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Injection induced seismicity along multiple faults: Magnitude and rate in a 3-D poroelasticity system

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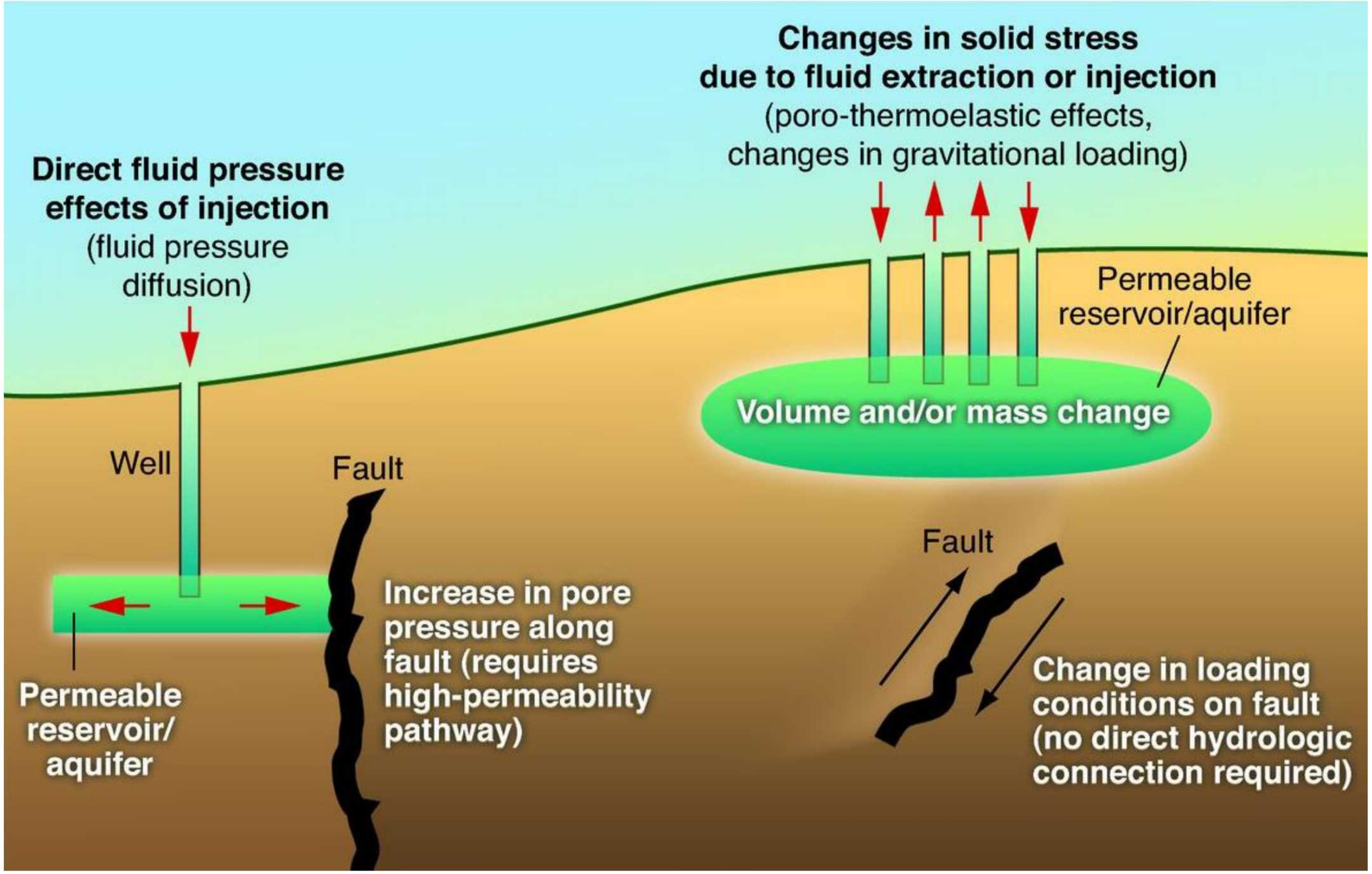
Possible mechanisms



(Ellsworth, 2013)

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

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

(+) for tension

Poroelastic stress **Pore pressure**

$\Delta\tau_s$ = 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)

Seismicity rate estimate

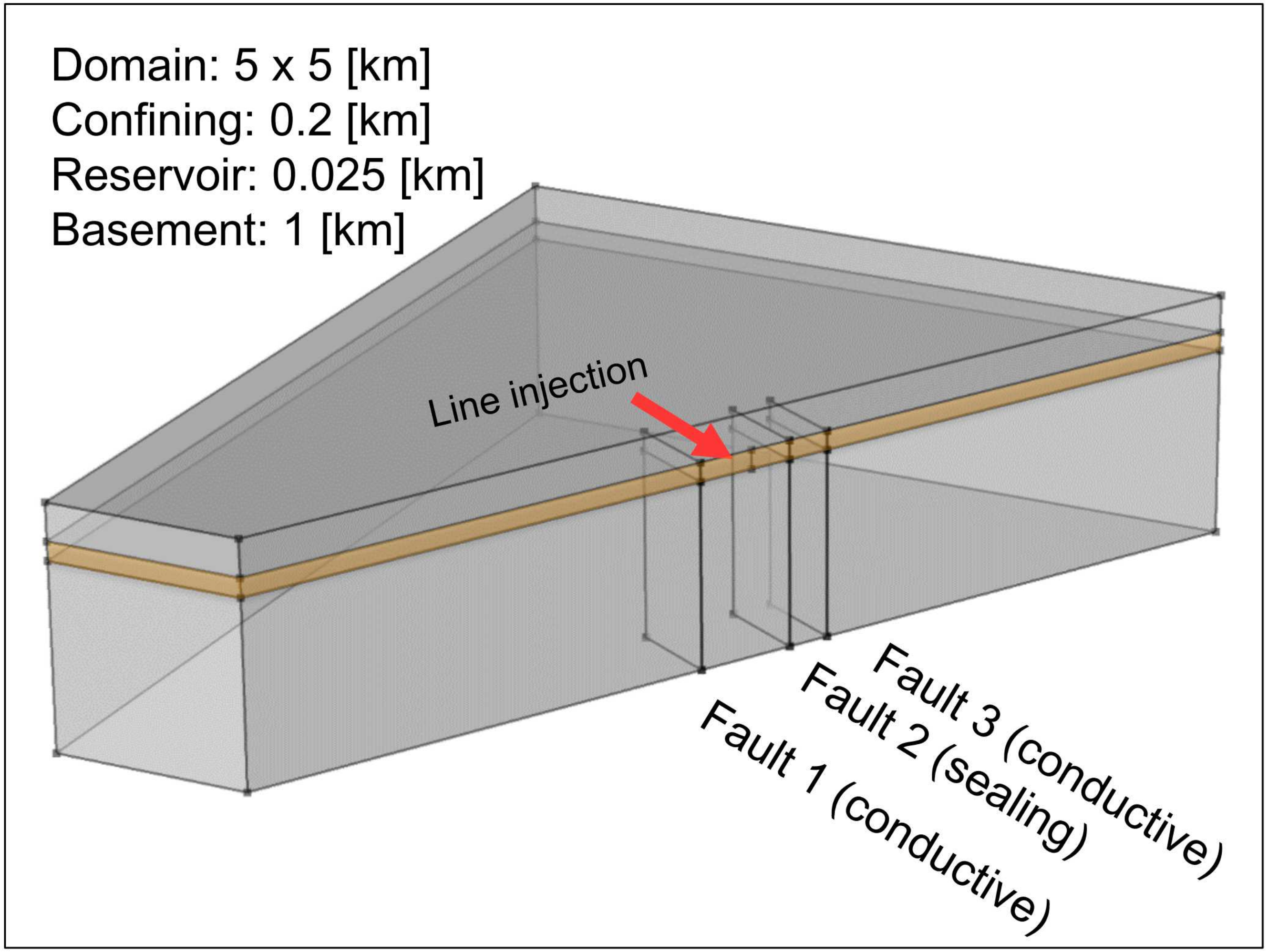
$$\frac{dR}{dt} = \frac{R}{t_a}\left(\frac{\dot{\tau}}{\dot{\tau}_0} - R\right)$$

(Segall & Lu, 2015, JGR)

t_a = characteristic decaying time

- R is the seismicity rate relative to an assumed prior steady-state seismicity rate at a background stressing rate

Model scheme: 3-D

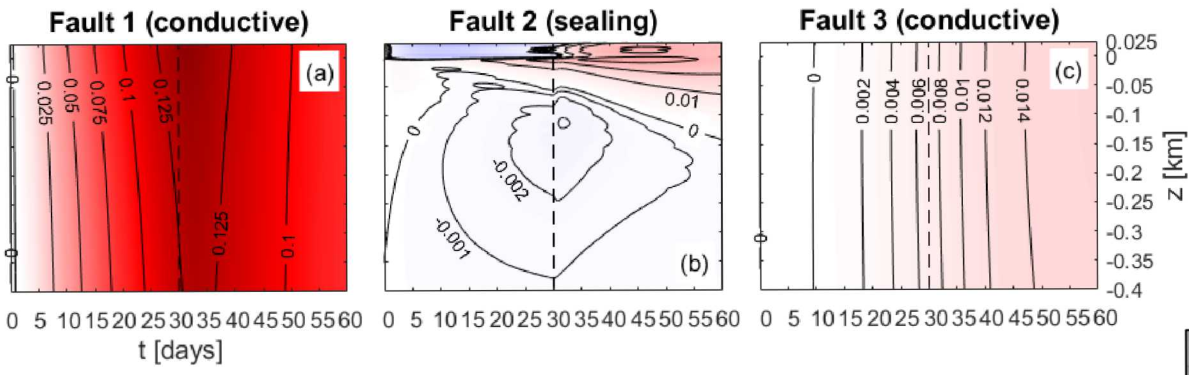


- Injection for 30 days with constant injection rate

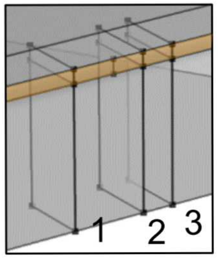
Results

$f\Delta p$

Pore pressure



(Chang & Yoon, 2018, JGR)

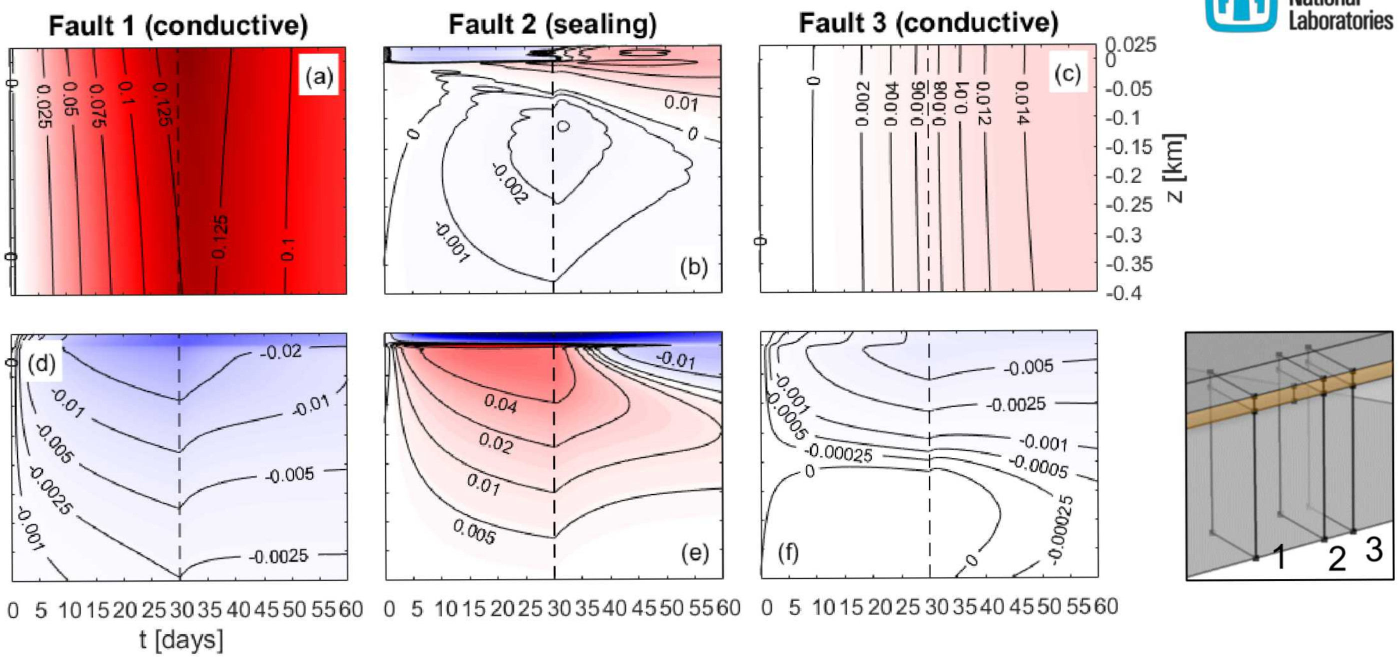


- Nearest conductive fault (fault 1) experience the most increases in pore pressure
- Along the sealing fault (fault 2), the poroelastic response generates -Δp or +Δp corresponding to well operation.
- The conductive fault (fault 3) has post shut-in increase in Δp due to delayed diffusion.

Results

fΔp
Pore pressure

$\Delta\tau_s + f\Delta\sigma_n$
Poroelastic stress



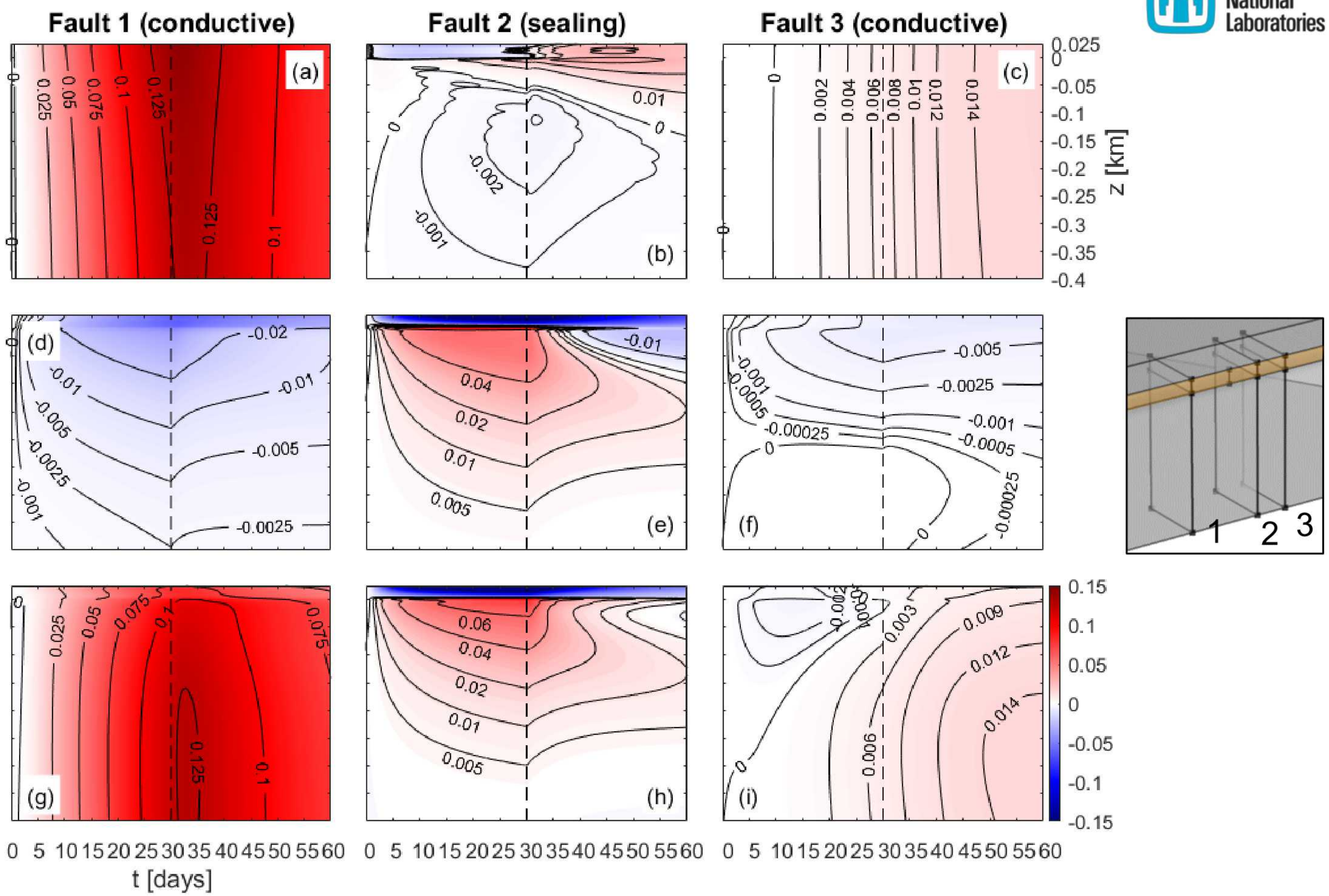
- Along the sealing fault (fault 2), the extensional stress caused by the reservoir expansion gives $+(\Delta\tau_s + f\Delta\sigma_n)$ in the upper fault zone.
- Both conductive faults experience $-(\Delta\tau_s + f\Delta\sigma_n)$ by reacting to the pressure buildup within the fault zone.

Results

fΔp
Pore pressure

$\Delta\tau_s + f\Delta\sigma_n$
Poroelastic stress

Δτ
Coulomb stress



- Direct diffusion gives +Δτ along the conductive faults.
- Poroelastic stressing causes +Δτ along the sealing fault.

Results

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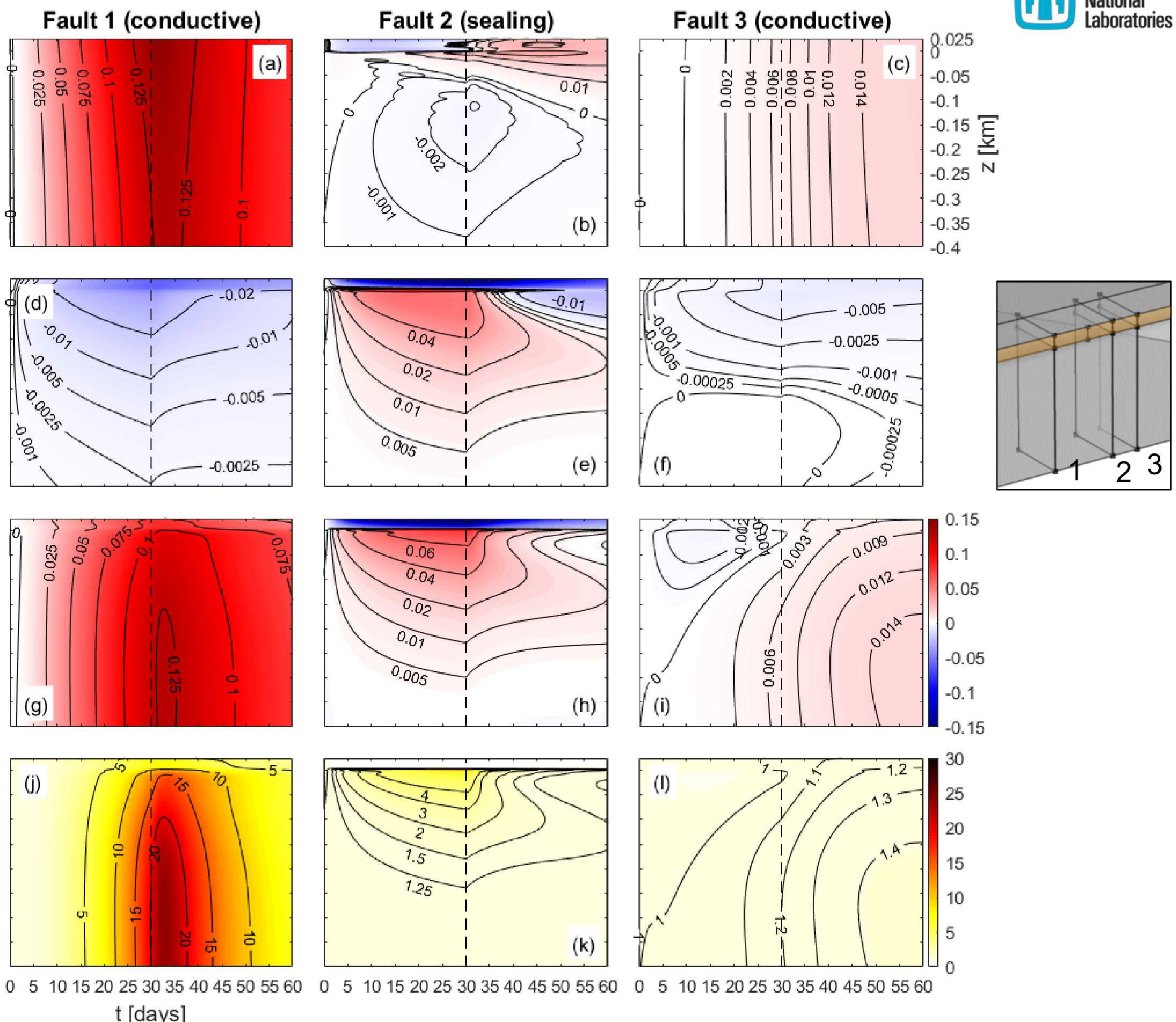
fΔp
Pore pressure

$\Delta\tau_s + f\Delta\sigma_n$
Poroelastic stress

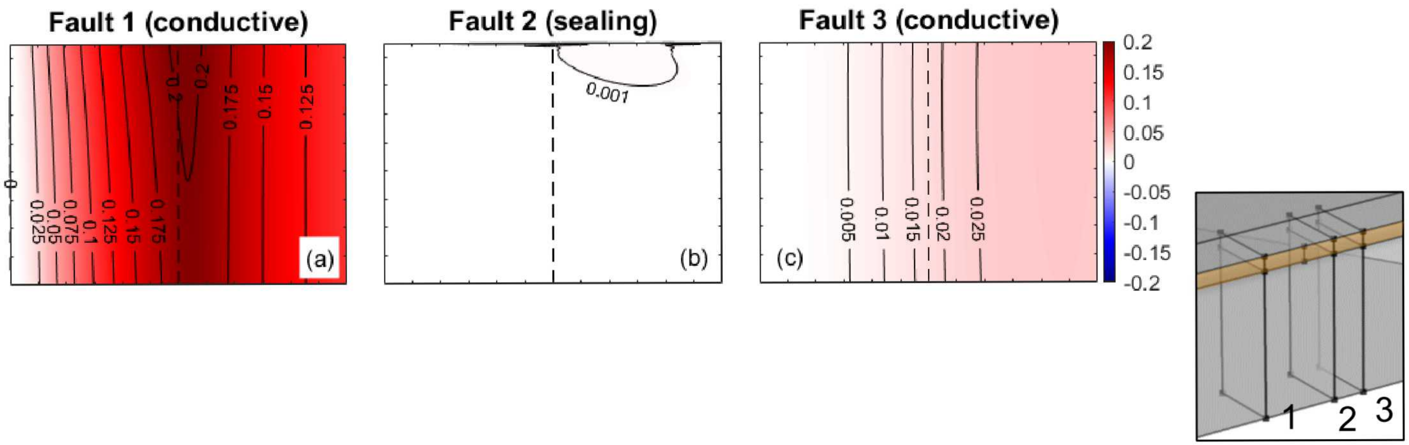
Δτ
Coulomb stress

R
Seismicity rate



Results: uncoupled model

$f\Delta p = \Delta\tau$



- Nearest conductive fault (fault 1) experiences significant pressure buildup
- Along the sealing fault (fault 2), almost no diffusion of pore pressure is observed.
- The conductive fault (fault 3) has post shut-in increase due to delayed diffusion.

Results: uncoupled model

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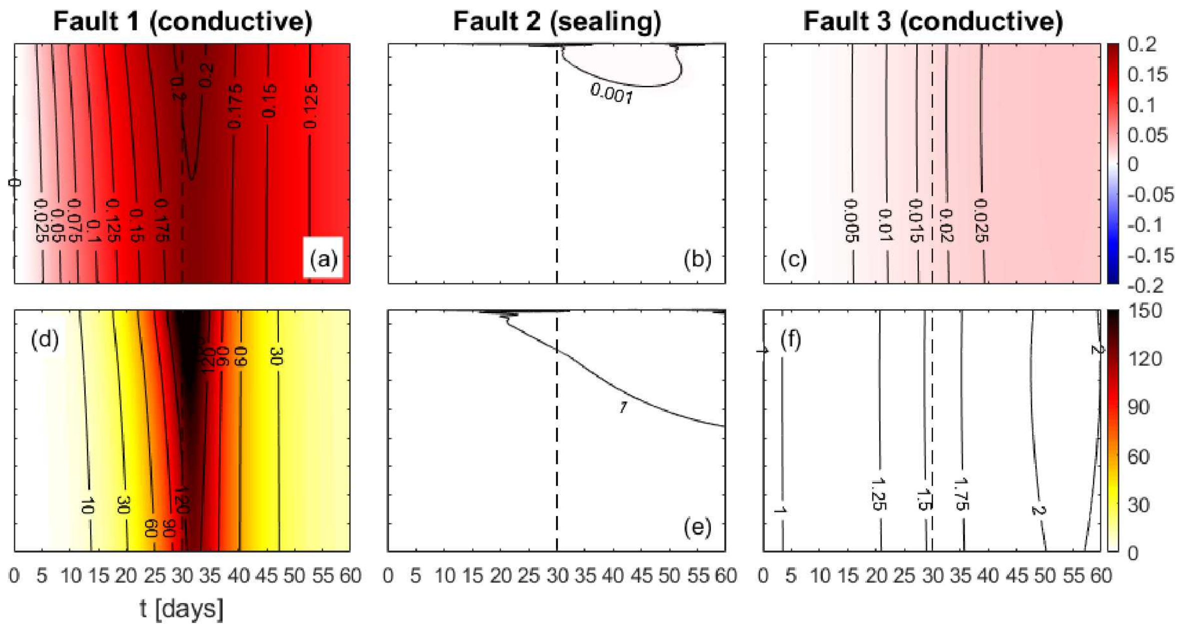
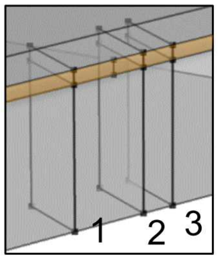
$f\Delta p = \Delta\tau$

R
Seismicity rate





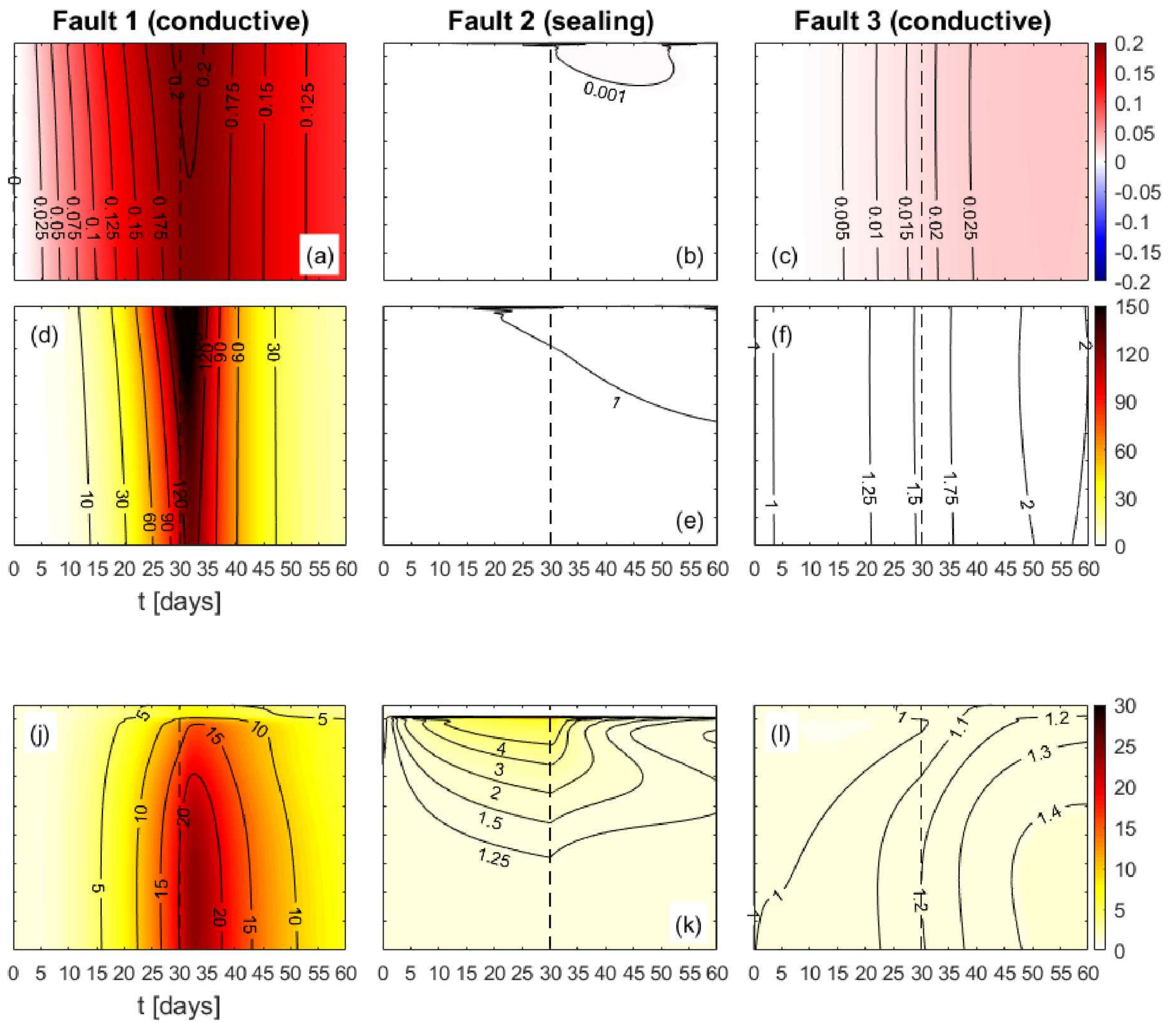
- Mechanical response is neglected, so direct pore-pressure diffusion is the only mechanism to induce seismicity.
- The maximum R is observed at the uppermost fault zone corresponding to the pore-pressure propagation.

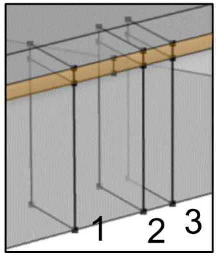
Results: uncoupled model

$f\Delta p = \Delta\tau$

R
Seismicity rate

R
Seismicity rate





Seismicity magnitude estimate

$$M_{0,max} = \frac{(1.5 - b)}{b} 2fK\Delta V$$

(McGarr, 2014, JGR)

K = drained bulk modulus

b = GR frequency-magnitude relation

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$$M_{0,max} = \frac{(1.5 - b)}{b} \frac{2f}{S} \Delta V$$

(Chang & Yoon, 2018, JGR)

$1/S$ = Biot's modulus

Seismicity magnitude estimate

Estimate based on ΔV

$$M_{0,max} = \frac{(1.5 - b)}{b} 2fK\Delta V$$

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$$M_{0,max} = \frac{(1.5 - b)}{b} \frac{2f}{S} \Delta V$$

(Chang & Yoon, 2018, JGR)

$1/S$ = Biot's modulus

Estimate based on u

$$M_{0,max} = G \int u \, dA$$

Results: seismicity magnitude

Governing parameter	Seismic moment relation	Seismic moment (M_0, N·m) Maximum magnitude ($M_{W,max}$,-)			
		Overall formation	Fault 1	Fault 2	Fault 3
ΔV	McGarr	1.08×10^{12} 1.99			
	Chang & Yoon	1.66×10^{12} 2.11			
u			1.78×10^{11} 1.47	1.20×10^{11} 1.35	1.04×10^{11} 1.31

$$M_W = \frac{2}{3}[\log_{10} M_0 - 9.05]$$

Conclusions

- In the poroelasticity system, pore-pressure diffusion and/or poroelastic stressing can induce seismicity along faults of any hydraulic type.
- The location of induced seismicity can vary depending on fault properties due to the poroelastic effect.
- The 3-D modeling captures properly the hydraulic and mechanical interaction between faults and surrounding formations.

Q & A

References

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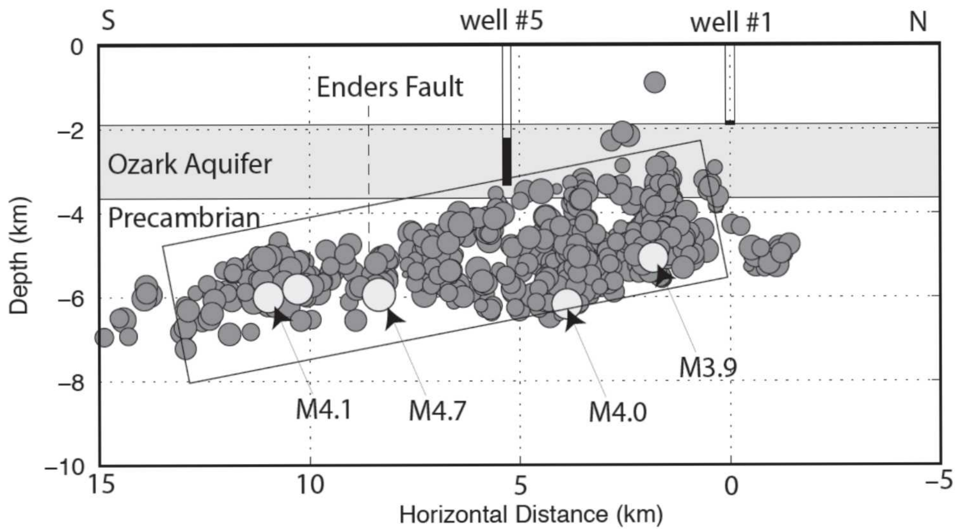
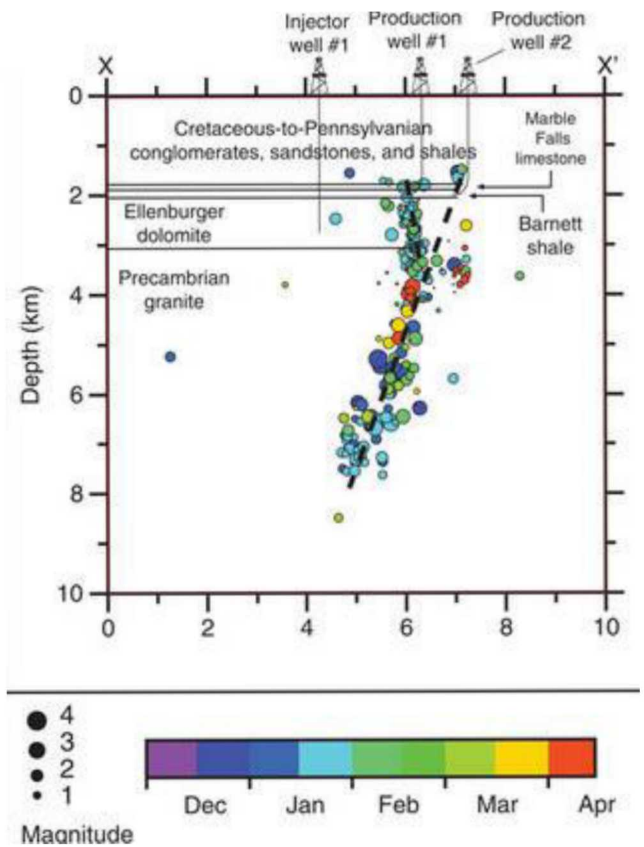
Seismicity along the basement fault



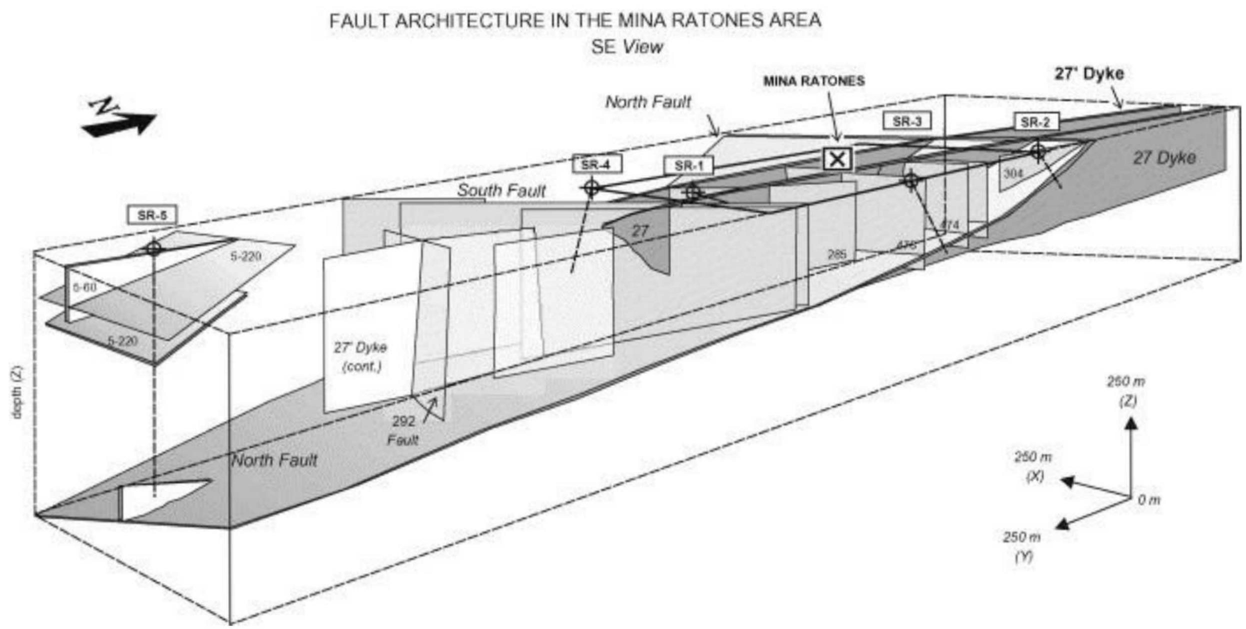
Guy, AR (Horton, 2012)



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

Poroelastic coupling

Pore pressure change

Rock deformation

- Stress equilibrium

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

- Diffusion

$$S(x)\frac{\partial p}{\partial t} - \frac{1}{\eta}\nabla \cdot [k(x)\nabla p] = -\alpha(x)\frac{\partial}{\partial t}(\nabla \cdot u) + Q(x,t)$$

Poroelastic coupling

Pore pressure change ⇄ Rock deformation

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$f\Delta p$
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$\Delta\tau_s + f\Delta\sigma_n$
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$\Delta\tau$
Coulomb stress

R
Seismicity rate