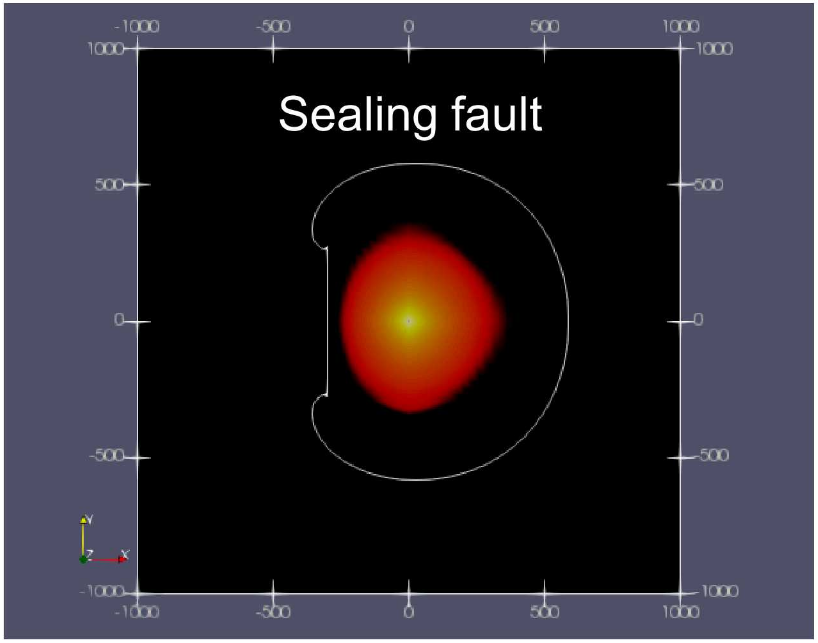
Results

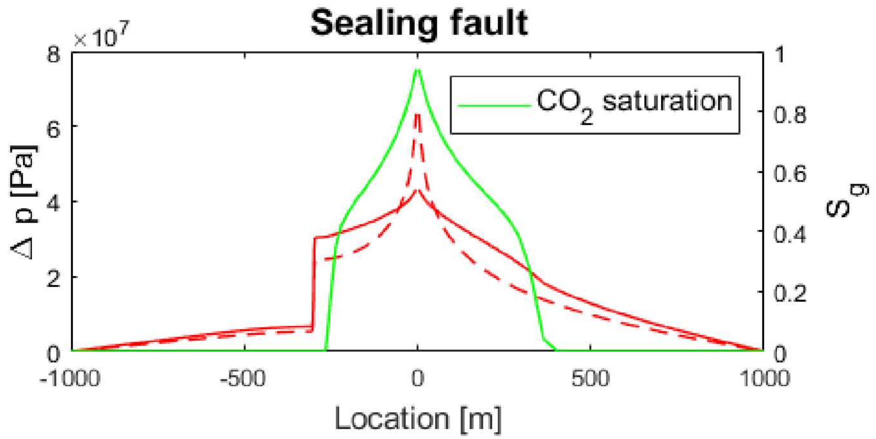




- CO_2 and pore pressure penetrate rapidly across the interface between reservoir and fault, and spread throughout the fault.
- Near the injection well (highly CO_2-saturated region) experiences less pressure buildup due to larger mobility.

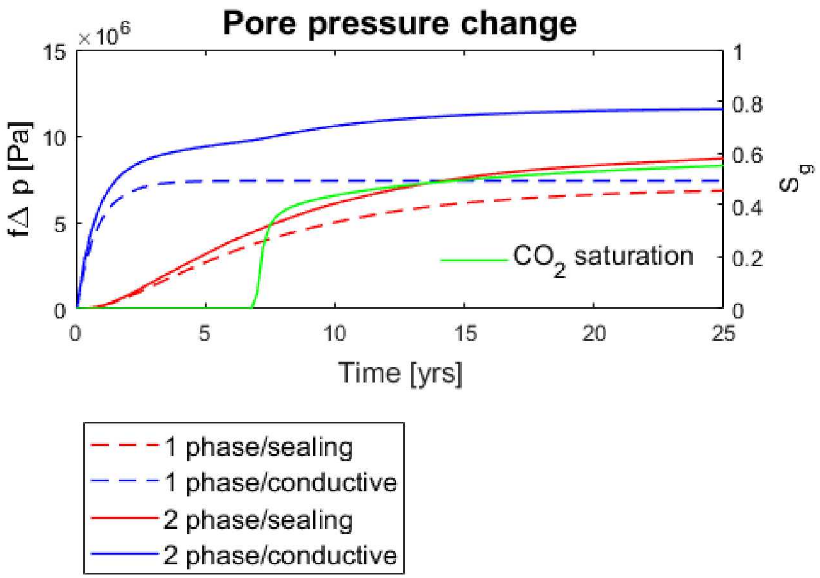
Results





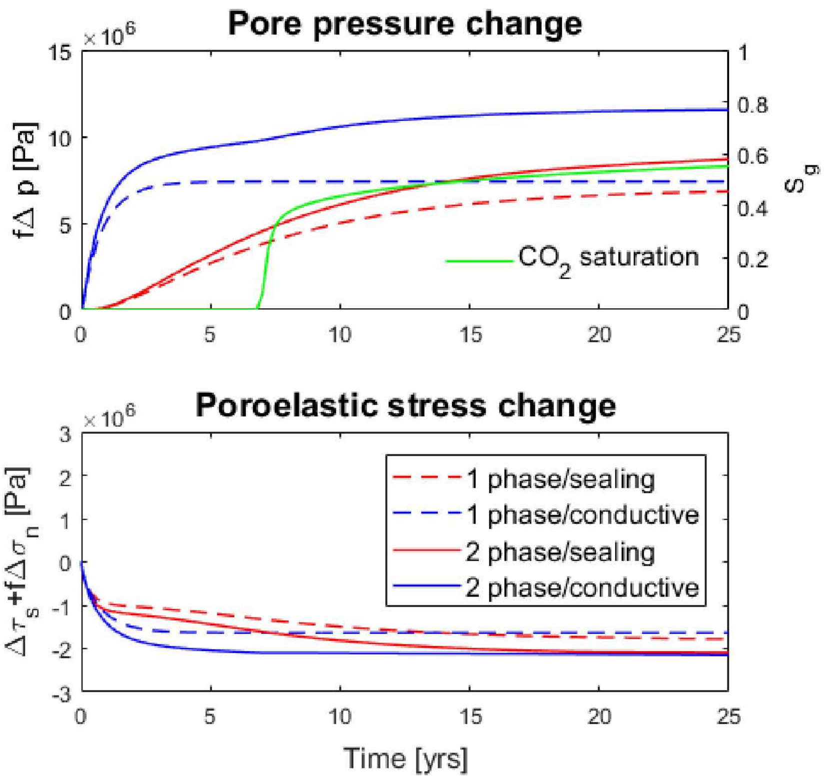
- Pore pressure accumulates along the fault acting as a "hydraulic barrier".
- The water-wet fault and nearby formation also act as a "capillary barrier" formed by the large contrast in permeability across the interface.

Results



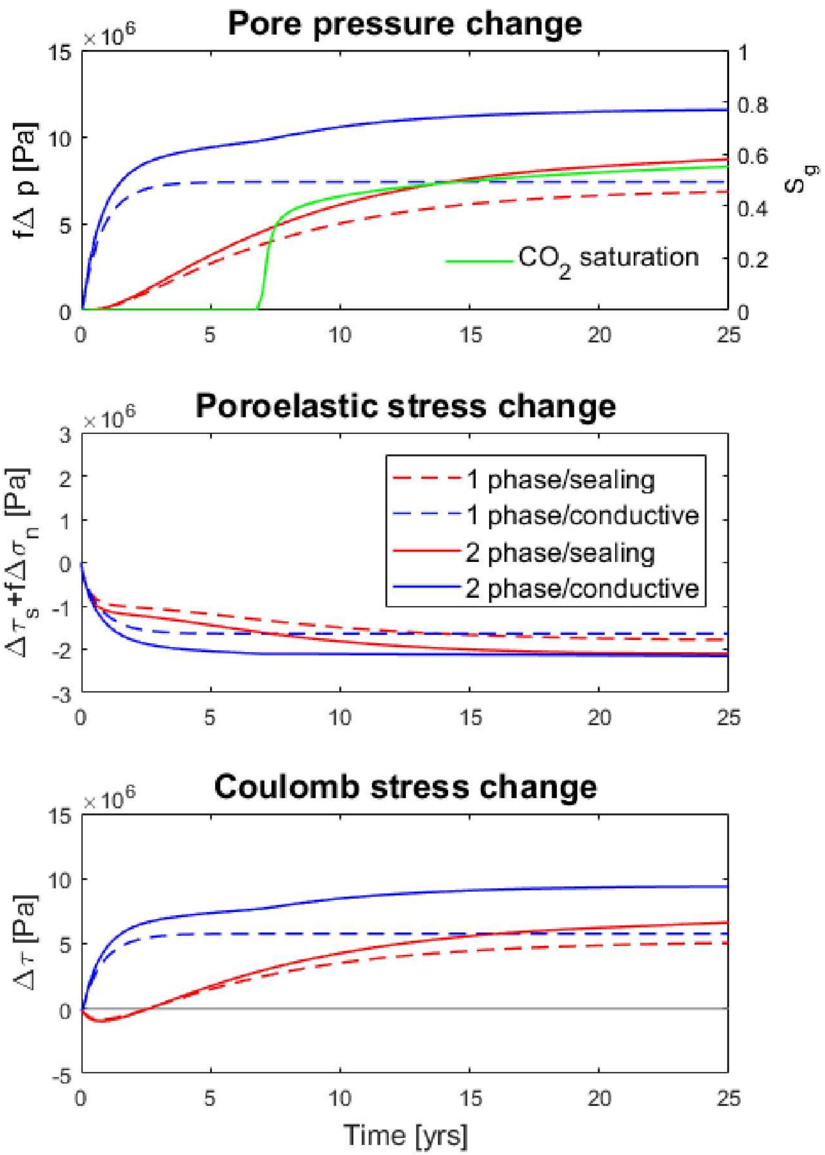
- Pore pressure (fΔp) increases rapidly in the conductive faults (blue lines).
- Once CO_2 plumes encounter the fault, capillary pressure generates larger fΔp.
- The sealing faults have slower pore-pressure buildup due to low diffusivity.

Results



- The reservoir surrounding faults expands with CO_2 injection, which generates compressional stresses within the fault zones, generating (-) $\Delta\tau_s+f\Delta\sigma_n$.

Results



- The compressive poroelastic stresses reduce the direct impact of elevated pore pressure along the fault.
  - For the conductive faults, direct diffusion of pore pressure controls the fault stability substantially, generating (+)$\Delta\tau$.
  - For the sealing faults, poroelastic stressing enhances the fault stability initially, generating (-)$\Delta\tau$, and gradually pressure buildup destabilizes the fault over time.

Conclusions

- Near the injection well, larger mobility of CO_2 reduces pressure buildup within the highly CO_2-saturated zone.
- Depending on the fault permeability, the fault can act as a hydraulic or capillary barrier against fluid phases, which can enhance the potential of induced seismicity along the fault.
- Poroelastic coupling can reduce the direct impact of pore-pressure buildup on the fault instability. The immediate mechanical response to CO_2 injection can enhance the stability of the sealing fault as a poroelastic response.

Q & A

References

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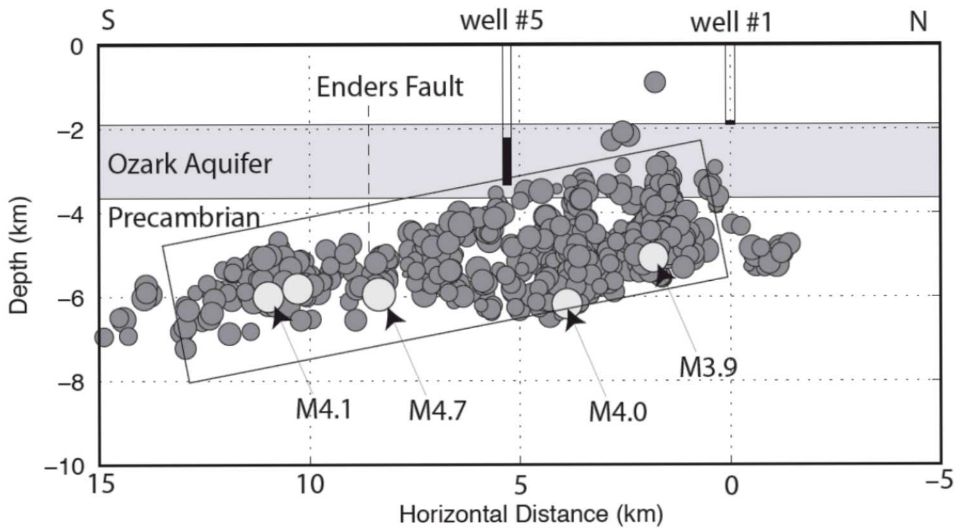
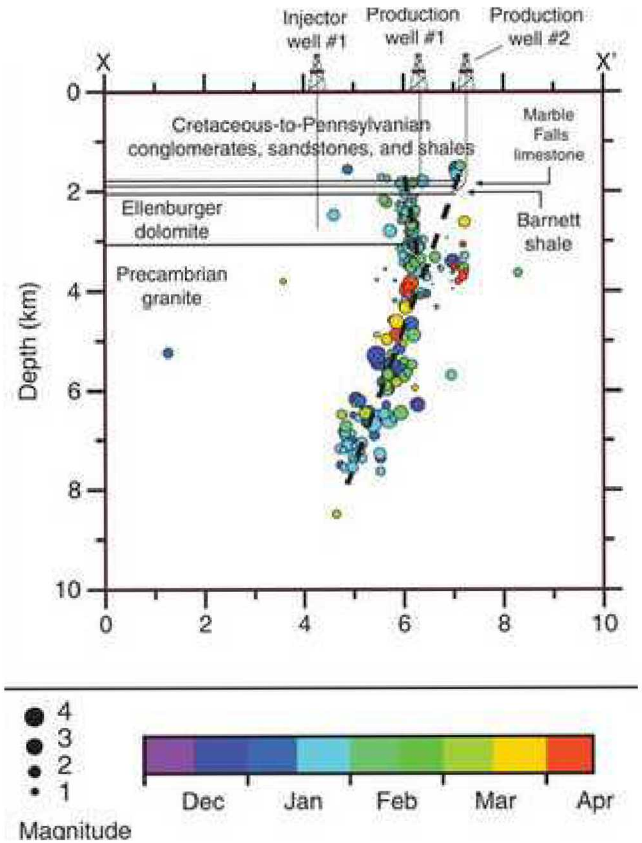
Seismicity along the basement fault



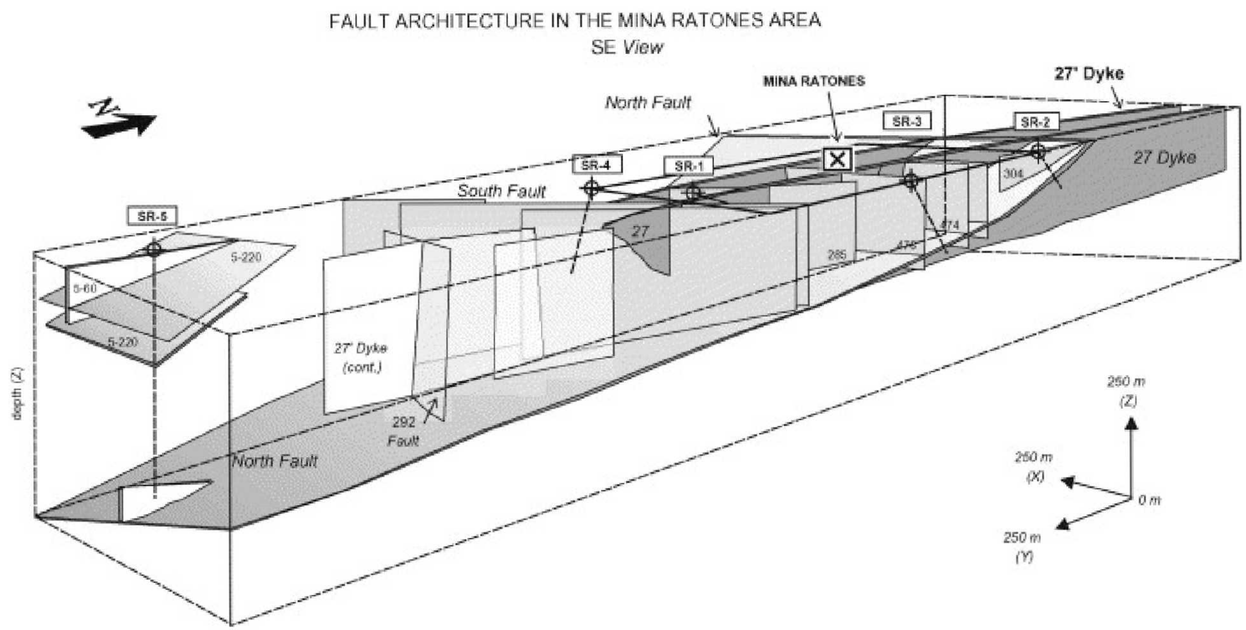
Guy, AR (Horton, 2012)



Azle, TX (Hornbach, 2015)

- Injection-induced earthquakes occur along the fault within the basement.

In-situ fault structure



(Escuder-Viruete et al., 2003)

- Geological characterization of the faulting system shows the complexity of the fault-zone structure embedded in a multi-layered system