Poro-elastic and Earthquake Nucleation Effects in Injection Induced Seismicity

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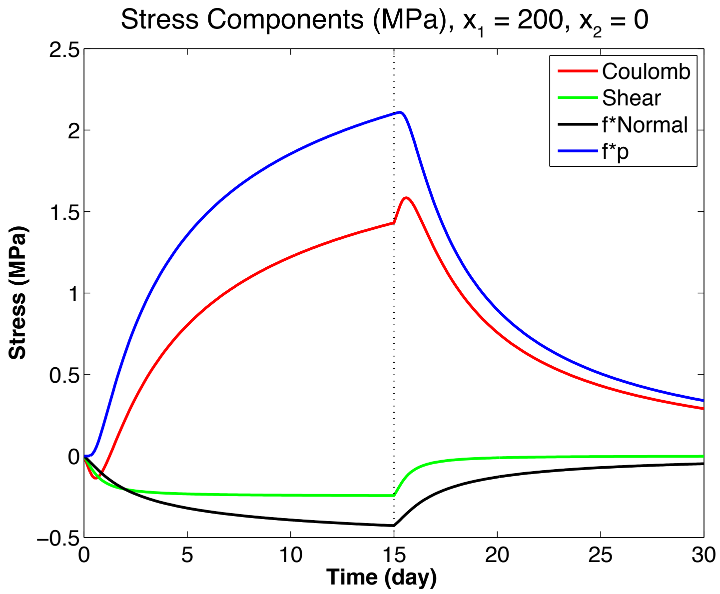

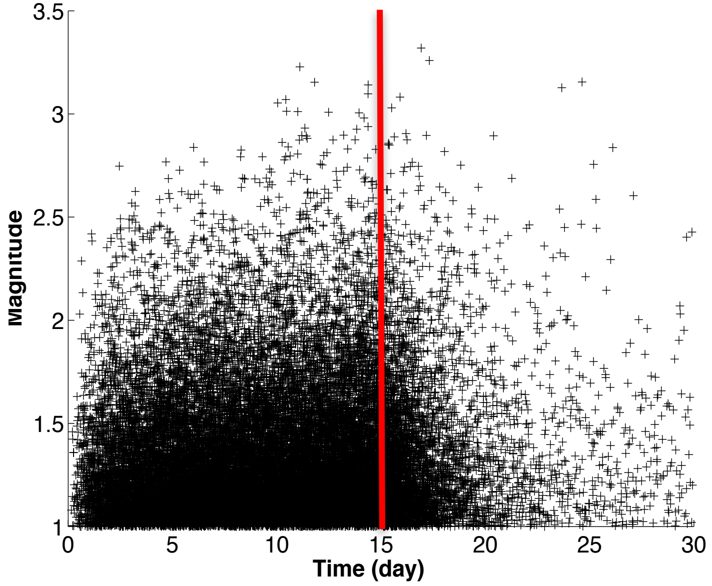

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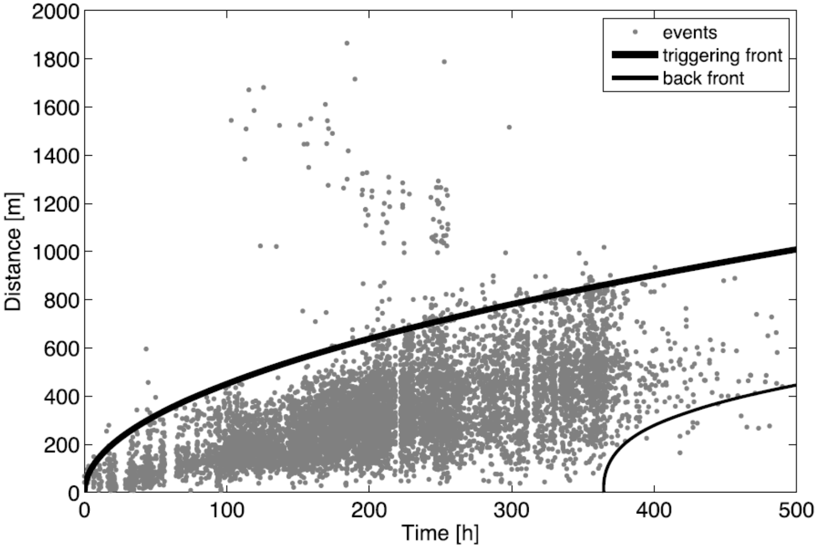
Motivation

Injection induced seismicity (IIS) has historically been interpreted in terms of pore-pressure diffusion and changes in **effective normal stress**, changing fault strength via:

$$\tau = c + f\,(\,\sigma - p(t)\,)$$



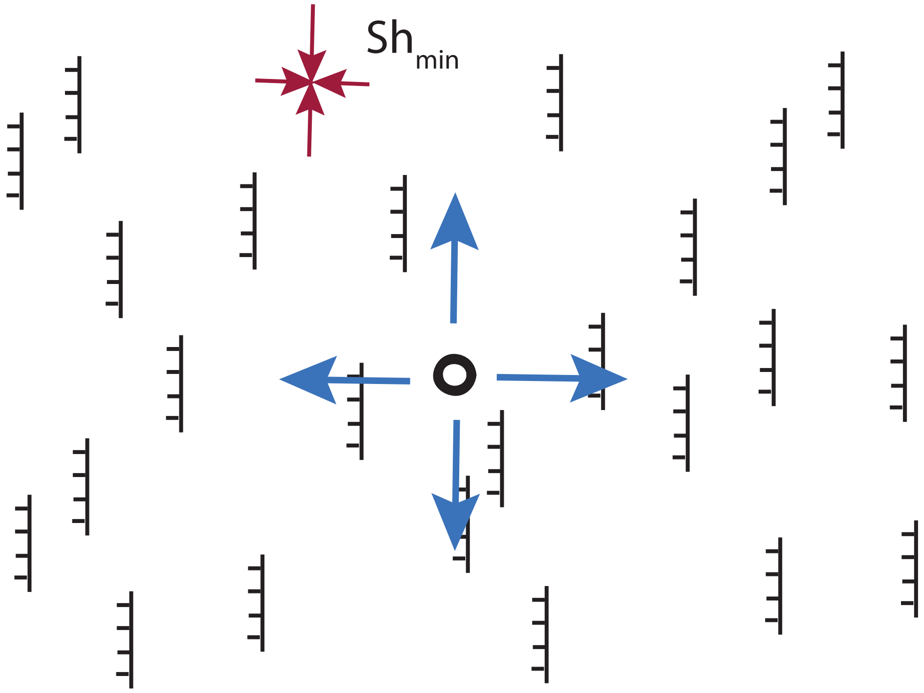
Shapiro and Dinske (2009)

Questions:

- Poro-elastic effects are thought to dominate production induced seismicity. How might poro-elastic effects influence IIS? $\tau(t) = c + f\,(\,\sigma(t) - p(t)\,)$

- Laboratory stick-slip events exhibit time dependent nucleation. Is the space-time pattern of IIS solely due to pore-pressure diffusion?

Injection Model



- Point source injection in *homogeneous*, poro-elastic full space

- Uniformly distributed and oriented faults

- Fault hydraulic properties same as background

Point Injection Source in Homogeneous Full Space

Rudnicki (1986)

Injection flux

$$p(\vec{x},t) = \frac{C_1}{r^3}\int_0^t q(t')\xi^3 e^{-\frac{1}{4}\xi^2}\,dt'$$

$$C_1 = \frac{(\lambda_u - \lambda)(\lambda + 2\mu)}{(4\pi)^{\frac{3}{2}}\rho_0\alpha^2(\lambda_u + 2\mu)} \qquad \xi \triangleq \xi(t - t') = \frac{r}{\sqrt{c(t - t')}}$$

Hydraulic diffusivity

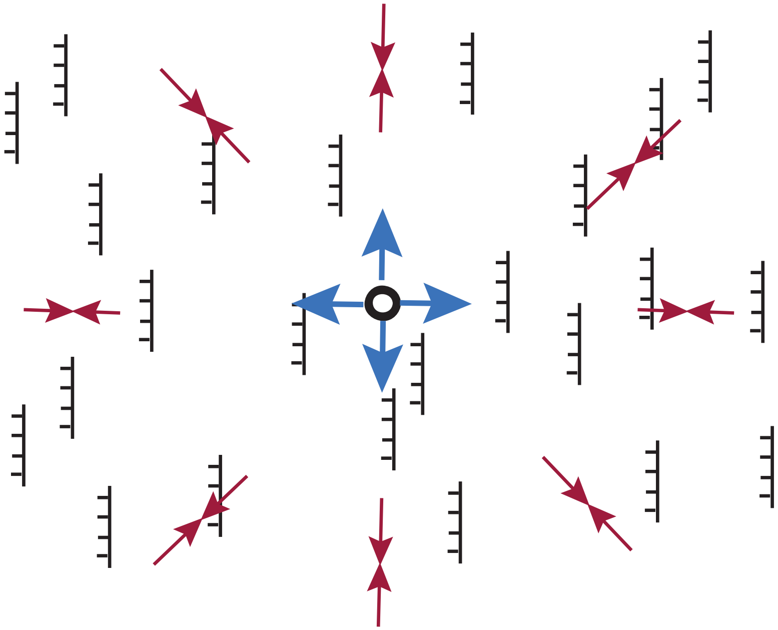
$$\sigma_{ij}(\vec{x},t) = \frac{C_2}{r^3}\int_0^t q(t')\left[\delta_{ij}(g(\xi) - \xi g'(\xi)) + \frac{x_i x_j}{r^2}(\xi g'(\xi) - 3g(\xi))\right]dt'$$

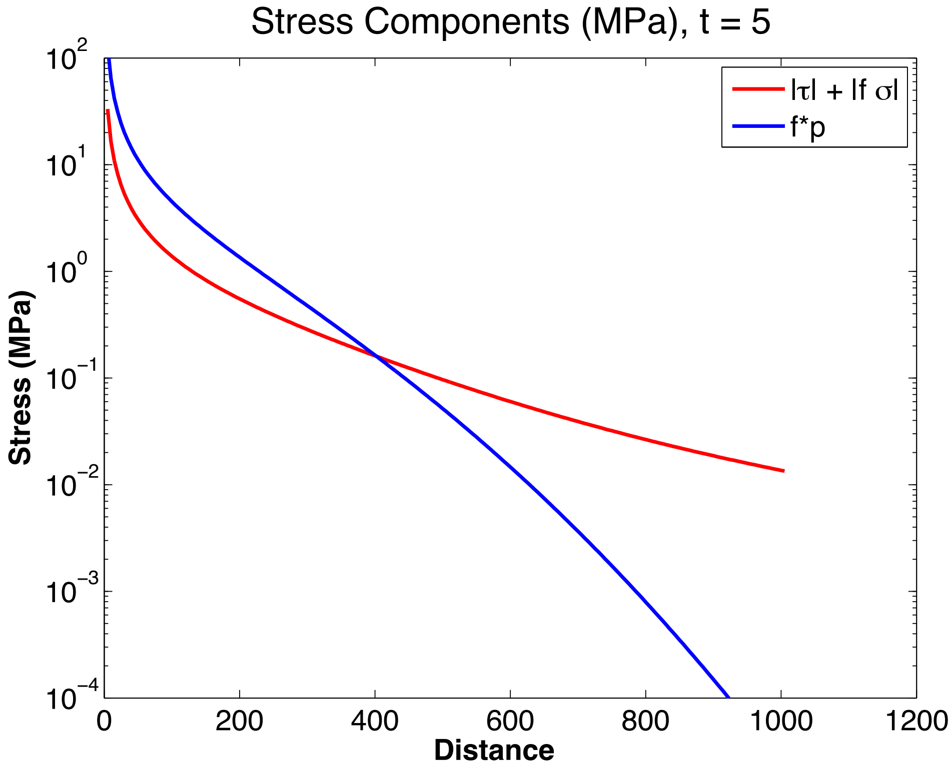
$$C_2 = \frac{\mu(\lambda_u - \lambda)}{2\pi\rho_0\alpha(\lambda_u + 2\mu)} \qquad g(\xi) \triangleq \operatorname{erf}\left(\frac{1}{2}\xi\right) - \frac{\xi}{\sqrt{\pi}}e^{-\frac{1}{4}\xi^2}$$

Total Stress Changes!

For constant flux, q(t) = q_0, integration can be done exactly

Poro-elastic Stress





Seismicity Rate Theory [Dieterich, 1994]

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

R	Seismicity rate relative to background rate
$\tau_c = \tau - f\sigma$	Coulomb stress, f is friction coefficient
$\dot{\tau}_0$	Background stressing rate
$t_a \equiv a\sigma/\dot{\tau}_0$	characteristic decay time, and a constitutive parameter

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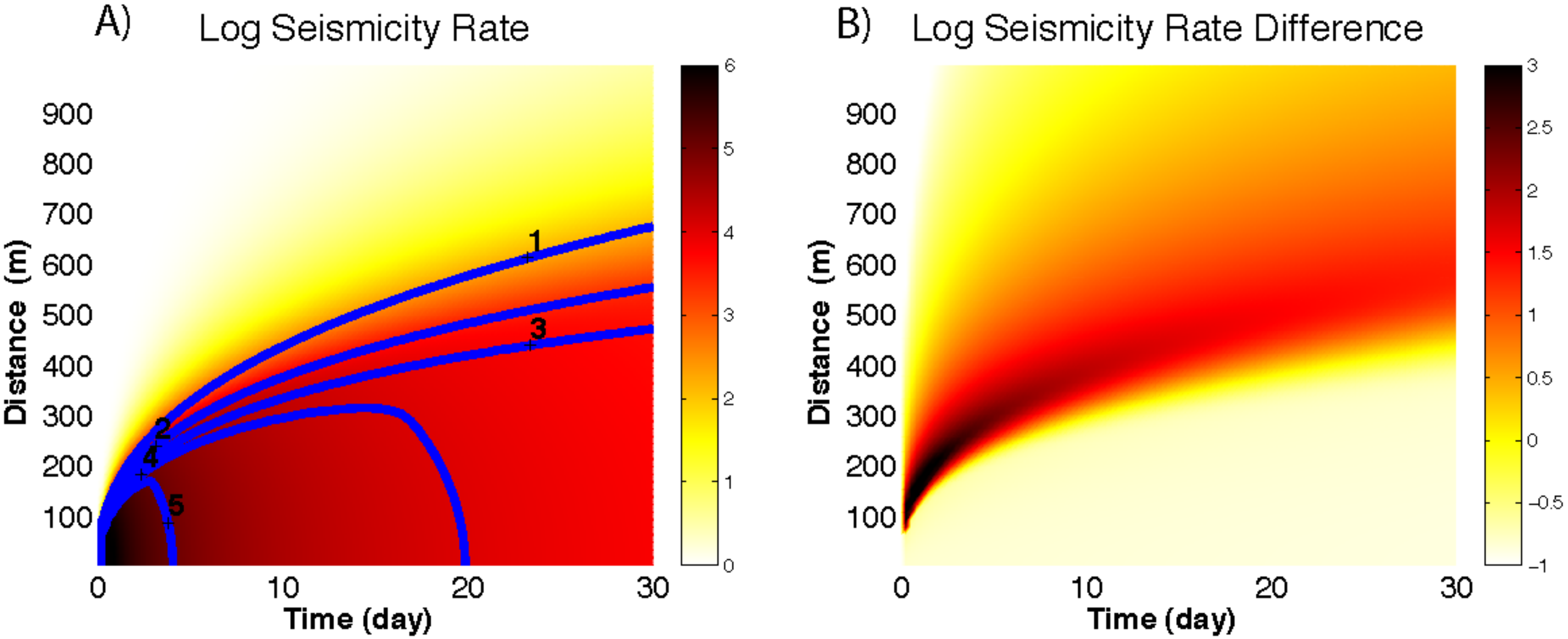
Properties of the Seismicity Model

- At Steady state: $R = \dot{\tau}_c/\dot{\tau}_0$.
- For rapid stressing: $R = \exp(\tau_c/a\sigma)$.
- Following rapid change: $R = [e^{-\Delta\tau/a\sigma} + t/t_a]^{-1}$ Omori Law

- Models nucleation only; does not predict magnitude

Effect of Poroelastic Coupling

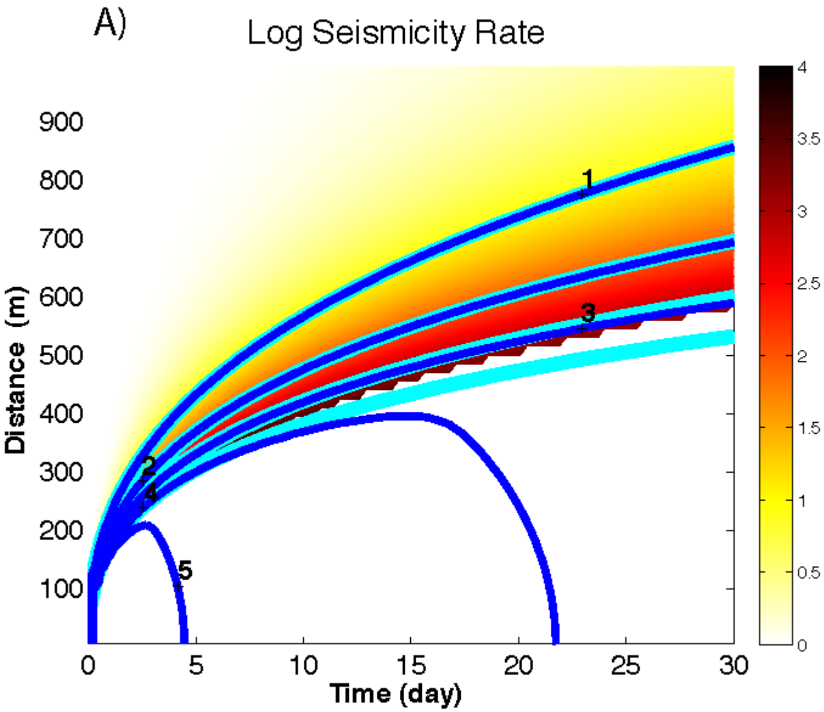


Color = uncoupled
Contours = coupled

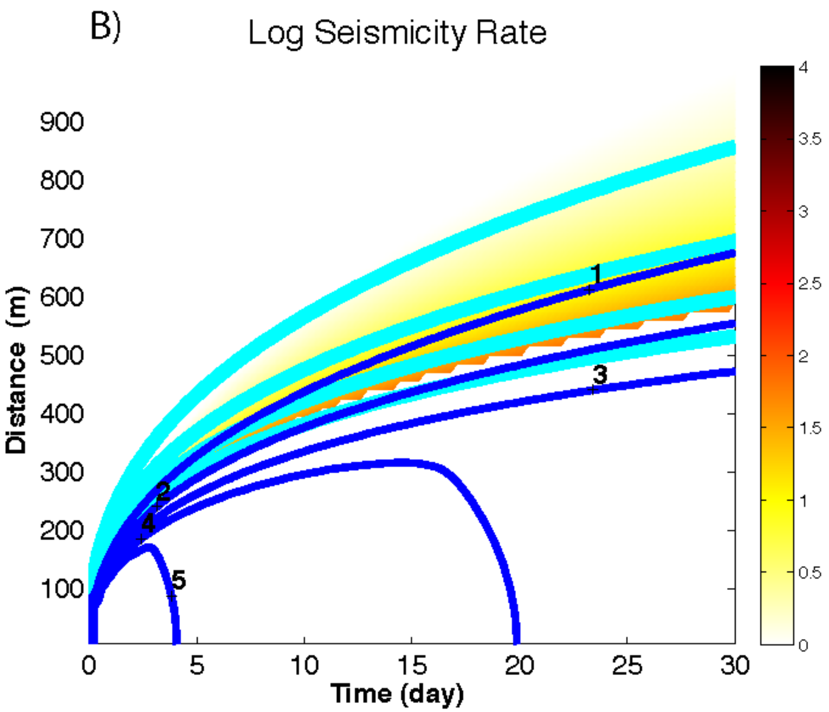
$$\log_{10}\left[\frac{R_u - R}{R}\right]$$

Seismicity Onset Time

Uncoupled



Coupled

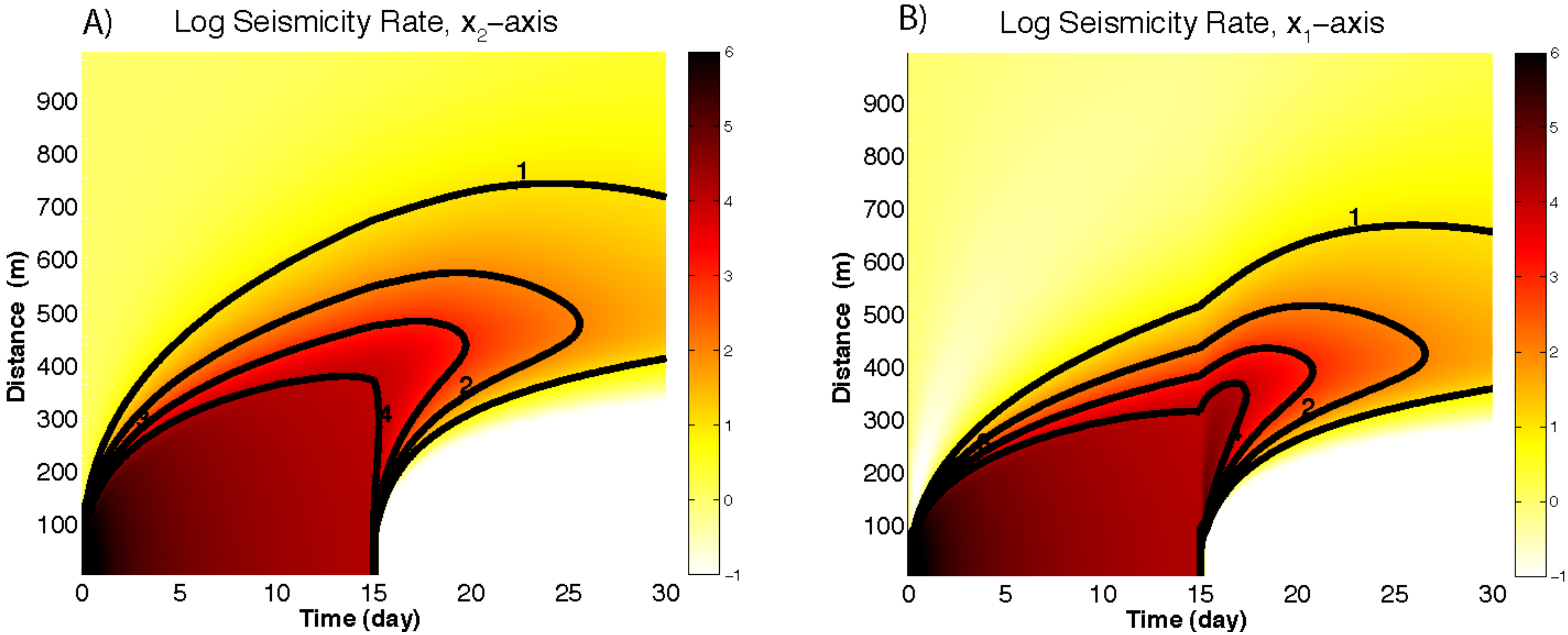


Short time approximation

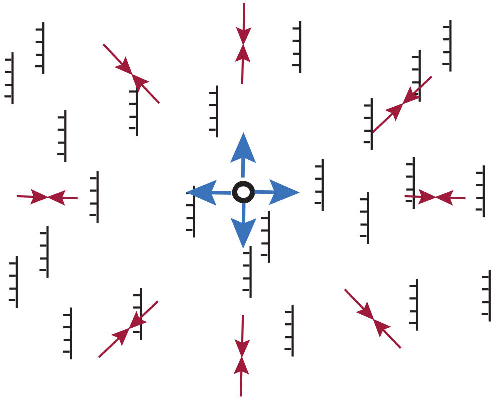
$$R(\boldsymbol{x},t) \approx \exp[fp(\boldsymbol{x},t)/a\sigma]$$

$$\begin{aligned} r &\approx \sqrt{f_c(r,R_c)ct} \\ f_c(r,R_c) &\equiv \left\{2\,\mathrm{erfc}^{-1}\left[\frac{a\sigma}{f\Lambda}\frac{4\pi r}{r_q}\log(R_c)\right]\right\}^2 \end{aligned}$$

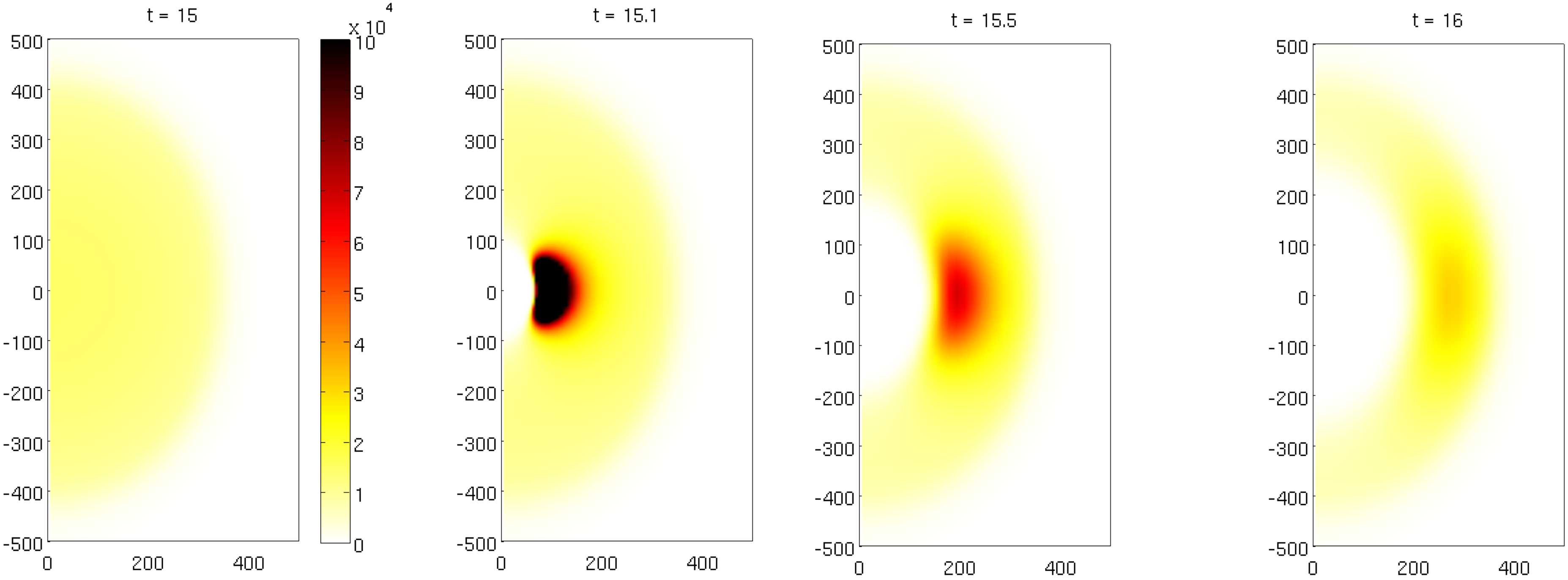
Seismicity Rate: Finite Duration Injection



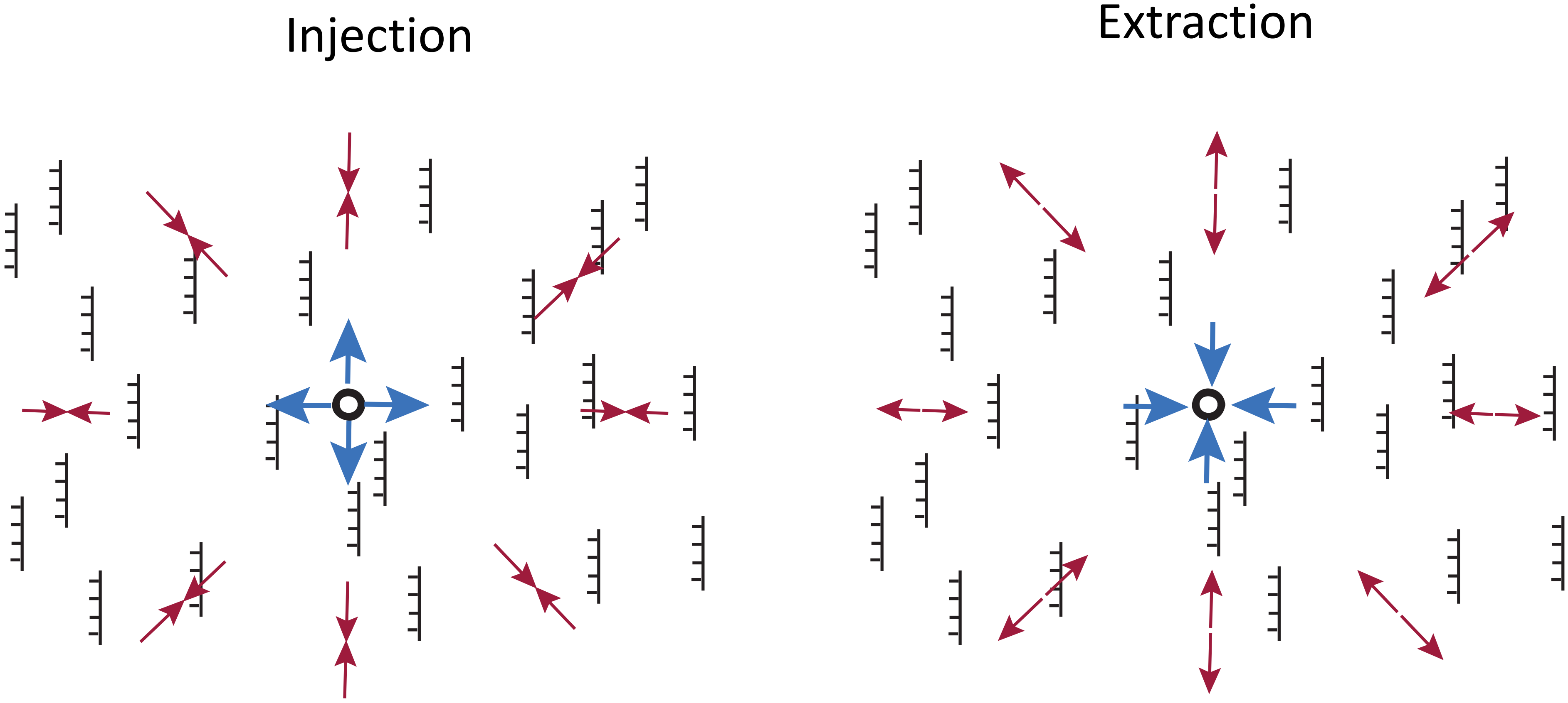
- Fault orientation breaks symmetry
- Post shut-in rate increase



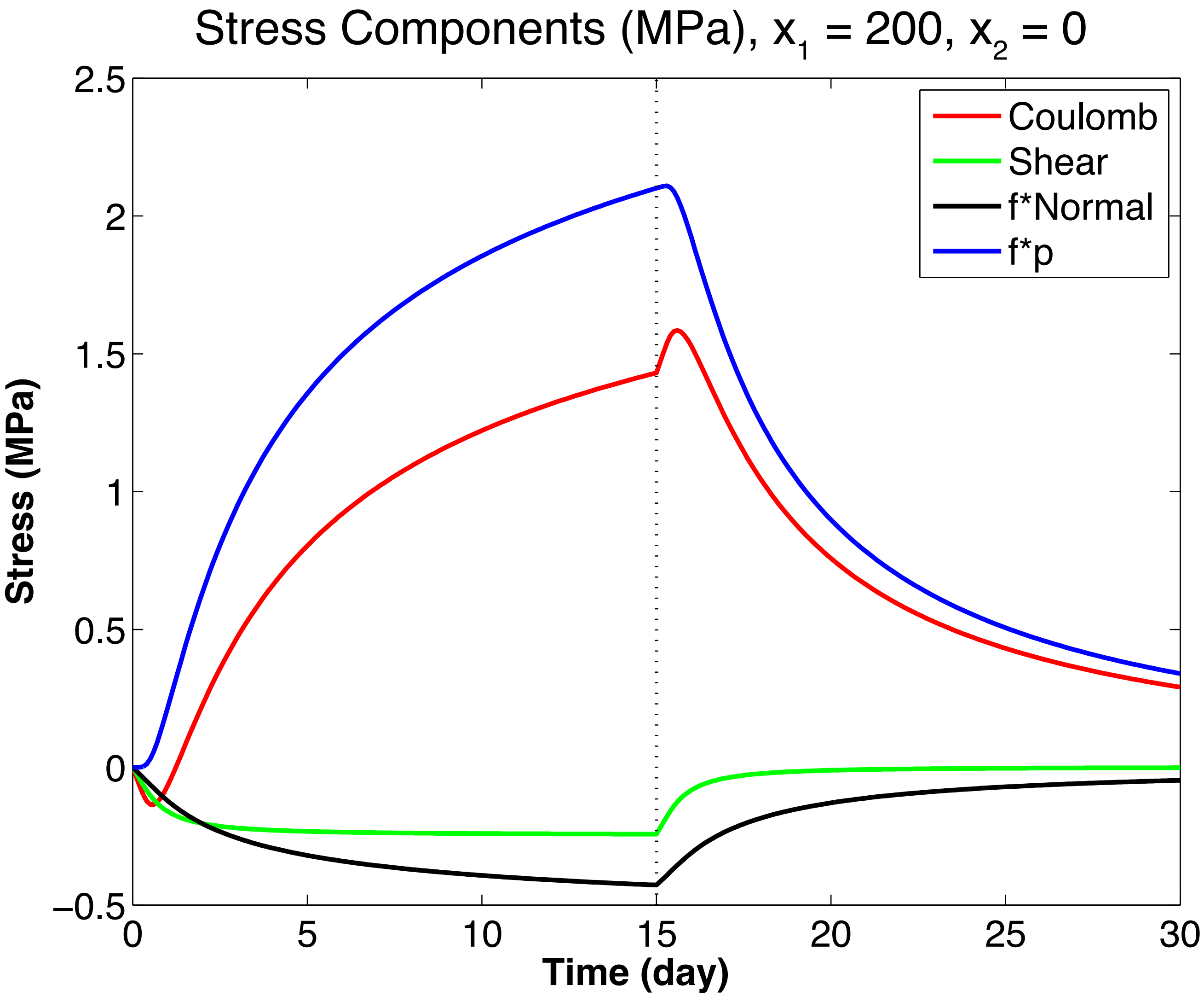
Increased Rate Following Shut-in



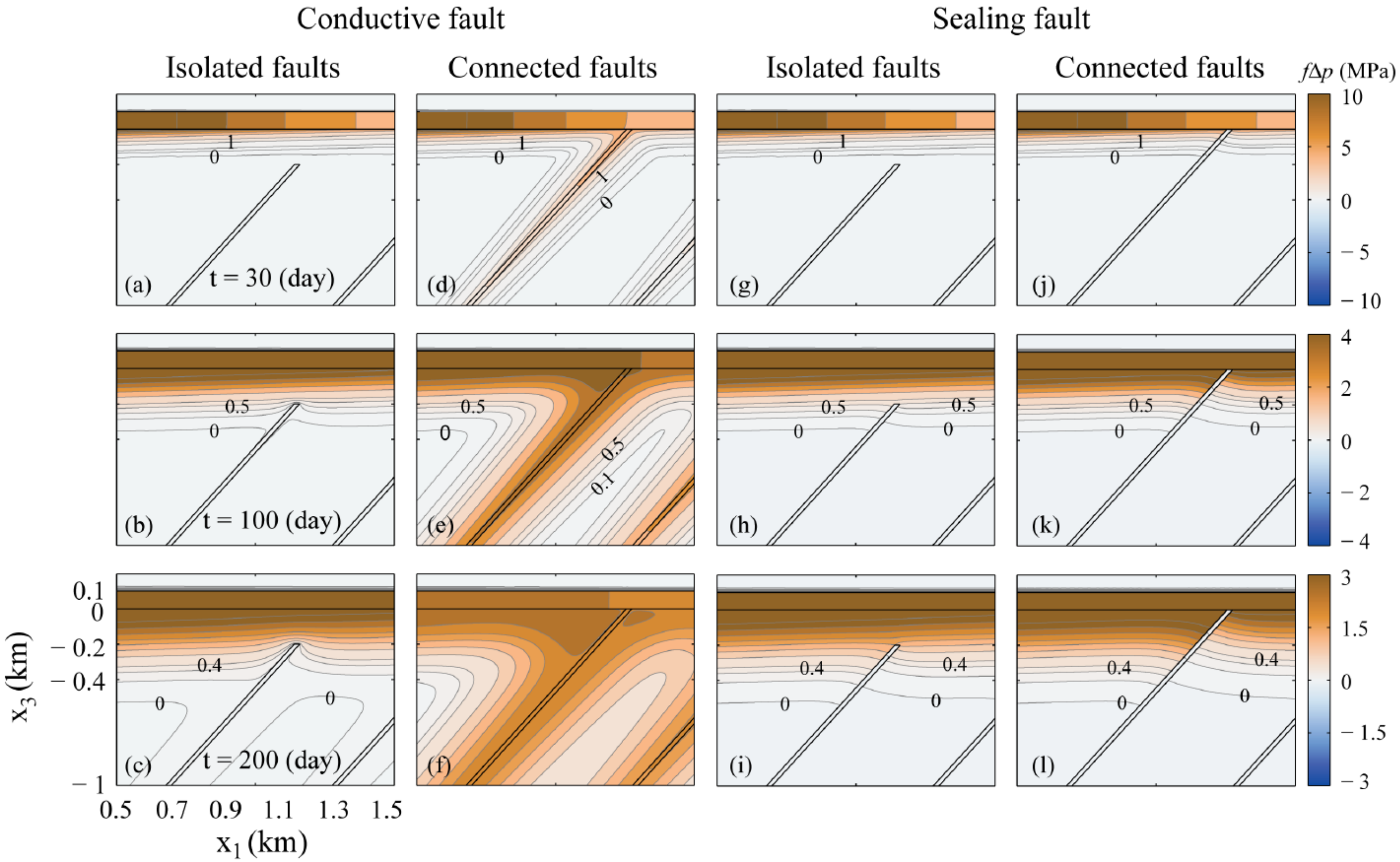
Poro-elastic Stress



Coupling Induces Stress Changes

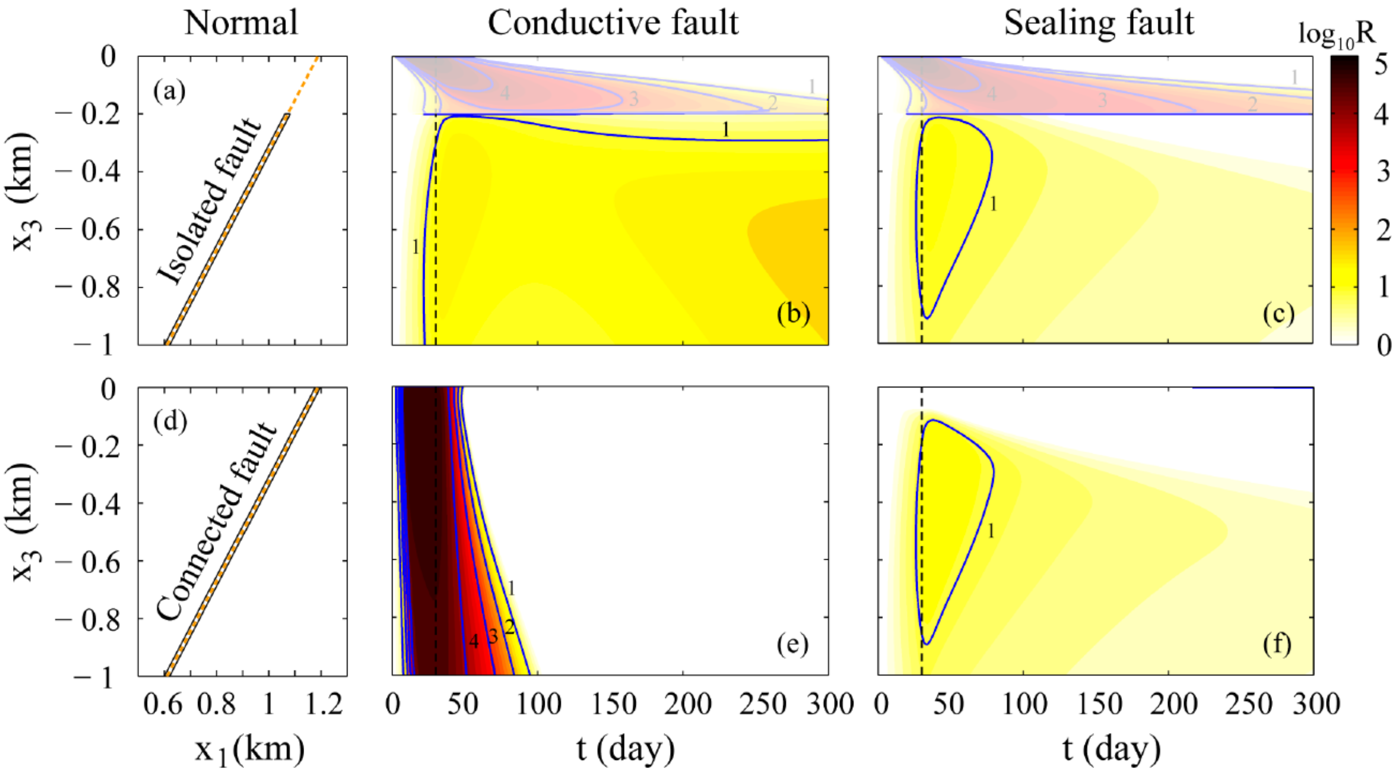


Pore pressure change $f\Delta p$



Chang and Segall, JGR, 2016

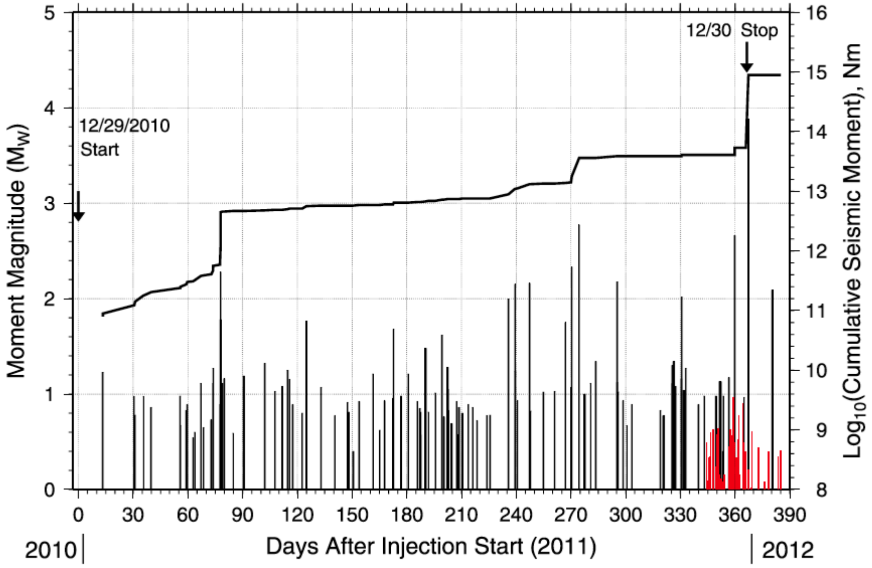
Seismicity rate *R* on fault zone



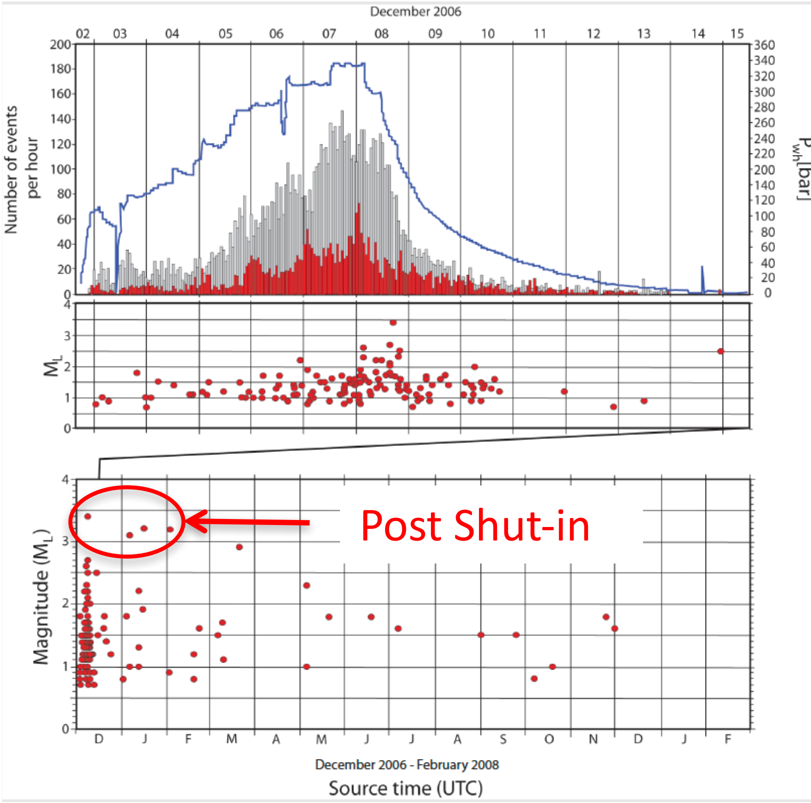
Chang and Segall, JGR, 2016

Largest Event Post Shut in

Youngstown, Ohio



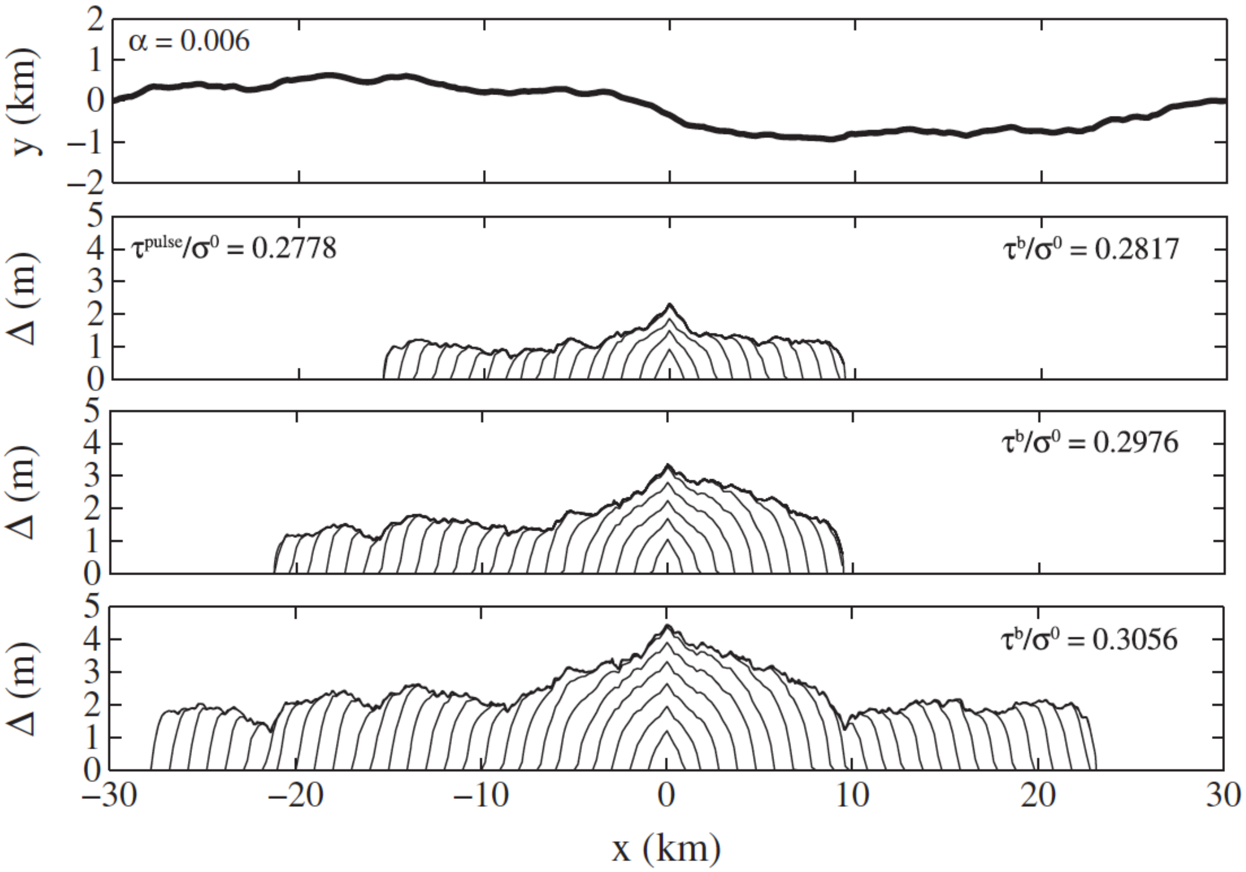
Basel, Switzerland



- Probability of triggering a fault of a given size, depends on volume of perturbed zone hence time (e.g., Baisch 2010; Shapiro et al, 2013, Dieterich et al, 2015).

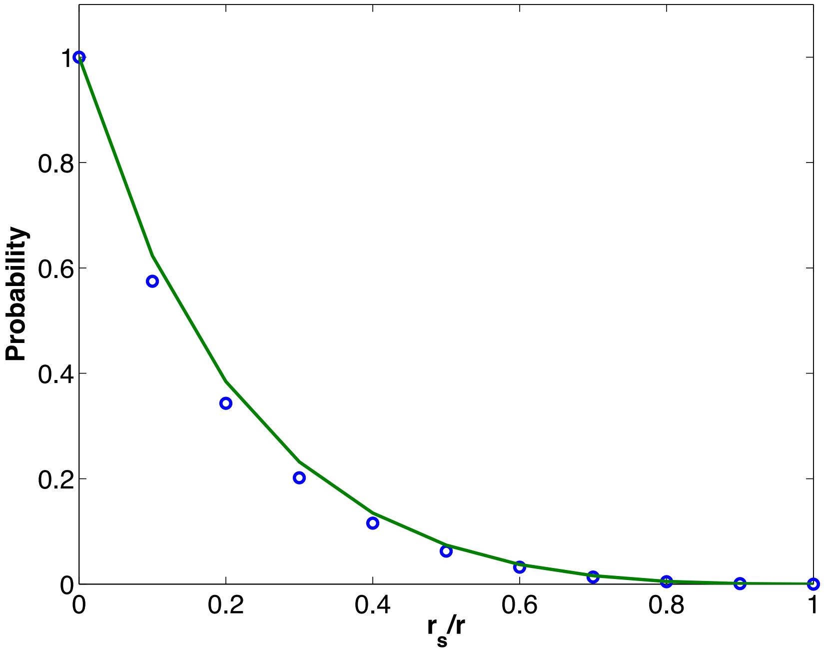
- Induced earthquake magnitudes follow Gutenberg-Richter, independent of time ([Van der Elst, 2016)

Background Stress Level Determines Rupture Extent



Fang and Dunham, Additional shear resistance from fault roughness and stress levels on geometrically complex faults, JGR 2013

Predicted Magnitudes



Normalized Source Radius

In high background stress environments, ruptures extend outside stimulated zone.

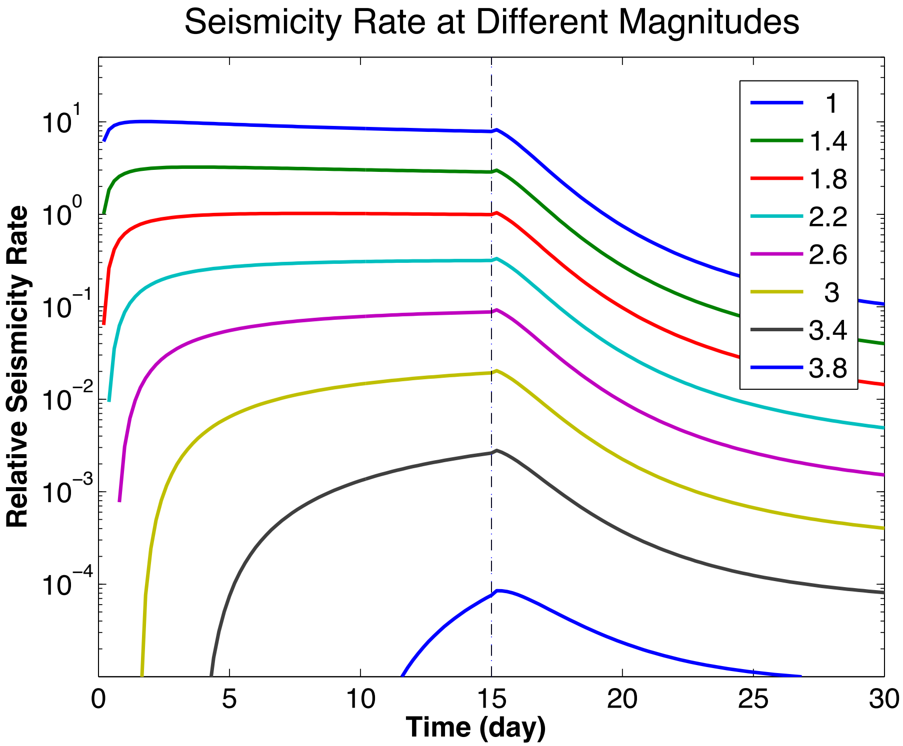
For low background stress the rupture may be contained within or near the perturbed region.

$$R_M(t) = k \underbrace{\int R(\vec{x},t)d\vec{x}}_{\text{Nucleation Rate}} \quad \underbrace{P\left(r_s(M)\right)}_{\text{Prob on source of } r_s} \quad \underbrace{P_{\text{in}}\left(\frac{r_s(M)}{\sqrt{ct}}\right)}_{\text{Prob source w/in perturbed volume}}$$

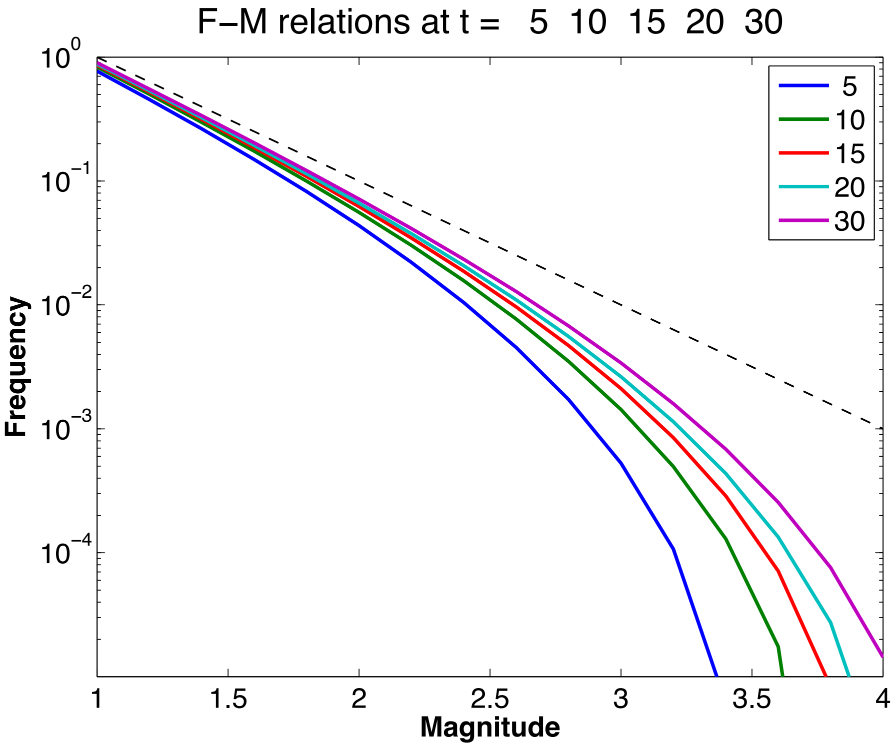
$$R_M(t) = k \underbrace{\int R(\vec{x},t)d\vec{x}}_{\text{Nucleation Rate}} \quad \underbrace{10^{-bM}}_{\text{Prob on source of } r_s} \quad \underbrace{P_{\text{in}}\left(\frac{r_s(M)}{\sqrt{ct}}\right)}_{\text{Prob source w/in perturbed volume}}$$

(see also Baisch 2010; Shapiro 2013)

Magnitude Time Effects



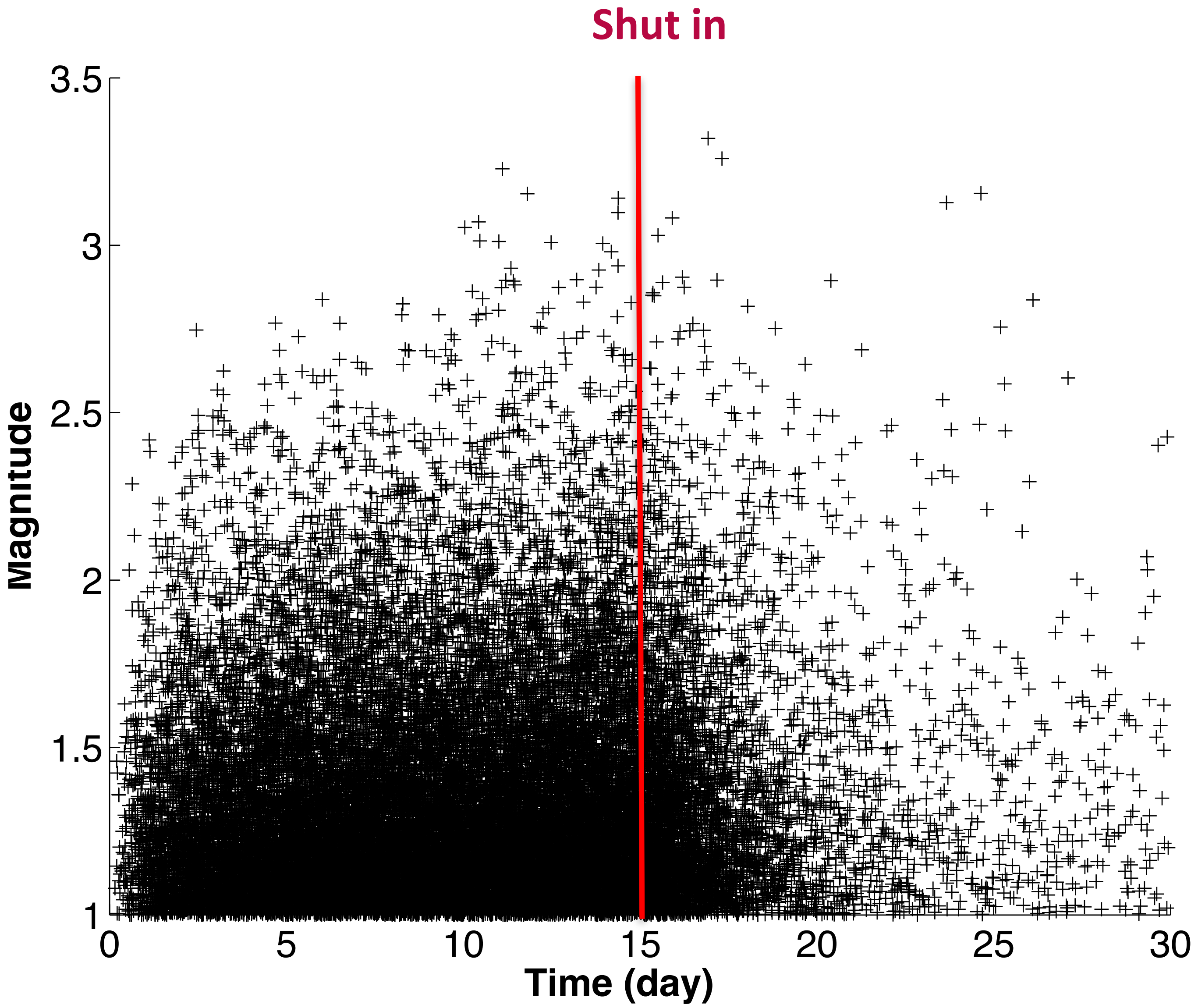
Seismicity Rate at Different Magnitudes



F−M relations at t =   5 10 15 20 30

$$R_M(t) = k \underbrace{\int R(\vec{x},t)\,d\vec{x}}_{\text{Nucleation Rate}} \quad \underbrace{10^{-bM}}_{\text{Prob on source of } r_s} \quad \underbrace{P_{\text{in}}\left(\frac{r_s(M)}{\sqrt{ct}}\right)}_{\text{Prob source w/in perturbed volume}}$$

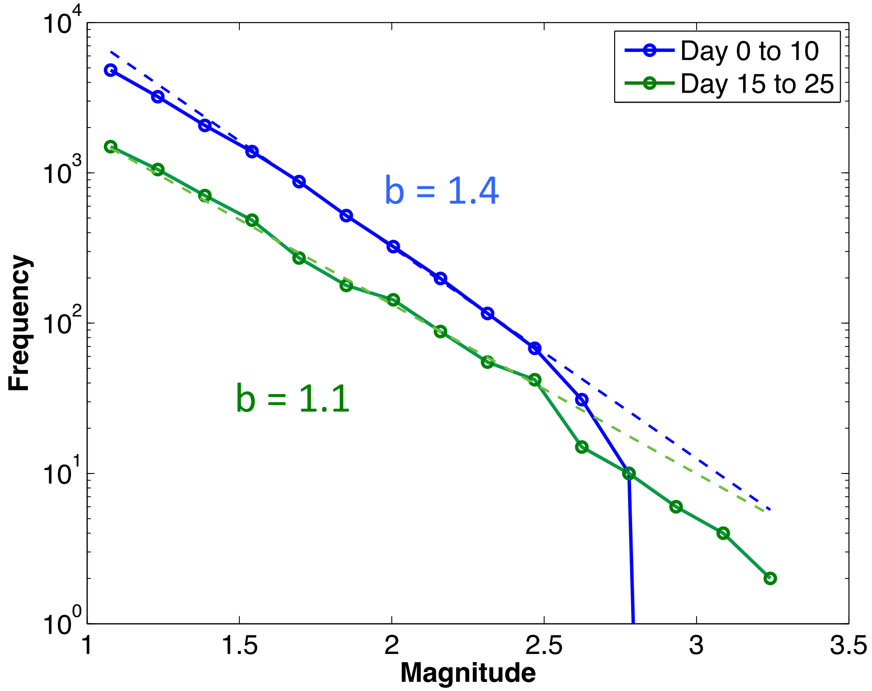
Simulation of Magnitudes

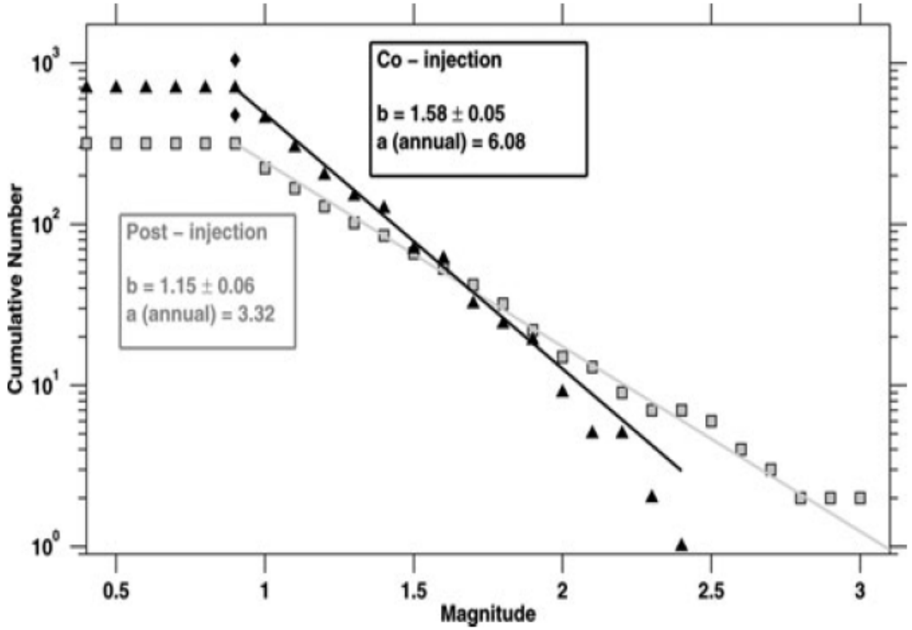


Predicted Frequency Magnitude

Simulation

Basel





(Bachmann et al, GJI 2011)

Conclusions

Poro-elastic stresses may either increase or decrease seismicity rate, depending on geometry.

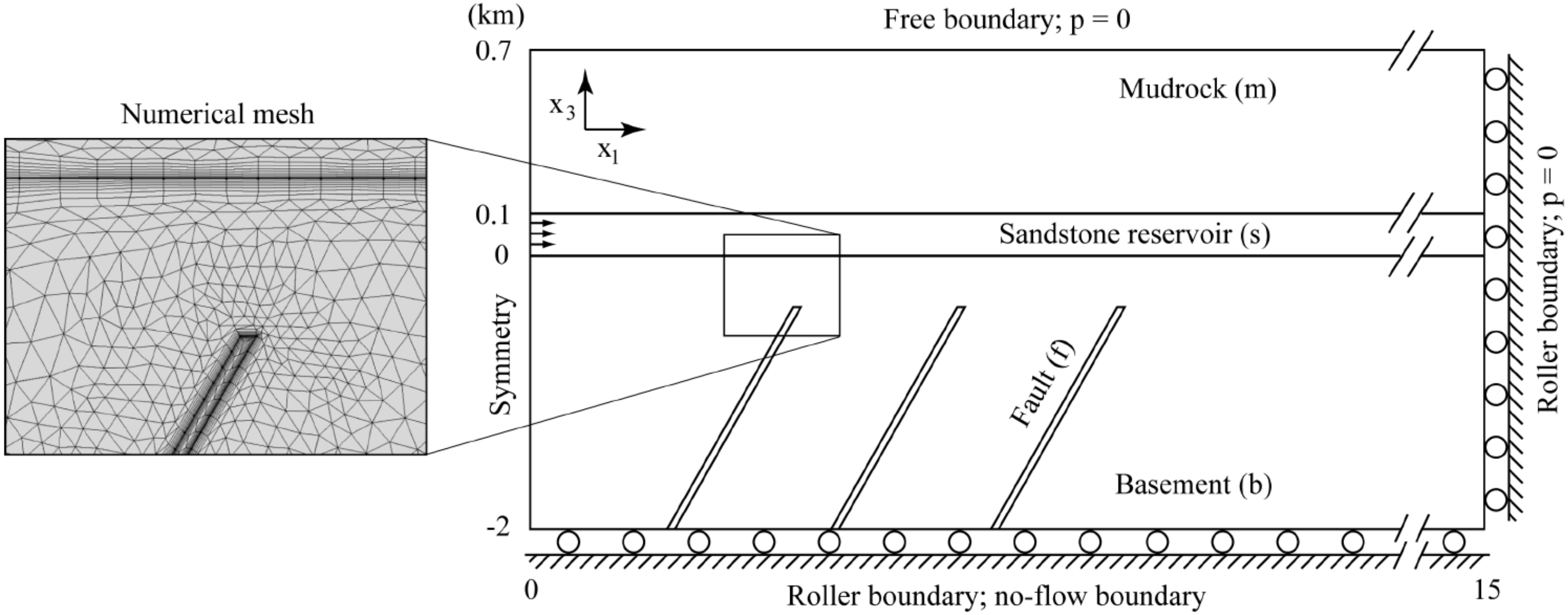
Seismicity onset follows pore-pressure front, although naïve considerations can bias diffusivity to high values.

In some cases sudden shut-in *may locally* increase seismicity rate.

In low background stress environments, larger events are likely to occur post shut-in, complicating "stop light" mitigation strategies.

Simulations exhibit frequency magnitude statistics similar to some observations.

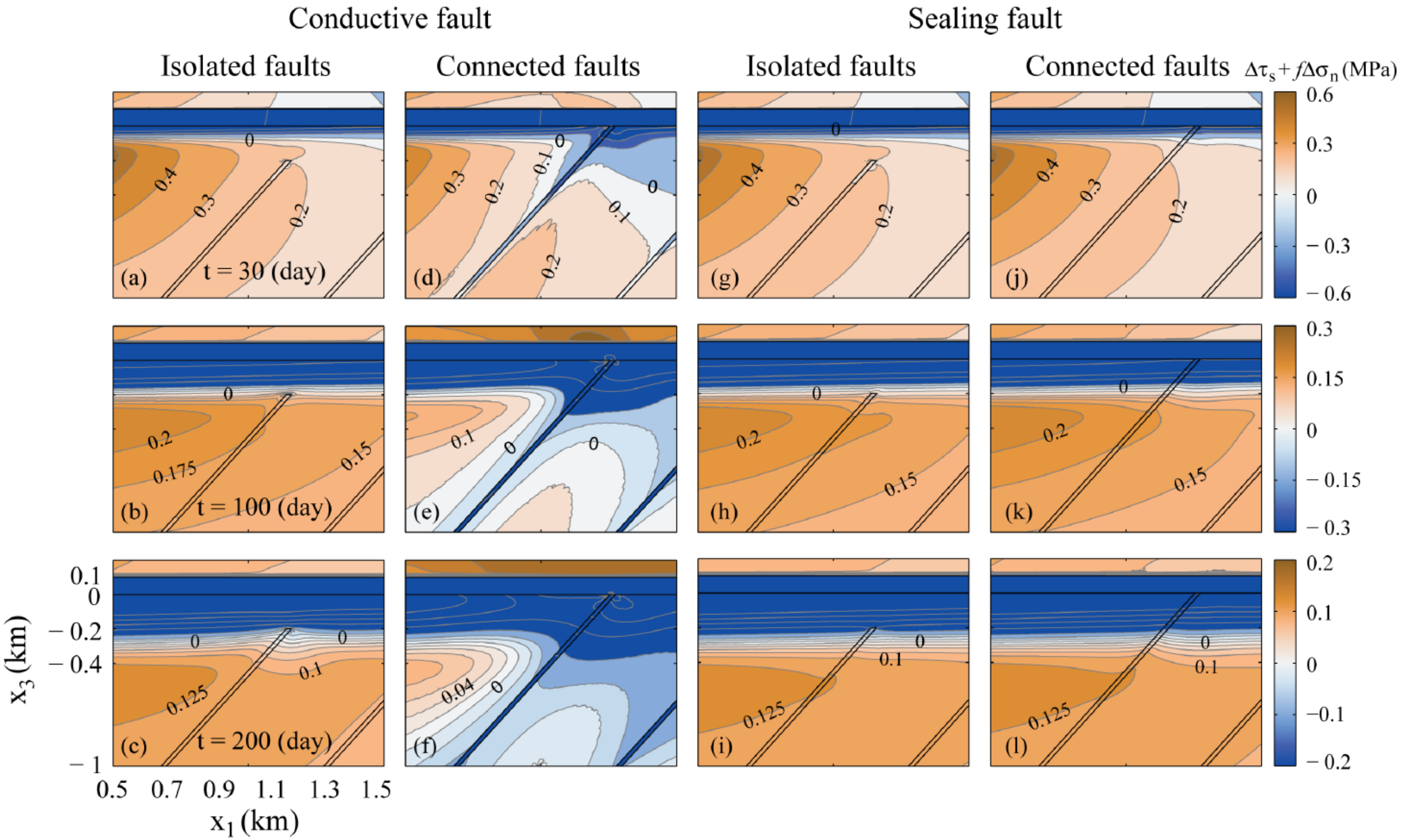
Injection Into Layers above Basement Faults



- Normal Faults in basement rocks
- Plane strain

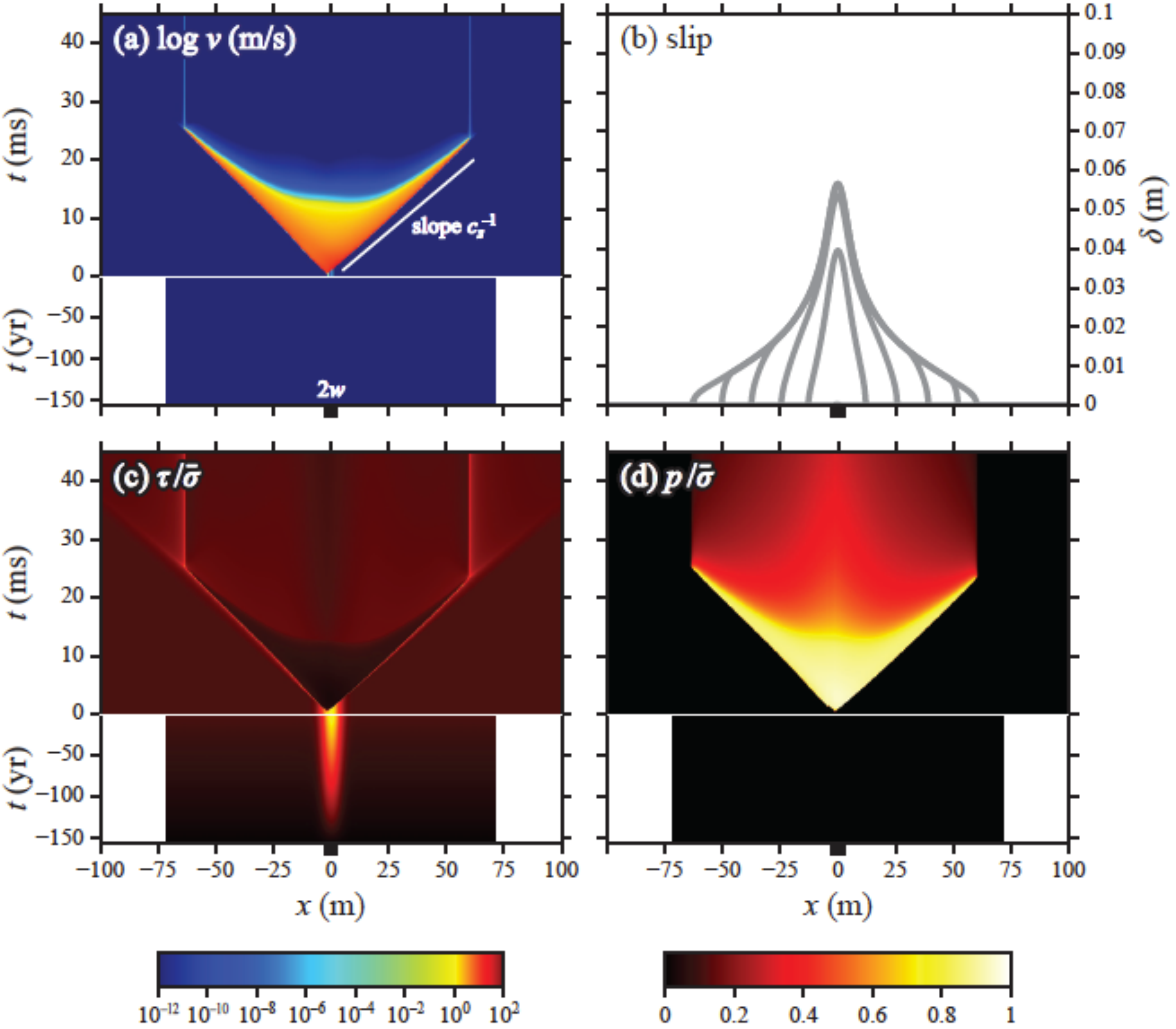
Chang and Segall, JGR, 2016

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



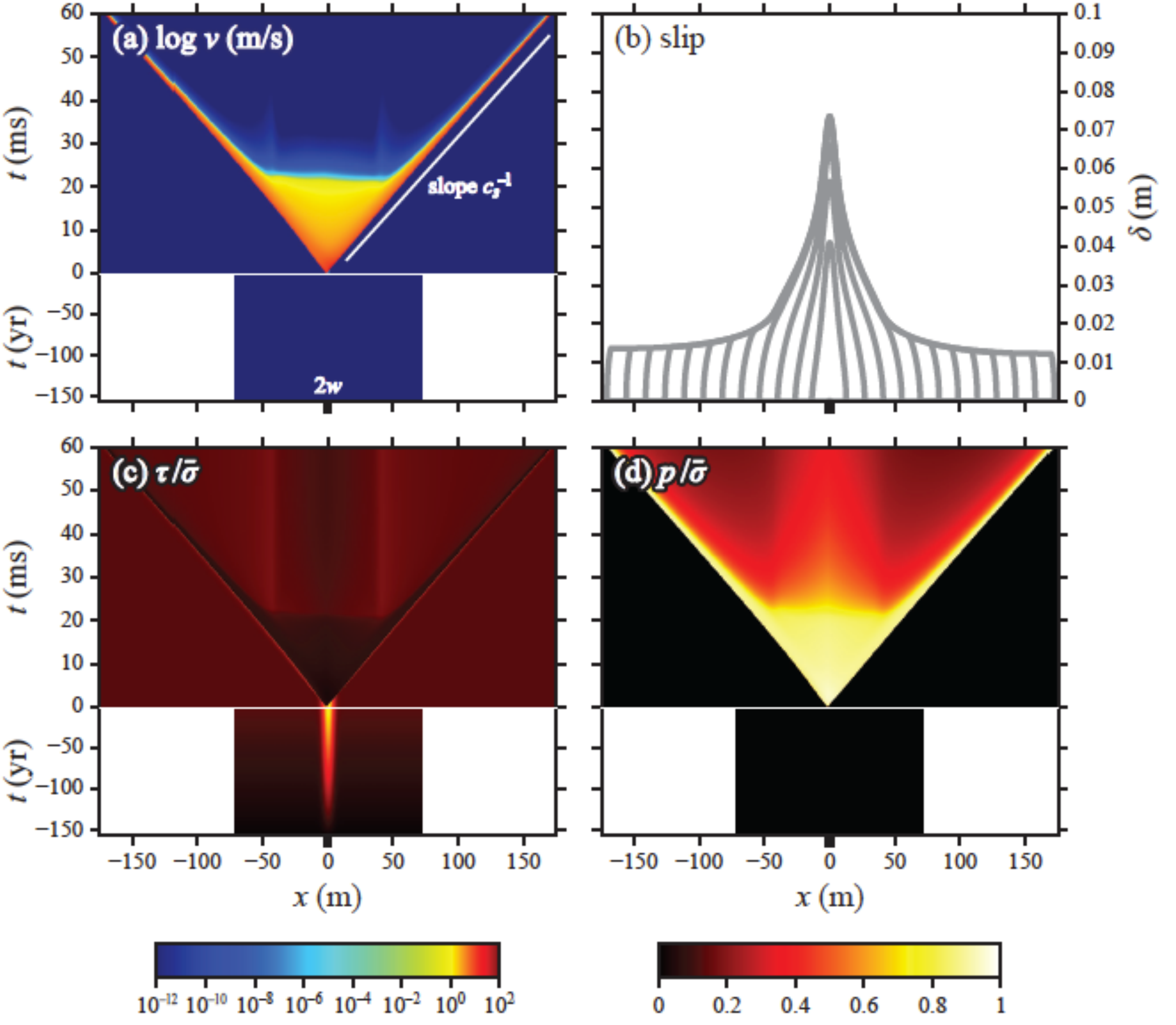
Chang and Segall, JGR, 2016

Dynamic Rupture into Low Stress Surroundings



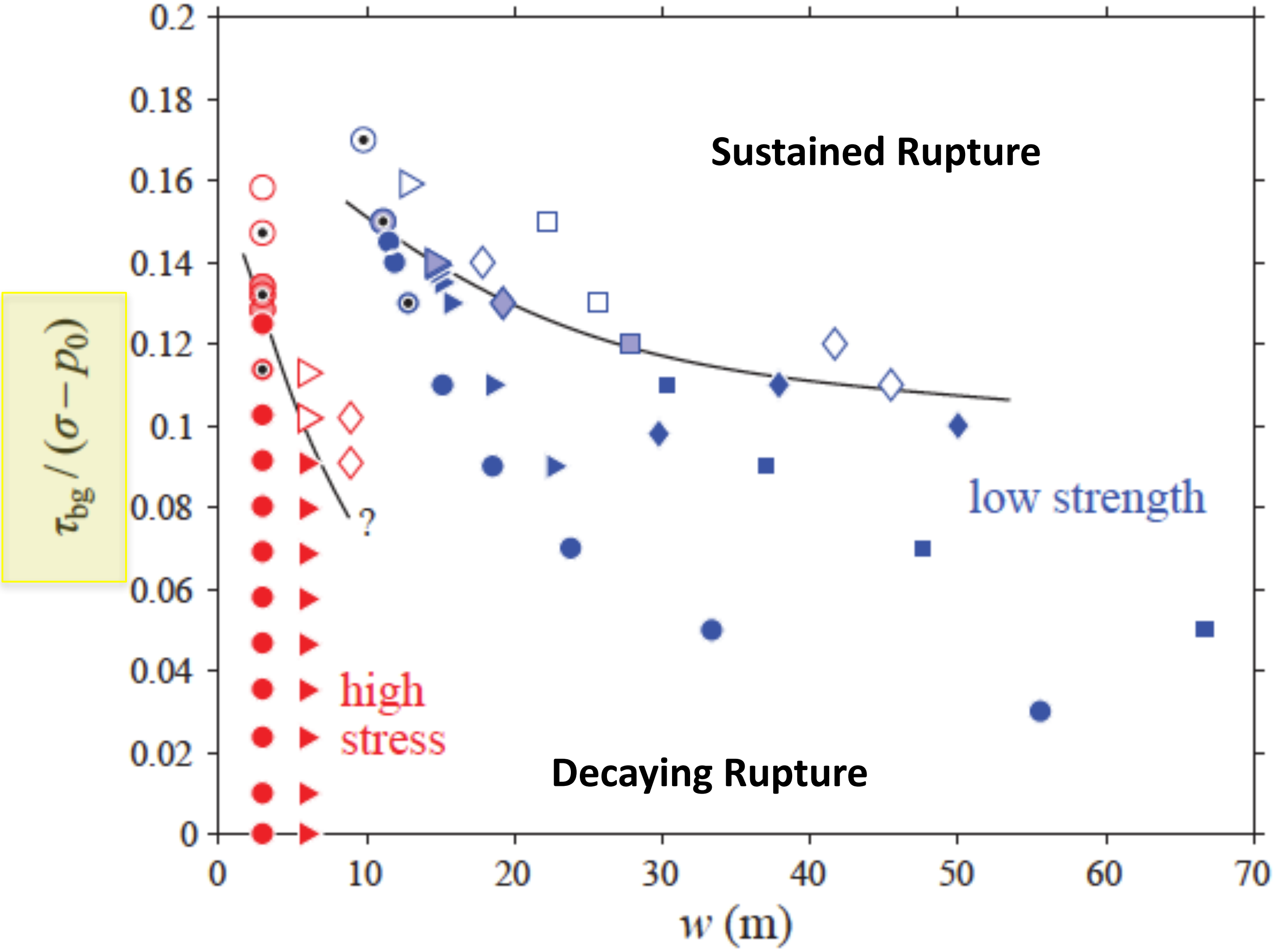
Schmitt, Segall, and Dunham JGR, in review

Dynamic Rupture into Low Stress Surroundings



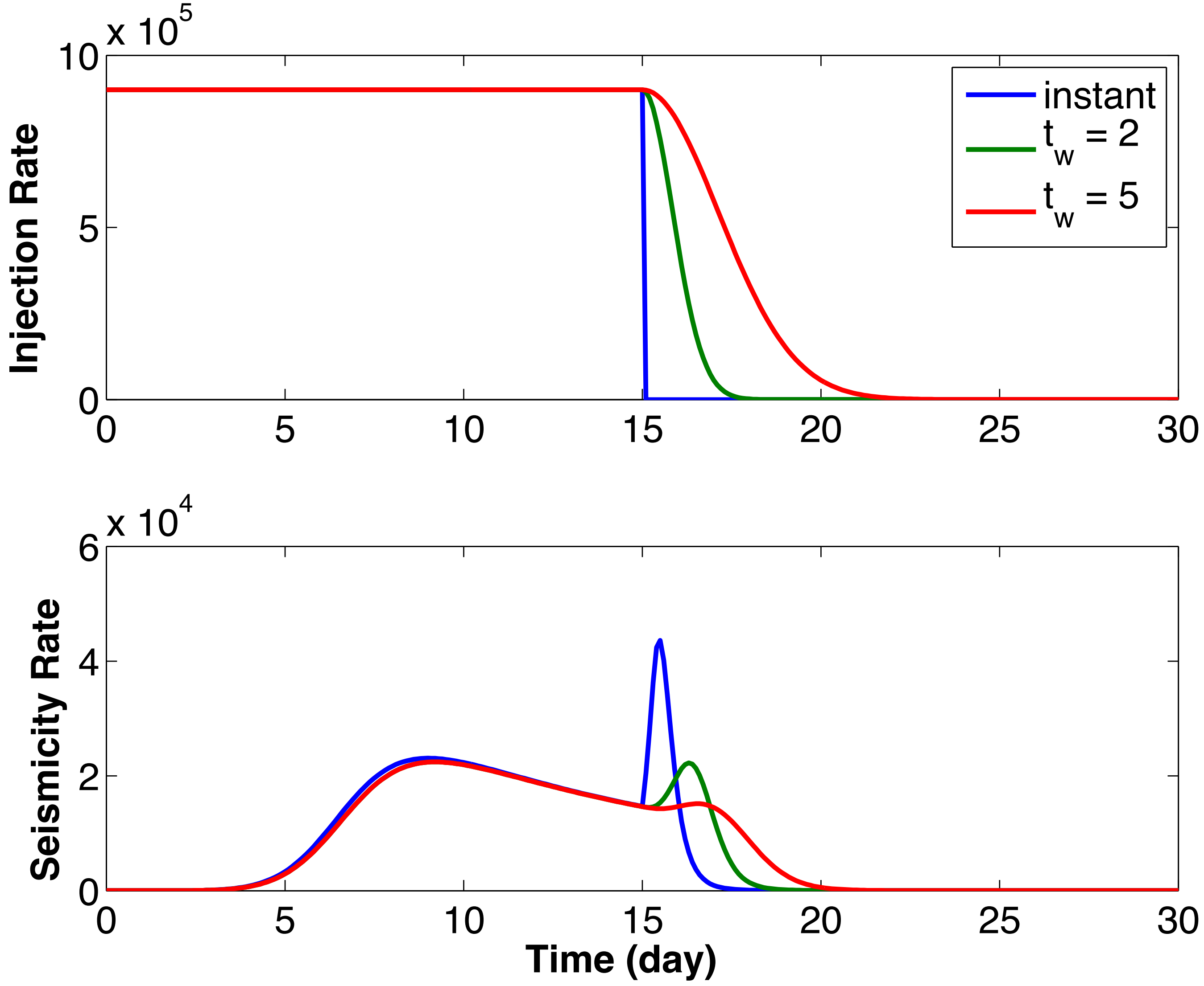
Schmitt, Segall, and Dunham JGR, in review

Rupture Extent & Shear to Effective Normal Stress

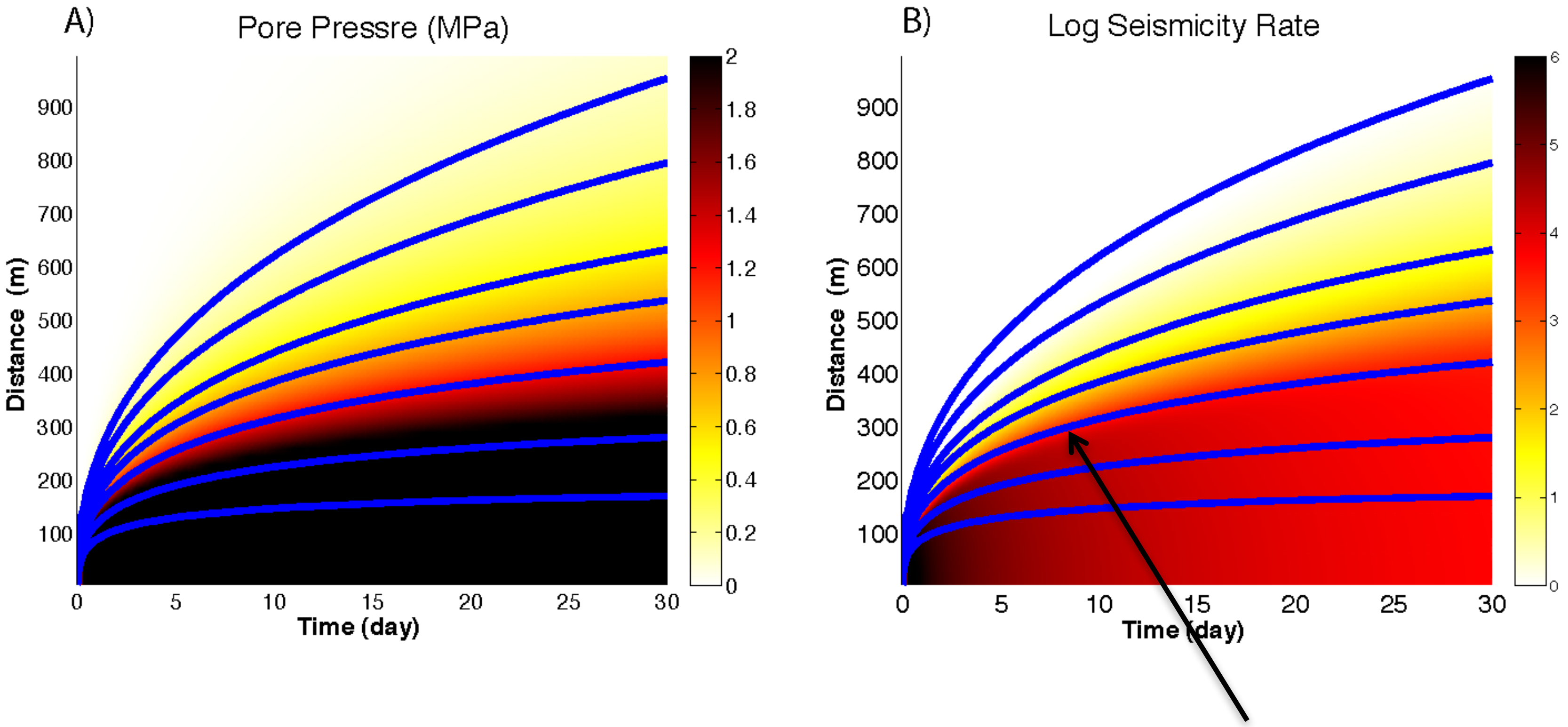


Schmitt, Segall, and Dunham JGR, in review

Gradual Shut-in Mitigates Rate Peak

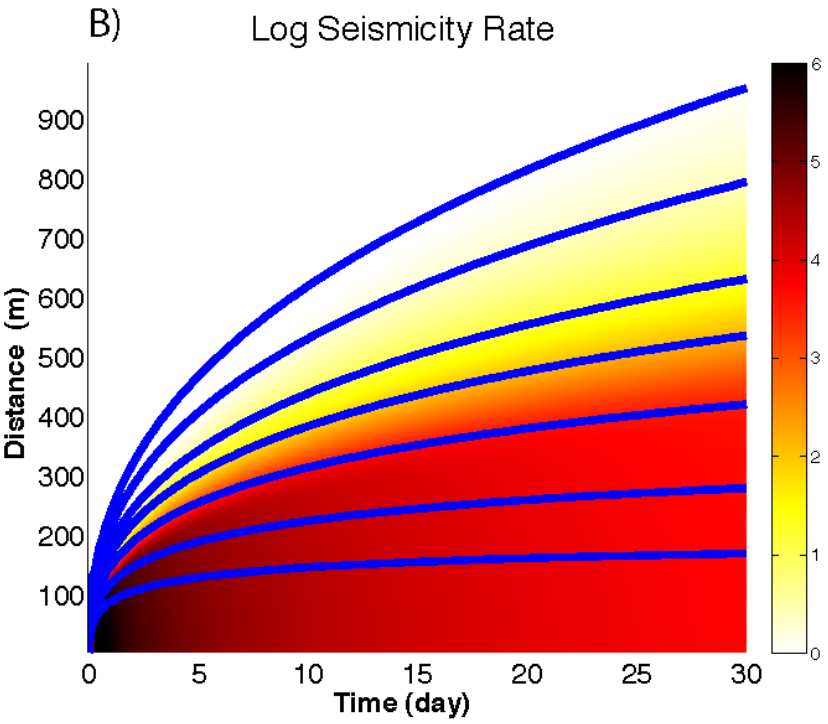


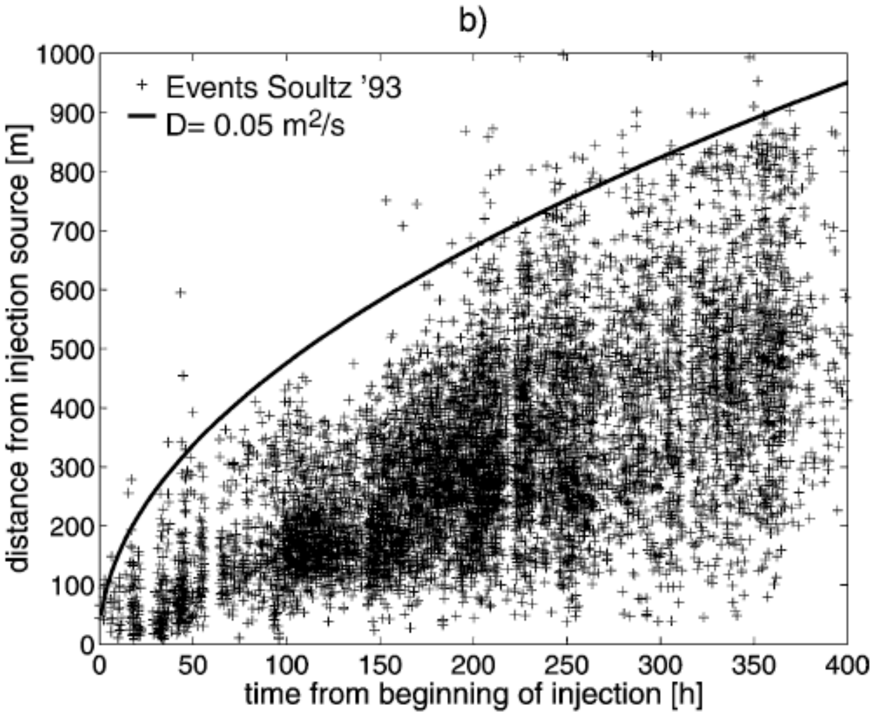
Seismicity Onset Follows Pore Pressure Front



Pore-pressure contours

Decay in Seismicity Rate Following Peak





Soultz, 1993 (Shapiro et al, 2002)