Application of earthquake simulations to seismicity induced by fluid injection

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Earthquake simulator – RSQSim

- Based on rate and state dependent friction

$$\frac{\tau}{\sigma} = \mu = \mu_0 + a\ln\left(\frac{\dot{\delta}}{\dot{\delta}^*}\right) + b\ln\left(\frac{\theta\dot{\delta}^*}{D_c}\right) \qquad d\theta = dt - \frac{\theta}{D_c}d\delta - \frac{\alpha\theta}{b\sigma}d\sigma$$

- Simulations avoid repeated solutions of a large system simultaneous equations → fast computation

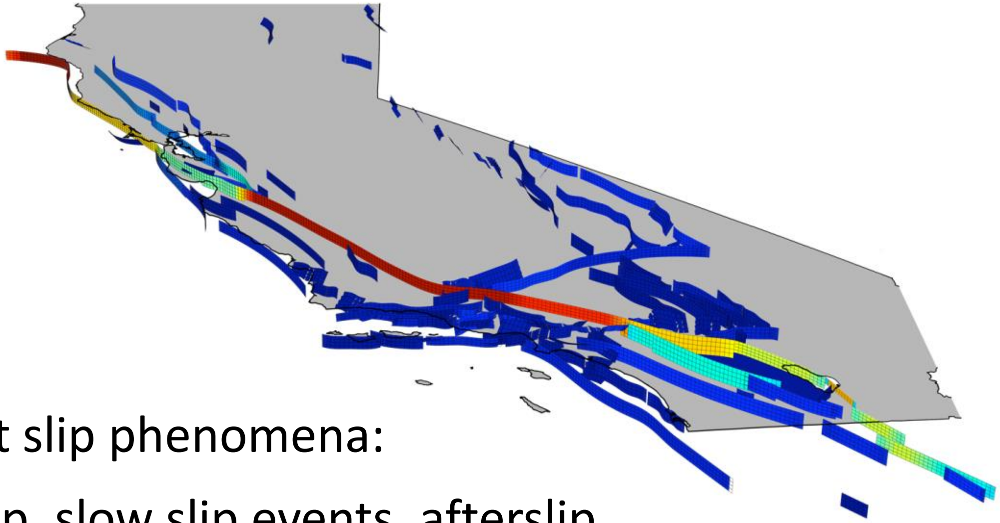
- Event driven computations based on changes of fault sliding state. A fault element may be at one of three sliding states
  - 0 – Aging by log time of stationary contact
  - 1 – Nucleating slip: Time- dependent accelerating slip to instability

    Analytic solutions with rate-state friction
  - 2 – Earthquake slip: quasi-dynamic – to a first approximatio. Slip speed set by by shear impedance.

$$\dot{\delta}_{EQ} = \frac{2\beta\Delta S}{G}$$

RSQSim

(**R**ate-**S**tate **Q**uake **Sim**ulator)



- Comprehensive simulation of fault slip phenomena:
  - → earthquakes, continuous creep, slow slip events, afterslip

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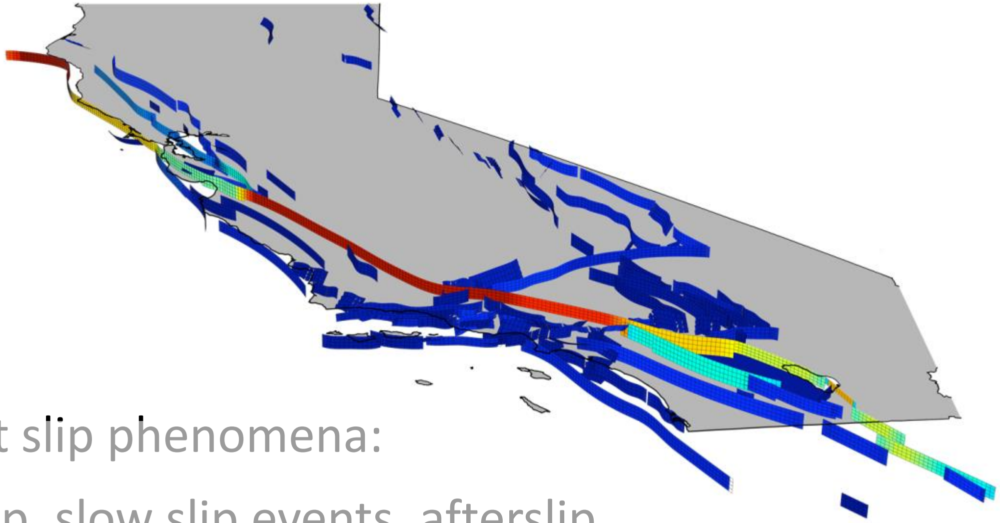

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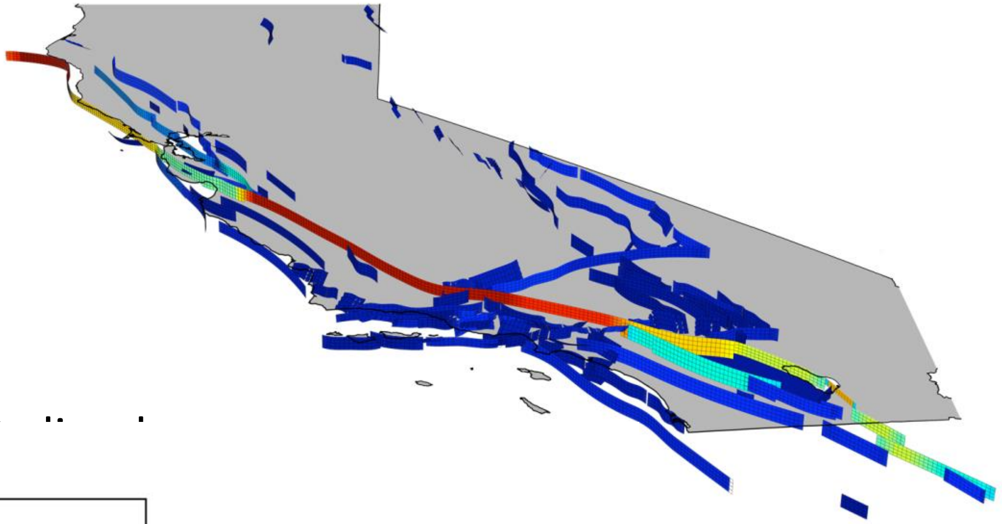

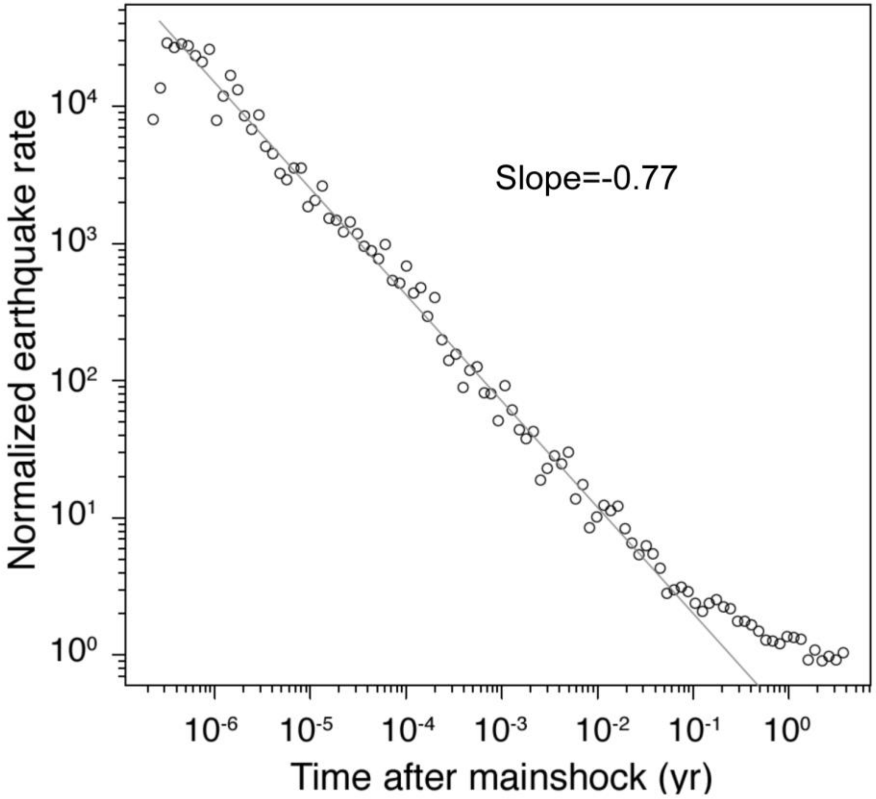

All-California simulation
Aftershocks follow the Omori Law for aftershock decay with time

RSQSim
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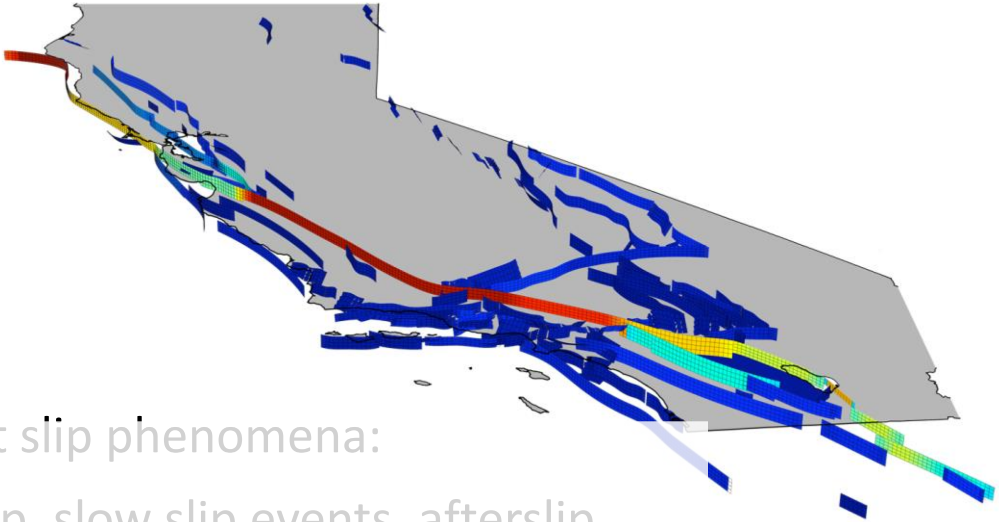

- Comprehensive simulation of fault slip phenomena:
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- High resolution models of geometrically complex fault systems
  - → Up to 10^6 fault elements
  - → Range of earthquake magnitudes M=3.5 to M=8

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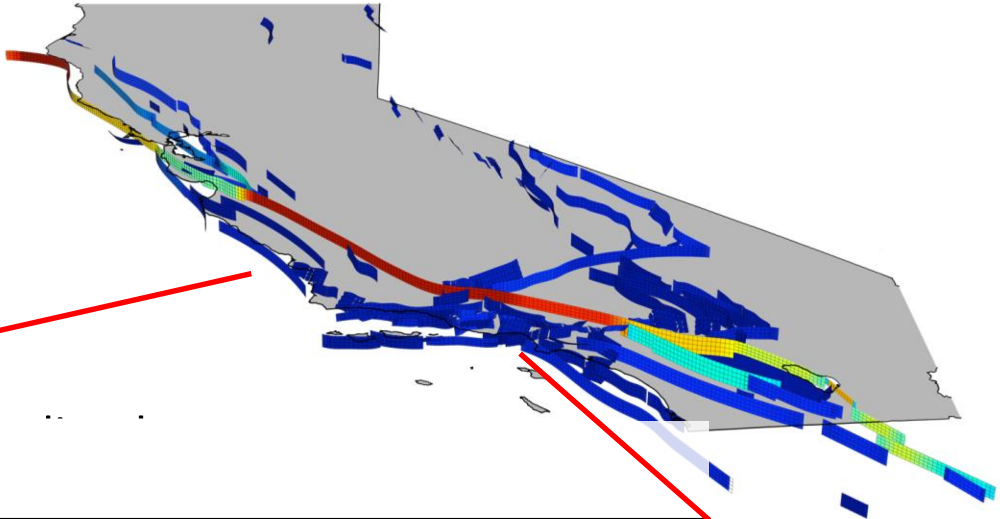

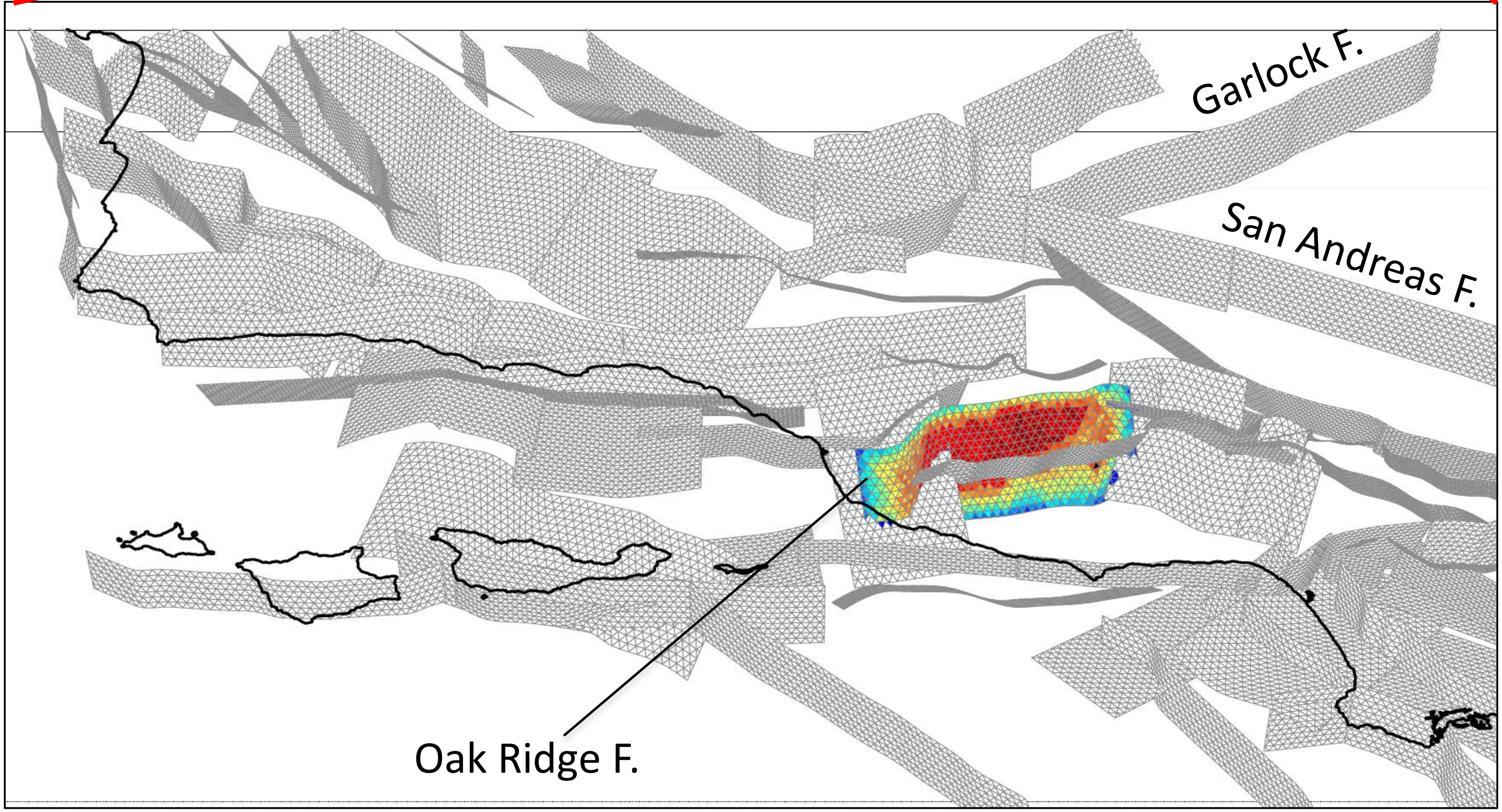

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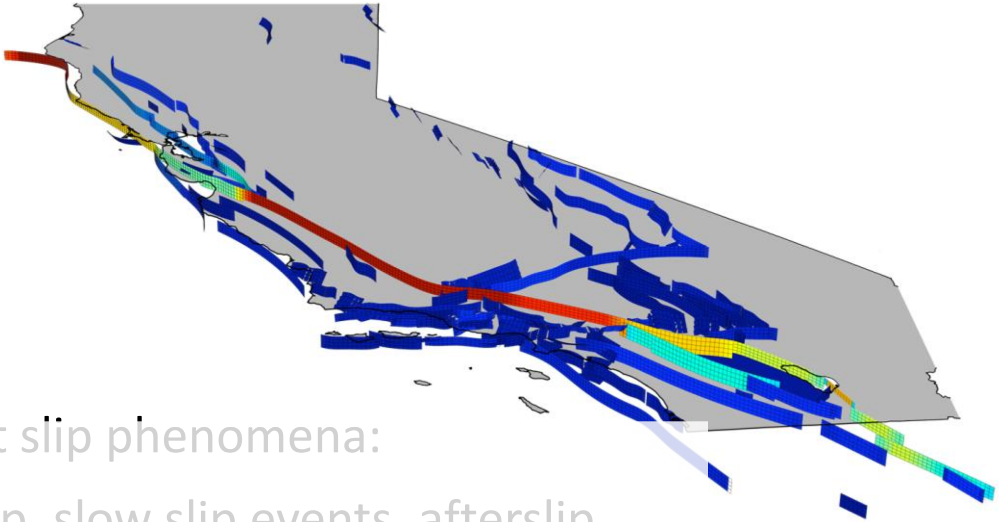

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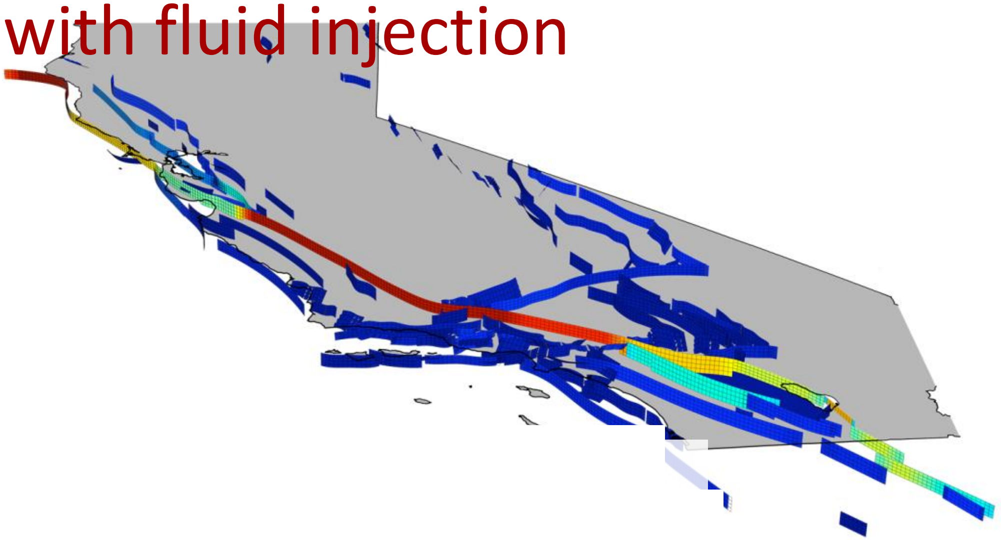
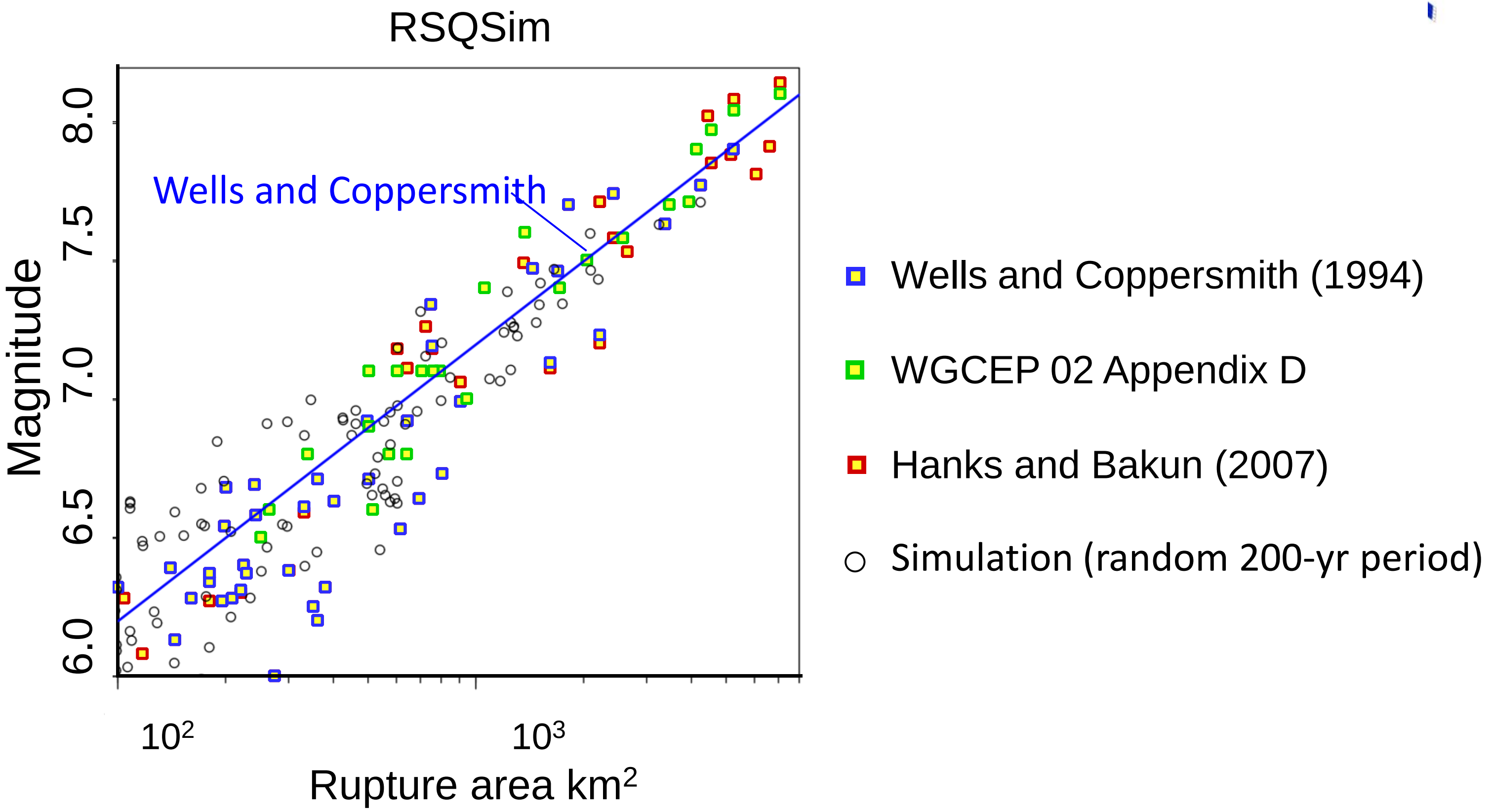
  - ➞ earthquakes, continuous creep, slow slip events, afterslip
- Implement rate- and state-dependent friction effects
  - ➞ Earthquake clustering effects (aftershocks and foreshocks)
- High resolution models of geometrically complex fault systems
  - ➞ Up to 10^6 fault elements
  - ➞ Range of earthquake magnitudes
- Long simulations of $>10^6$ earthquakes
  - ➞ Statistical characterizations are consistent with observations
  - ➞ Repeated simulations to explore parameter space

Tectonic stressing with fluid injection

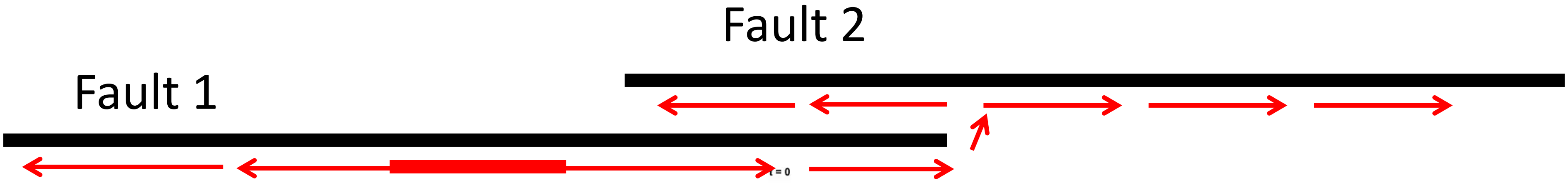
RSQSim

(**R**ate-**S**tate **Q**uake **Sim**ulator)

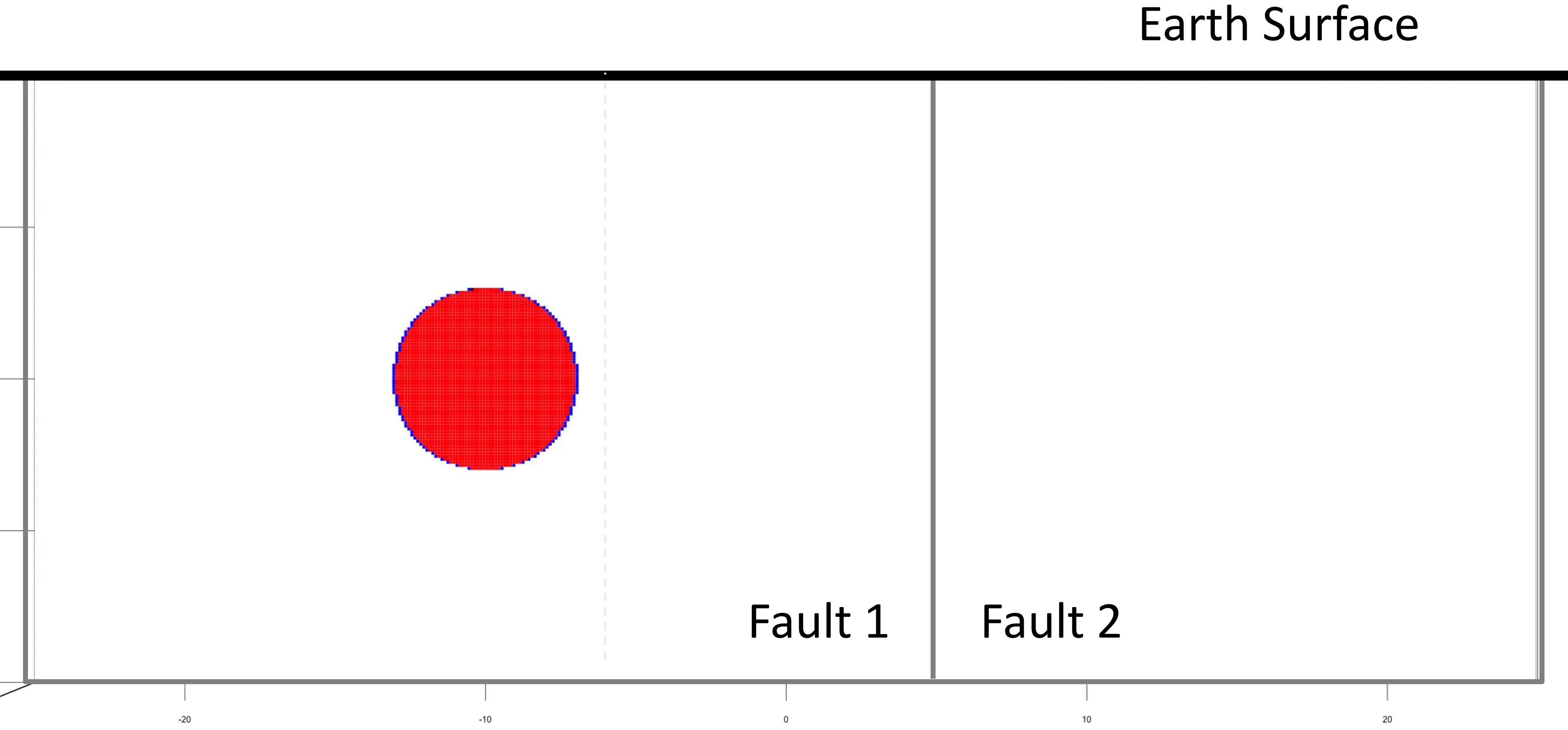




M=7.0 Multi-fault earthquake rupture simulation



Red shows areas that are actively slipping in the earthquake



Earthquake rate model
Based on rate-state nucleation solutions

Approach

The formulation is based on the premise that earthquake nucleation controls the time and place of initiation of earthquakes. Hence, processes that alter earthquake nucleation times control changes of seismicity rates. Assumes a steady-state seismicity rate that is proportional to stressing rate.

Implemented with a simple planar fault models with 400-1600 fault elements

Earthquake rate $$R = \frac{r}{\gamma \dot{\tau}_r} \quad , \quad d\gamma = \frac{1}{A\sigma}\left[dt - \gamma d\tau + \left(\frac{\tau}{\sigma} - \alpha\right) d\sigma\right]$$

Coulomb stress $$dS = d\tau - \mu d\sigma$$

Earthquake rate $$R = \frac{r}{\gamma \dot{S}_r} \quad , \quad d\gamma = \frac{1}{A\sigma}\left[dt - \gamma dS\right]$$

(Dieterich, 1994), Dieterich and others, Nature, (2000), Dieterich and others, USGS Prof - 1676 (2003)

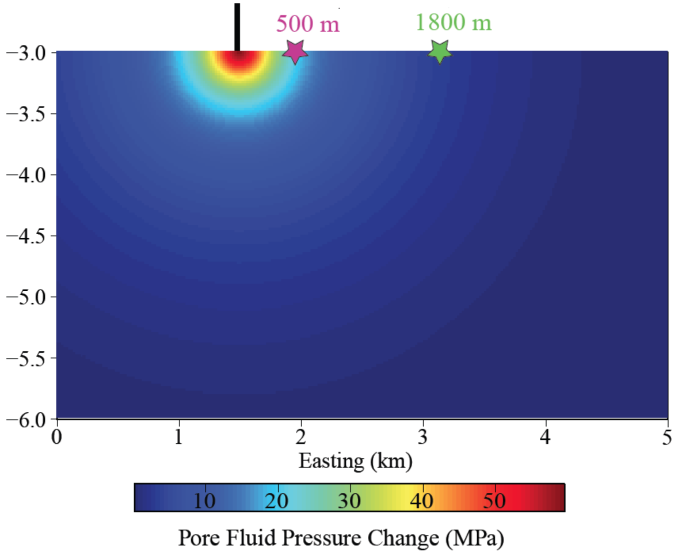
“Reservoir” Model

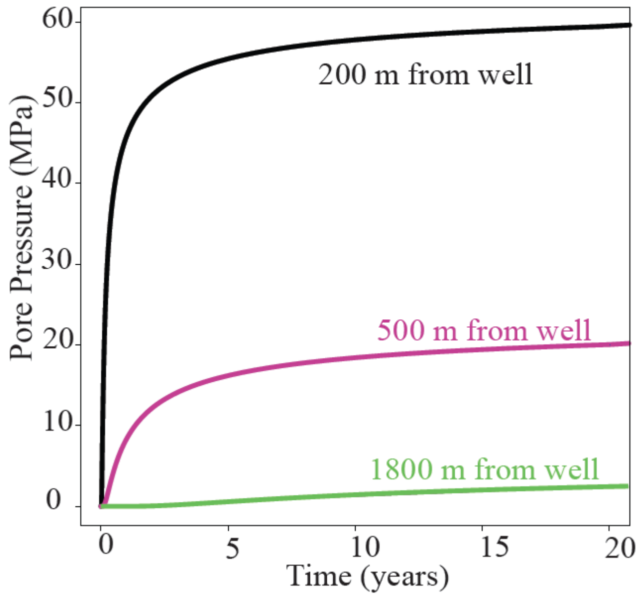
We use a simple analytic expression (Wang, 2000) for the diffusion of pore-fluid pressure, *P*, into a homogeneous full- or half-space from a point source, and only the effects of *P* on the effective normal stress (vs. more complete poroelastic effects).

$$P(t,x) = \frac{\dot{V}}{\kappa \psi x} f(t,x) \ ,$$

where, $\dot{V}$=injection rate, $\psi = 4\pi\phi c_T$, $f(t,x) = erfc \sqrt{\frac{|x|^2}{4\kappa t}}$

porosity compressibility





Zero Tectonic Stressing Rate Models

The semi-infinite reservoir model used in this initial study results in a long-term steady-state maximum fluid pressure that is inversely proportional to the distance from the point of injection. The maximum fluid pressure sets the minimum and maximum initial shear stress that will result in induced earthquakes

- If the initial shear stress τ_0 is greater than $\tau_{max:}$

$$\tau_{\max} = \sigma_0 \left[\mu_0 + (b-a) \ln \left(\frac{\theta_0 V^*}{D_c} \right) \right]$$

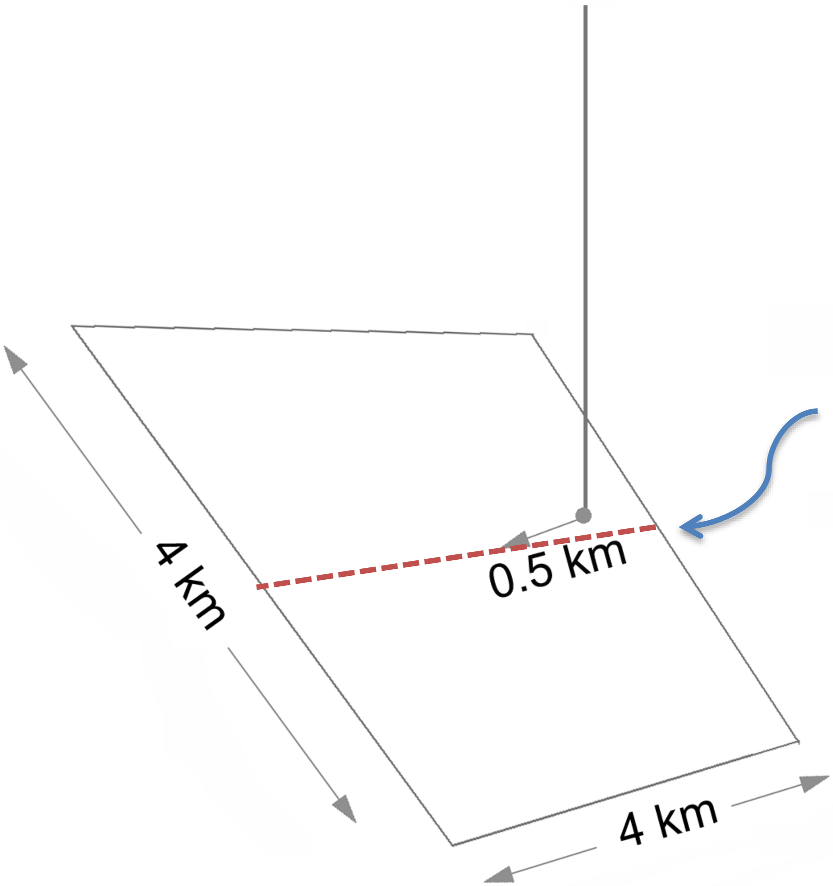
then events will nucleate even in the absence of pore-fluid pressure perturbations.

- If the initial shear stress τ_0 is less than $\tau_{min:}$

$$\tau_{\min} = (\sigma - P) \left[\mu_0 + (b-a) \ln \left(\frac{\theta_0 V^*}{D_c} \right) - \alpha \frac{b-a}{b} \ln \left(1 - \frac{P}{\sigma_0} \right) \right]$$

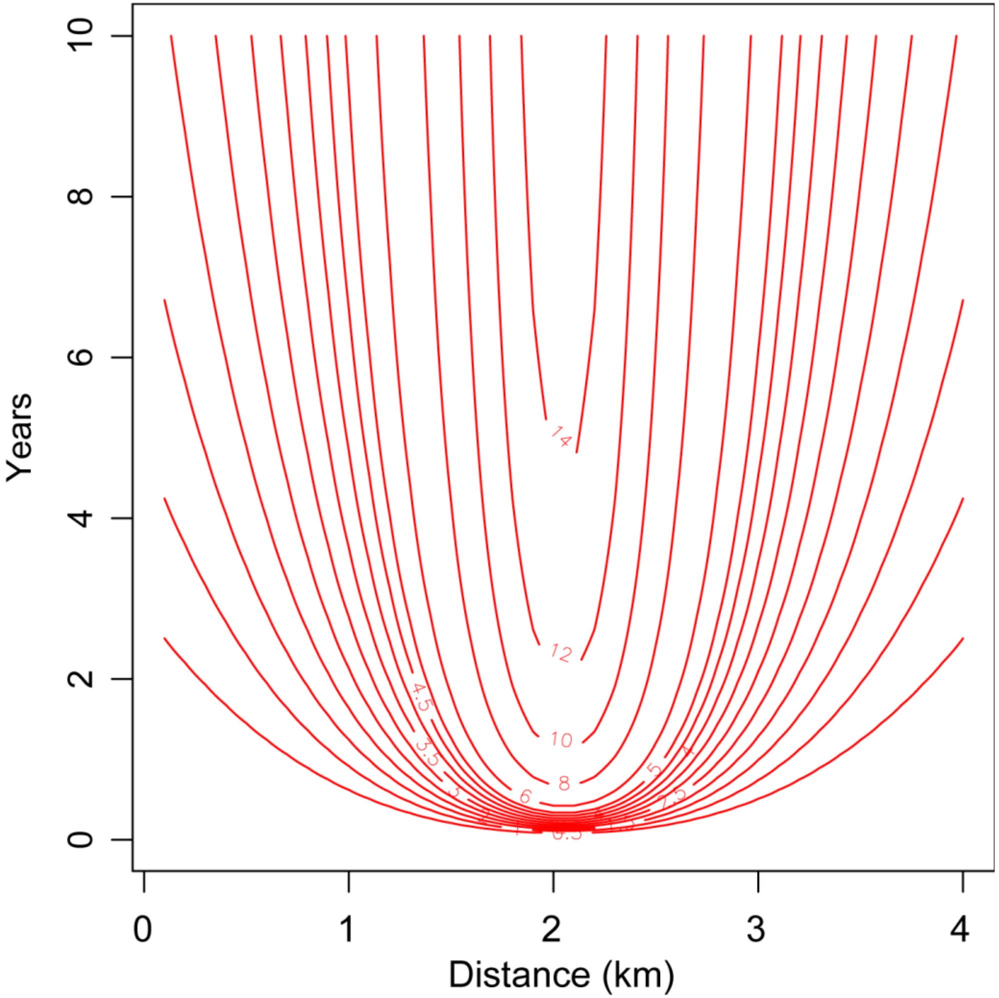
where *P* is the maximum pore-fluid pressure perturbation, then no events will ever nucleate.

Simple fault model with 1600 fault elements (100m x 100m)



Pressure and
Earthquake rate profiles

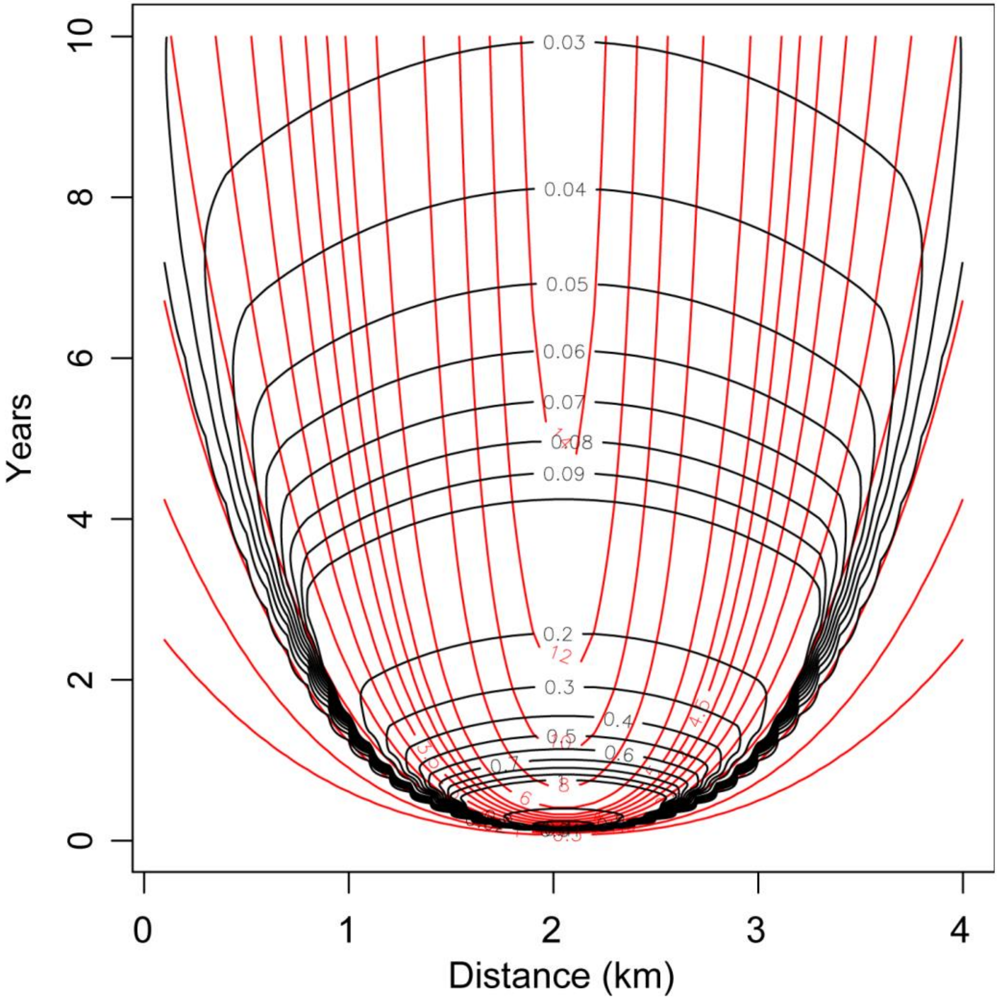
Change of fluid pressures along profile closest to injection point



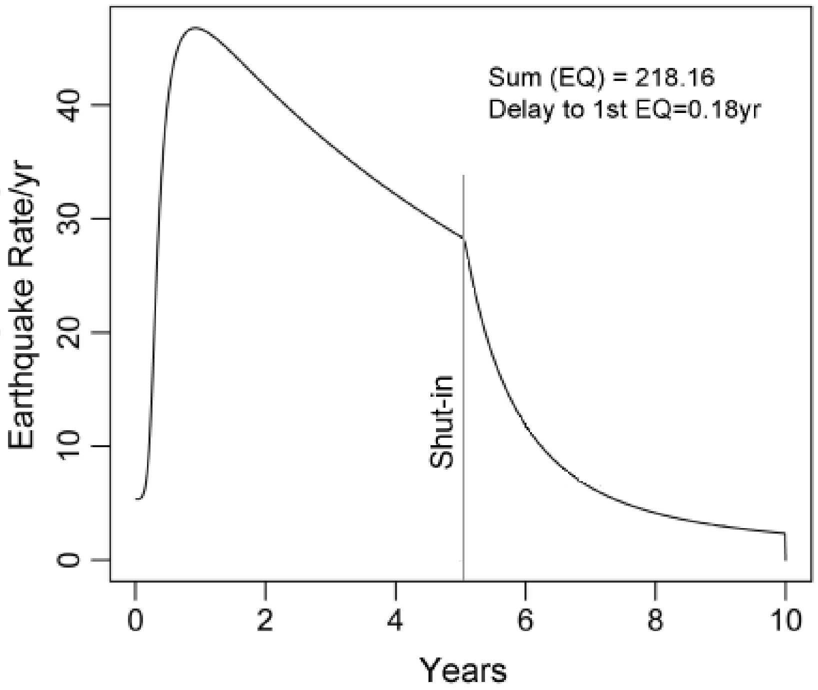
s0.5,

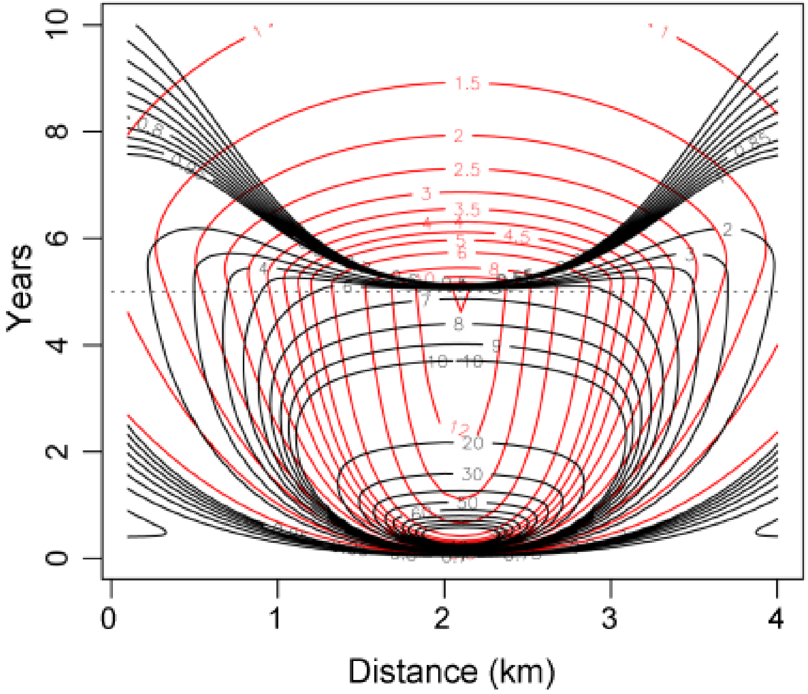
Change of fluid pressures along profile closest to injection point Earthquake rates (black)

Initial stress is 0.5 Mpa below that for stress for steady state seismicity



Earthquake rate model





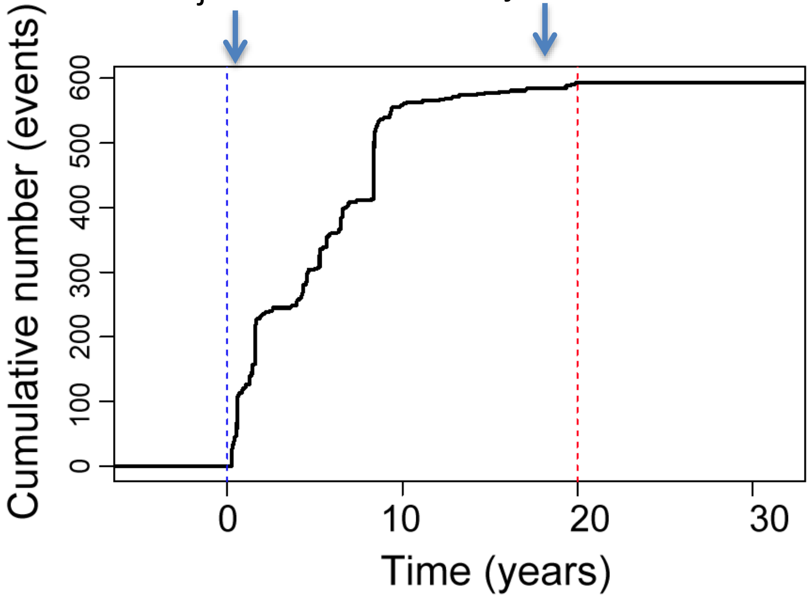
Diffusivity=0.01, Porosity=0.07, Initial Stress=-0.1MPa

Example of simulation of induced seismicity using RSQSim

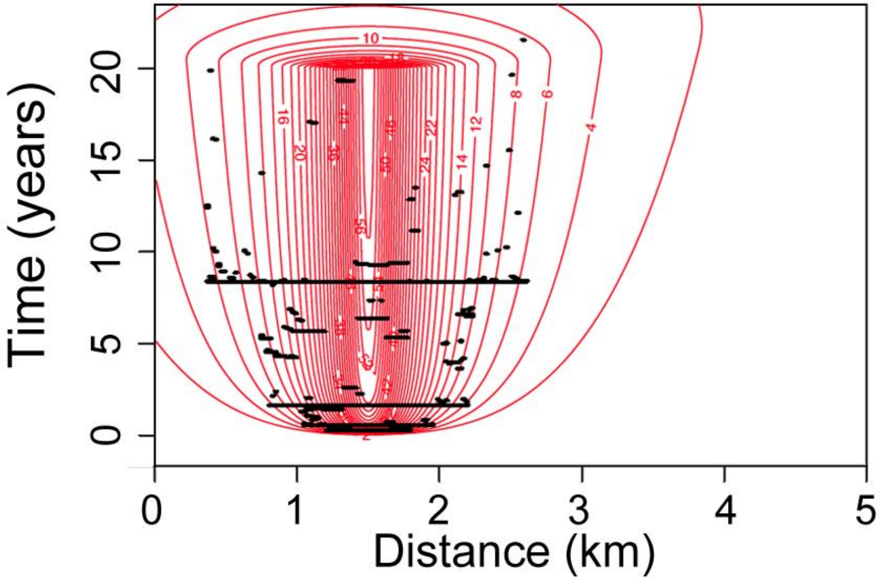
Model: Single fault with initial shear stress ~5MPa below critical stress (for failure without injection), no tectonic stressing, injection rate = 0.01M^3/s, injection point is 200m out of the plane of the fault

Start injection

End injection



Space-time plot of earthquake ruptures and fluid pressures (along upper edge of fault)

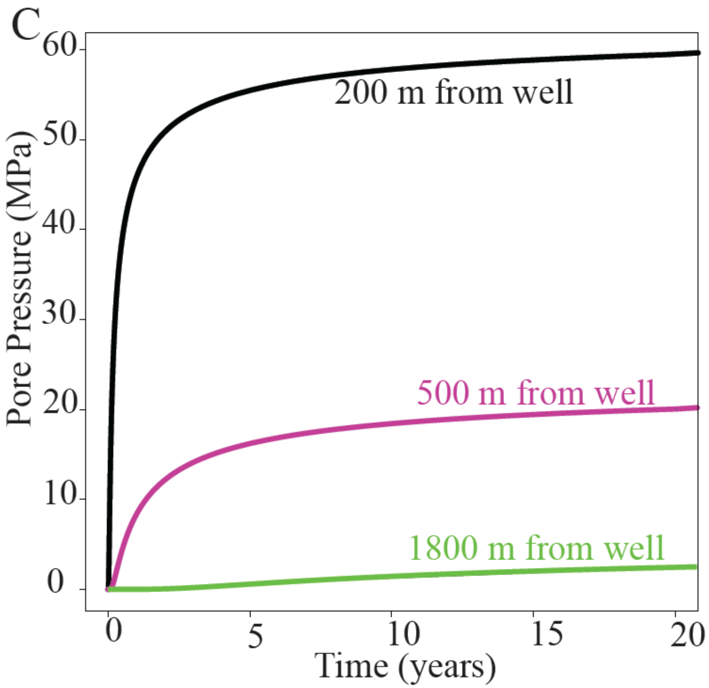


Initial shear stress and fluid pressures to induce earthquakes

The average initial stress τ on the fault surface strongly affects the characteristics of induced seismicity.

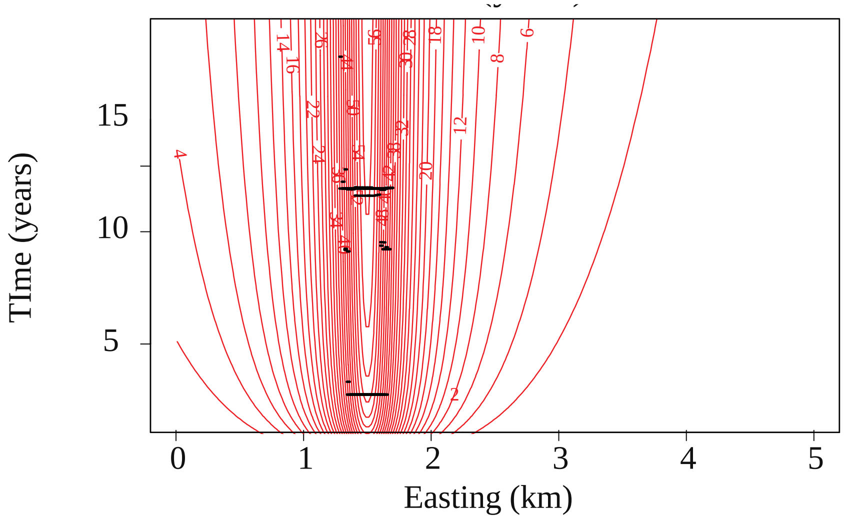
With increasing τ in the range τ_{min} to τ_{max} :

- The delay between the start of injection and onset of seismicity decreases,
- the magnitude of the first induced event increases,
- the magnitude of the largest event in the sequence increases,
- the cumulative number of induced earthquakes increases,
- the distance from the injection point to the most distance earthquake increases, and
- the seismicity following shut-in increases and persists for longer times.

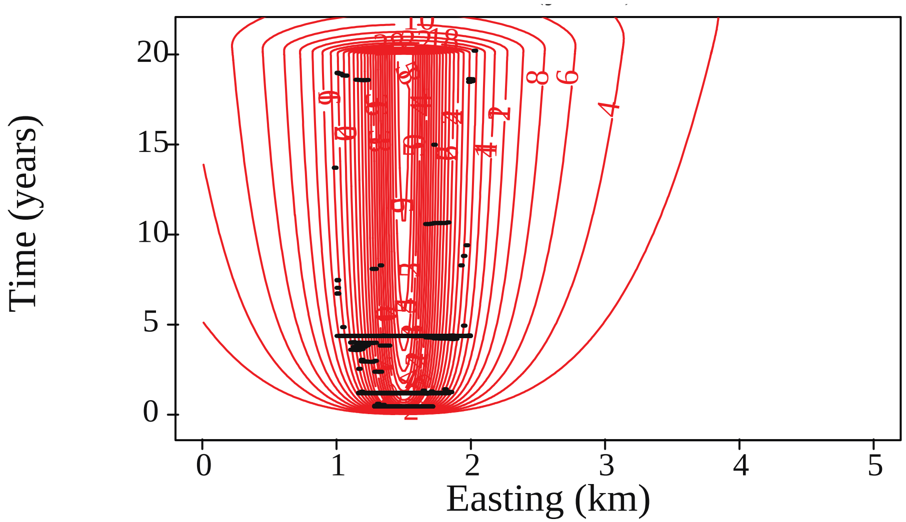


Effect of Initial Shear Stress

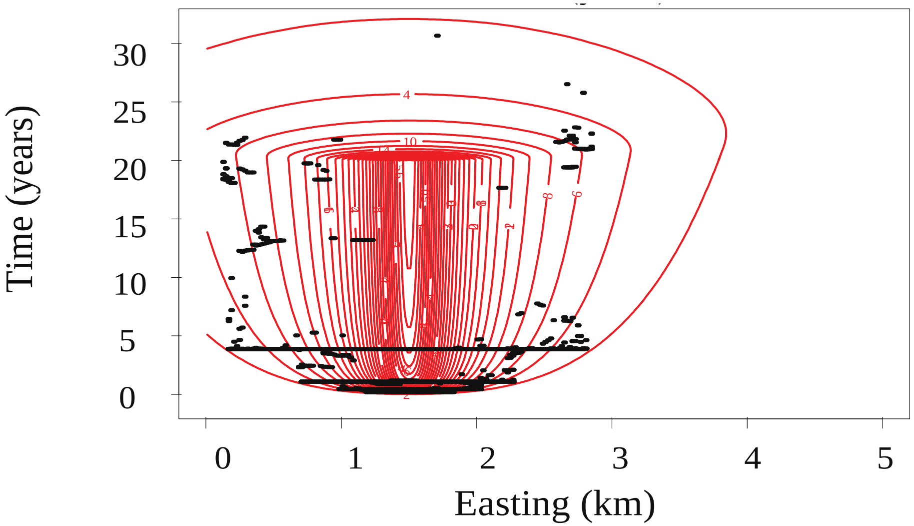
τ_0 = 36 MPa



τ_0 = 48 MPa

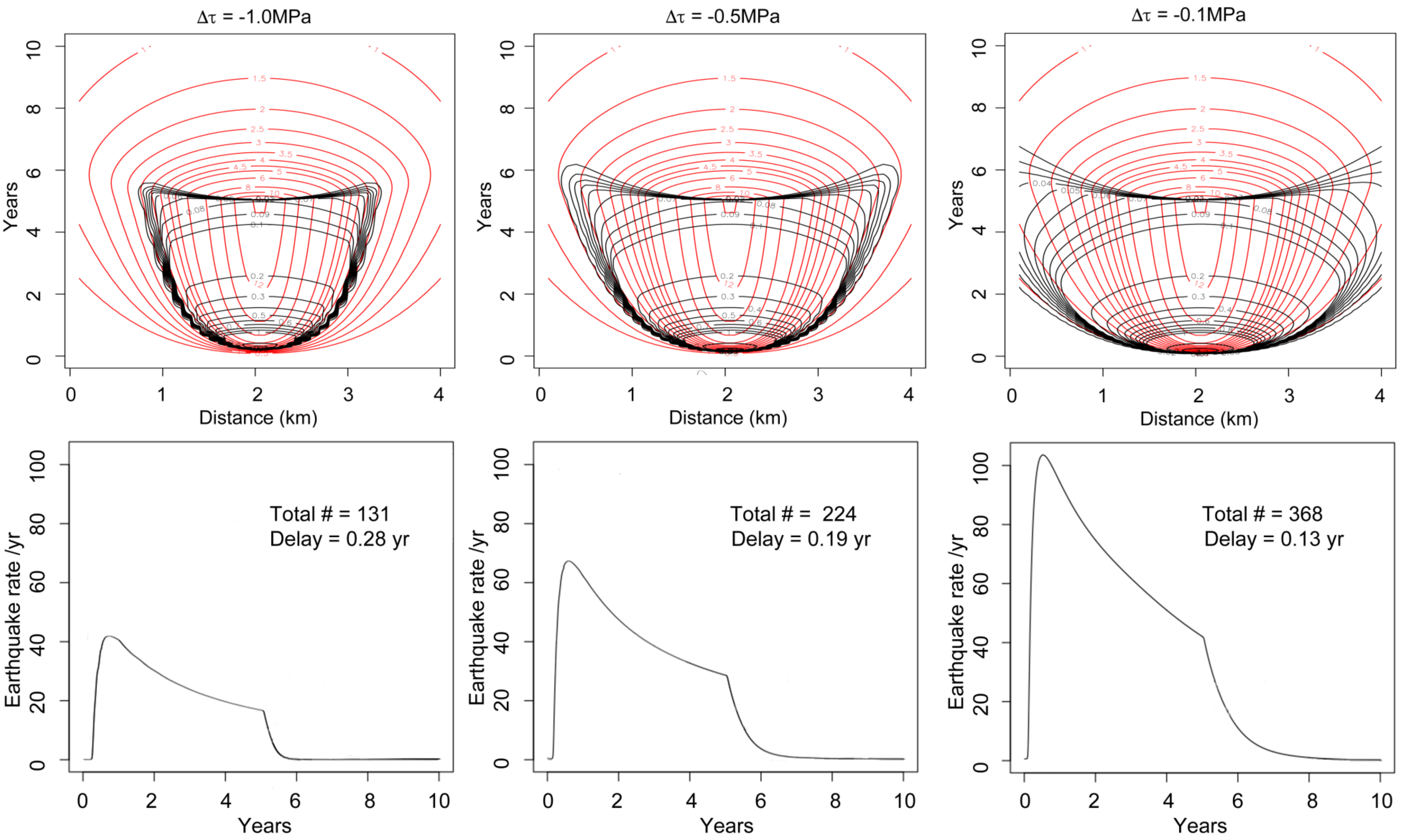


τ_0 = 56 MPa



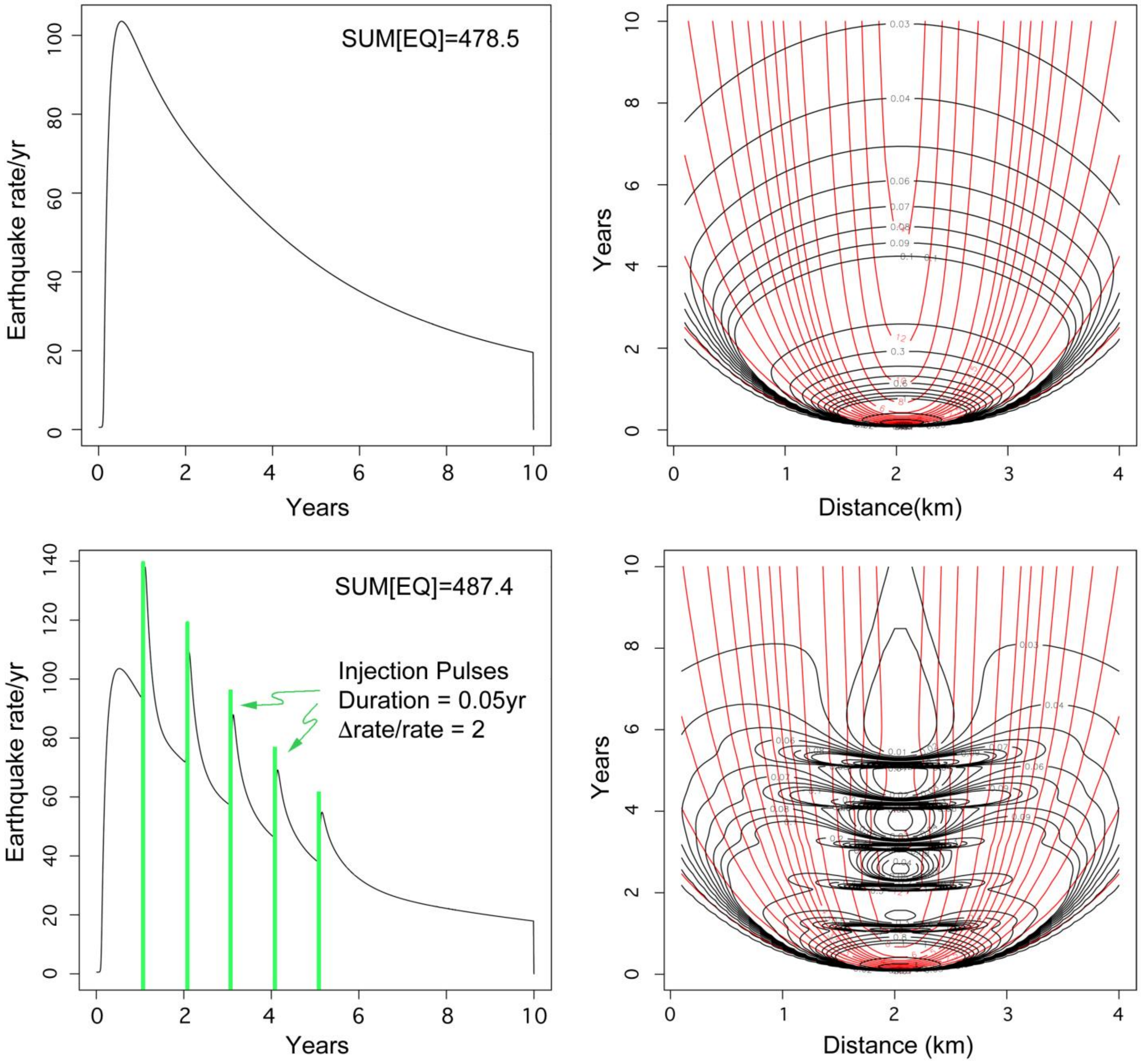
- At lower τ_0: events confined to area near injection point
- At higher τ_0:
  - events can rupture into areas of lower pore-fluid pressure
  - Post shut-in seismicity is enriched and continues for a longer time

Effect of Initial Shear Stress



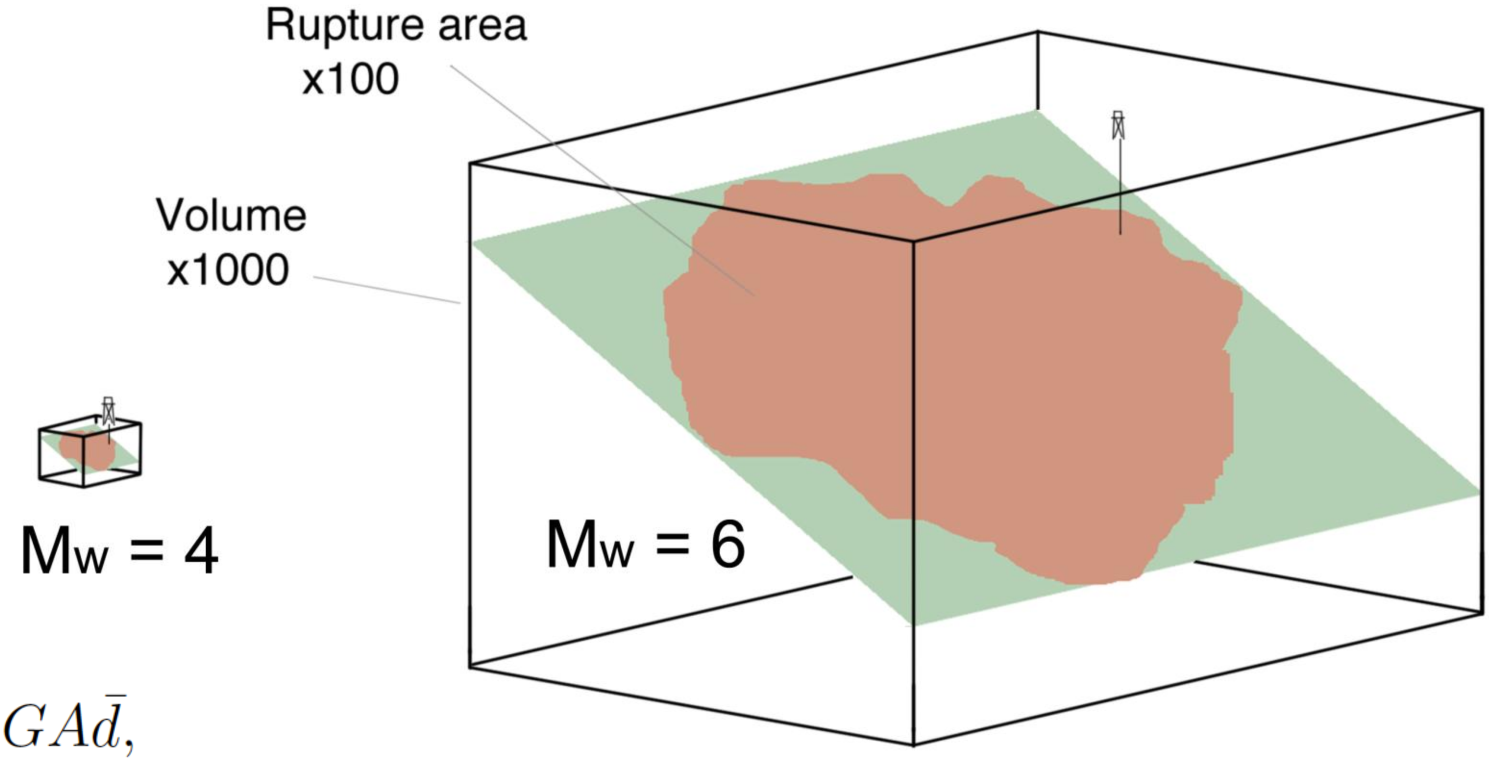
kappa=0.01, phi=0.02, asig=0.05,

Effect of injection pulses



Injection Pulses
Duration = 0.05yr
Δrate/rate = 2

The volume of the crust that contains an earthquake rupture scales by $10^{M1.5}$



$$M_0 = GA\bar{d},$$

$$M \sim \frac{2}{3}\log_{10}(M_0) \sim \frac{2}{3}\log_{10}(A^{3/2}) \sim \log_{10}(A)$$

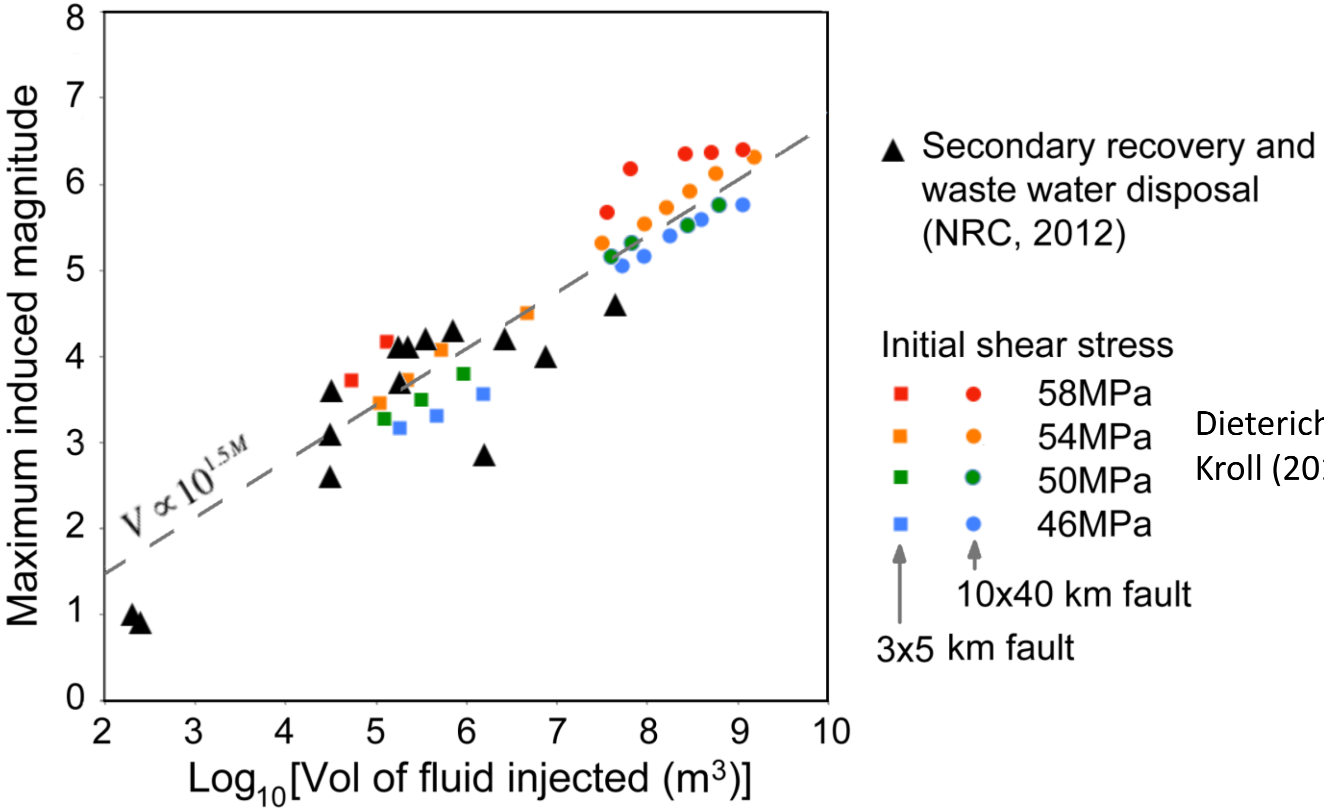
$$M \sim \log_{10}(V^{2/3}) \sim \frac{2}{3}\log_{10}(V)$$

Dieterich, Richards-Dinger, Kroll (2015, SRL)

For isolated fracture permeabilty: $M \sim 1.0 \log_{10}(V)$

Maximum magnitude and injected volume

The maximum possible earthquake magnitude is set by the fault dimensions. However, for faults with sub-critical initial stresses, $t_0 < t_{max}$ induced earthquake ruptures affect only a sufficiently pressured portion of the fault, and the maximum magnitude of the induced events increases with injected volume, in general agreement with observations.



Dieterich, Richards-Dinger, Kroll (2015, SRL)

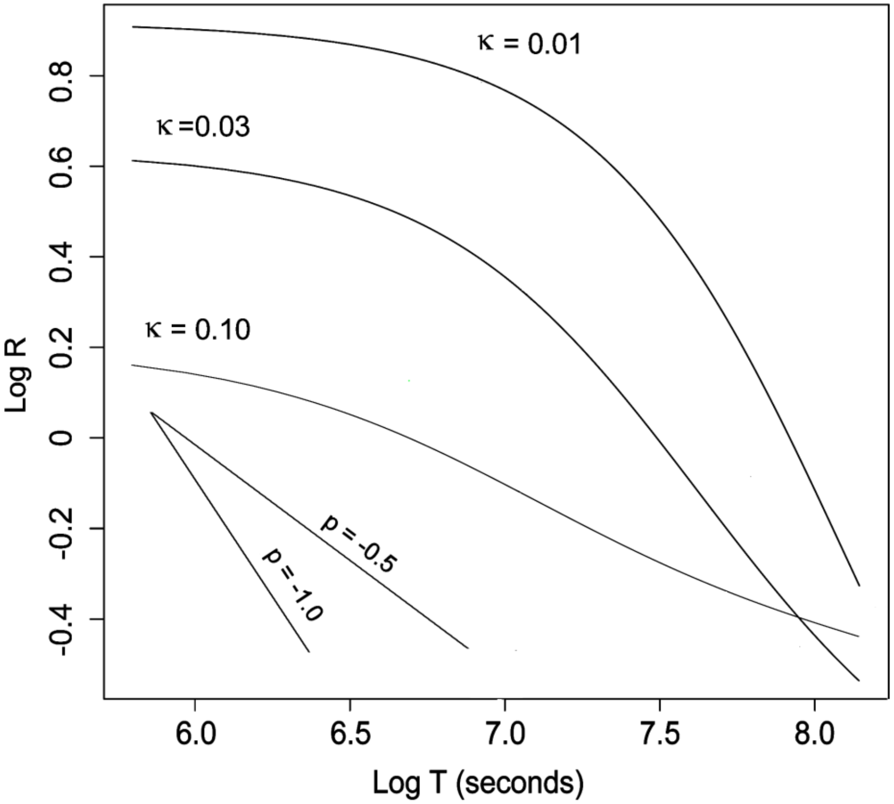
Figure. The volume of injected fluid needed to pressurize (by some fixed amount) the volume of crust that embeds an induced earthquake rupture, scales by $10^{1.5M}$ *, which has a slope of 2/3 on this plot (dashed line). Results from simulations are indicated by data points in color (see legend). All models have a normal stress of 100MPa. Additional parameters that affect maximum magnitude include reservoir storage capacity, and normal stress* σ *which controls earthquake stress drop.*

Many factors affect the rate of earthquake decay following shut-in

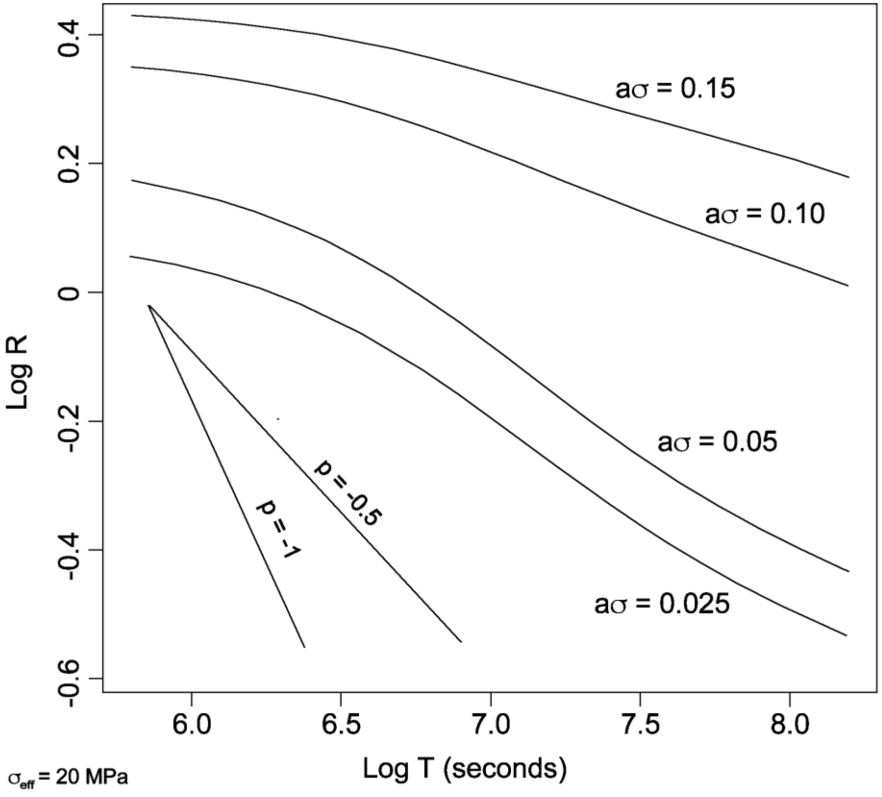
Diffusivity and aσ

$$R = \frac{r}{\gamma \dot{S}_r} \qquad d\gamma = \frac{1}{a\sigma}\left[dt - \gamma dS\right]$$

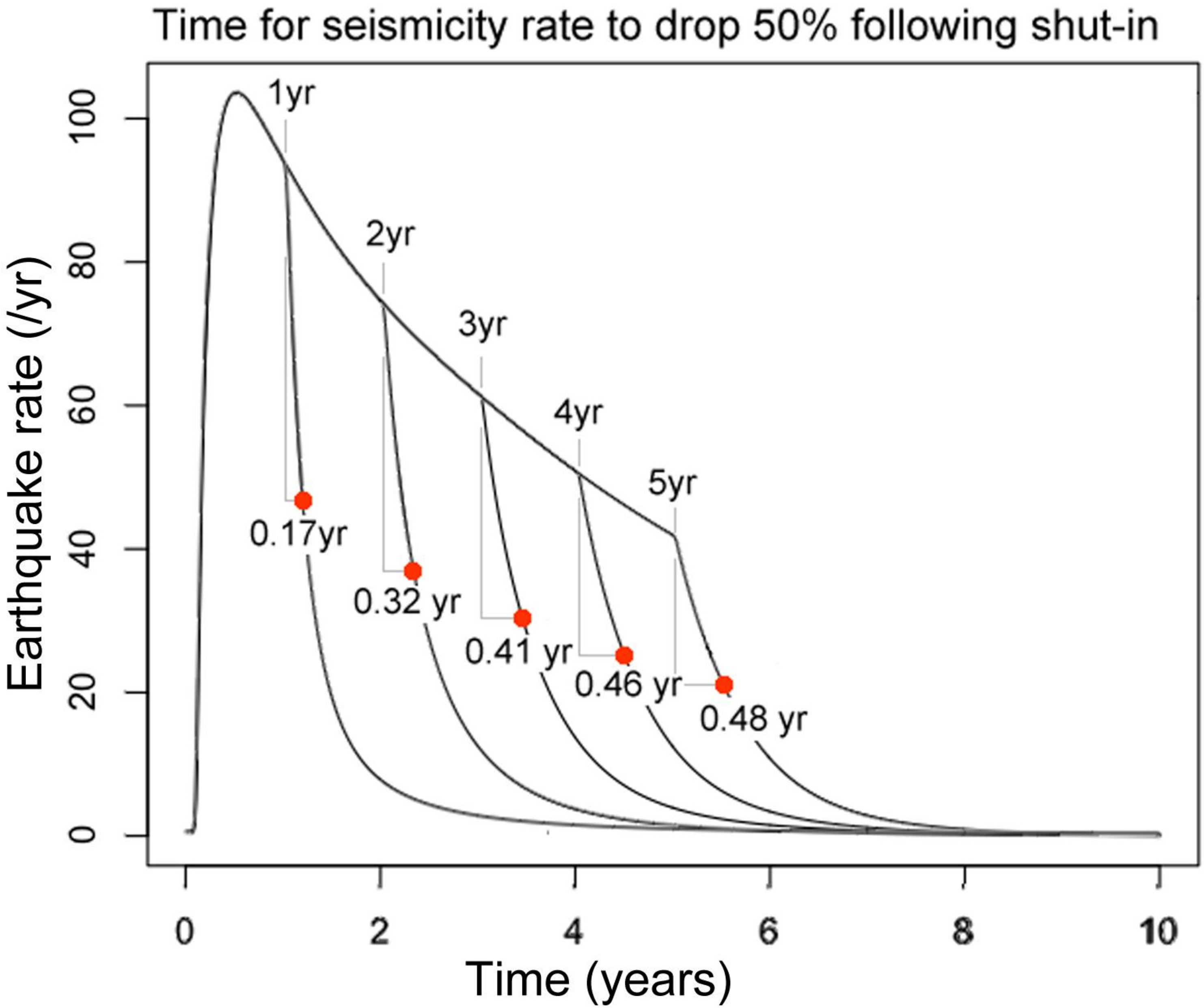
Effect of diffusivity κ on decay following Shut-in



Effect of aσ on decay following shut-in



Duration of seismicity following shut-in

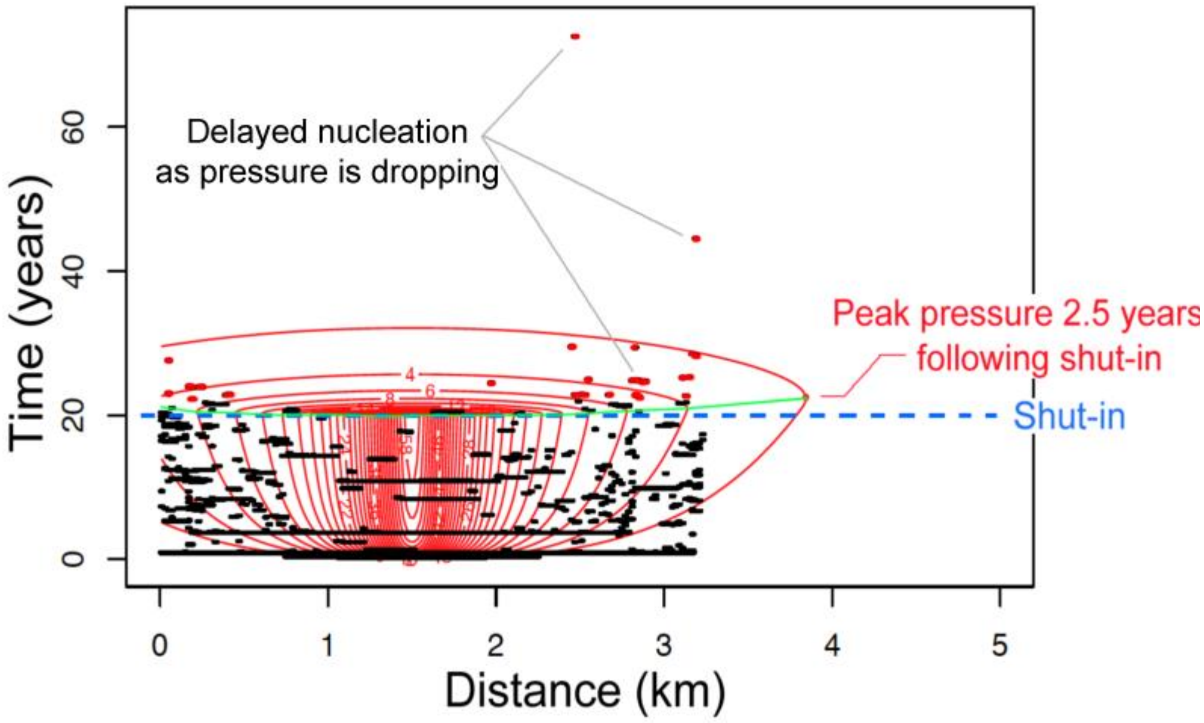


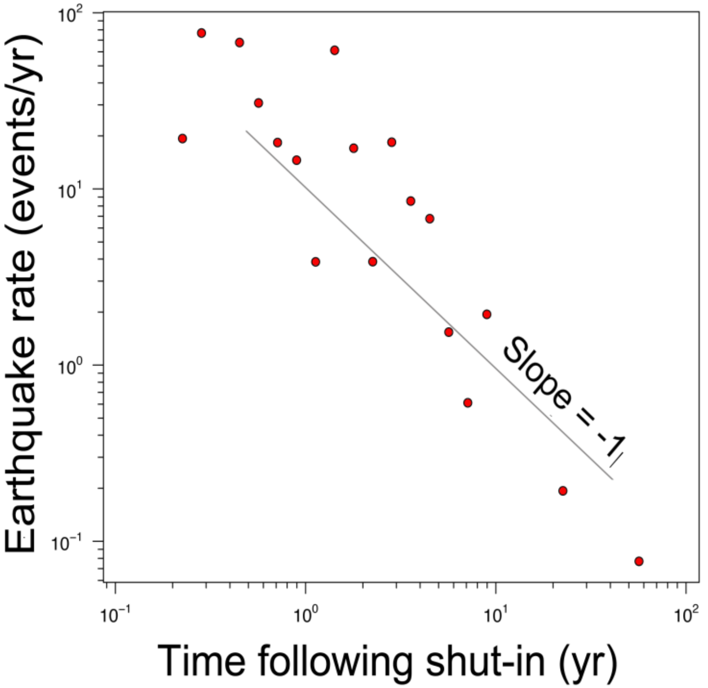
Continuing earthquakes following shut-in

Two effects may cause delayed earthquakes following shut-in:

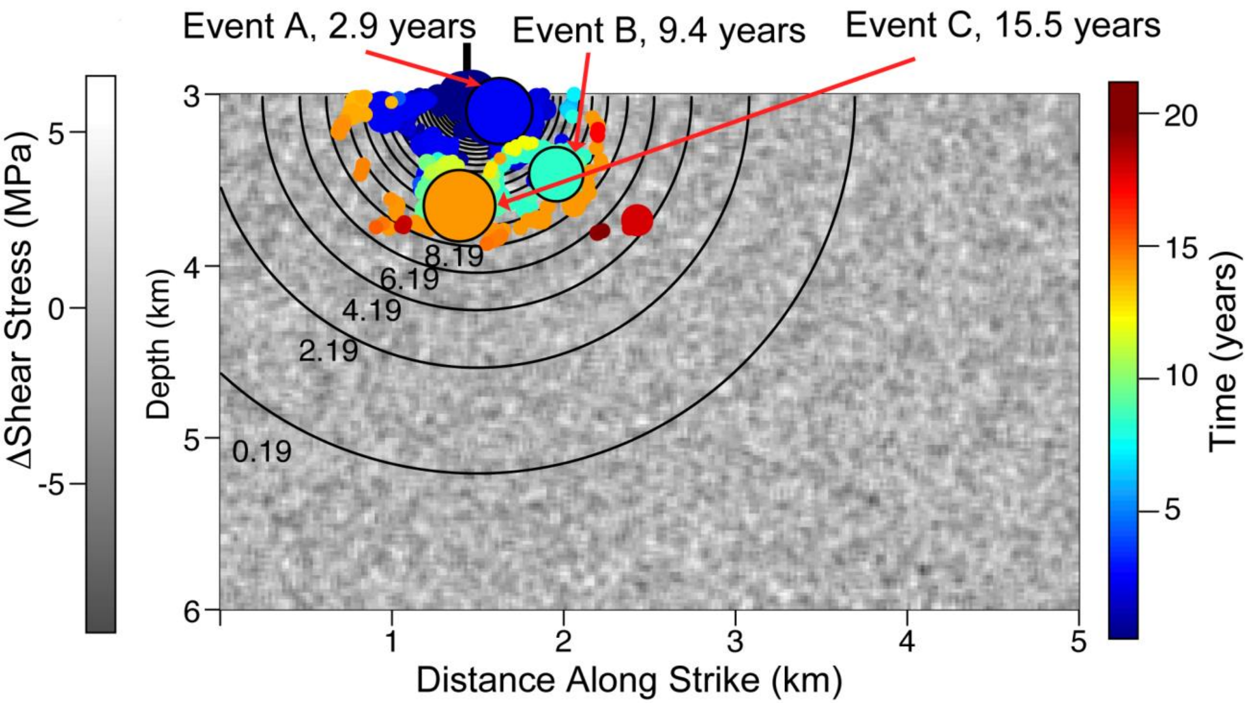
1) Continuing increase of pressure until the shut-in pulse reaches progressively distant points from the injection well.

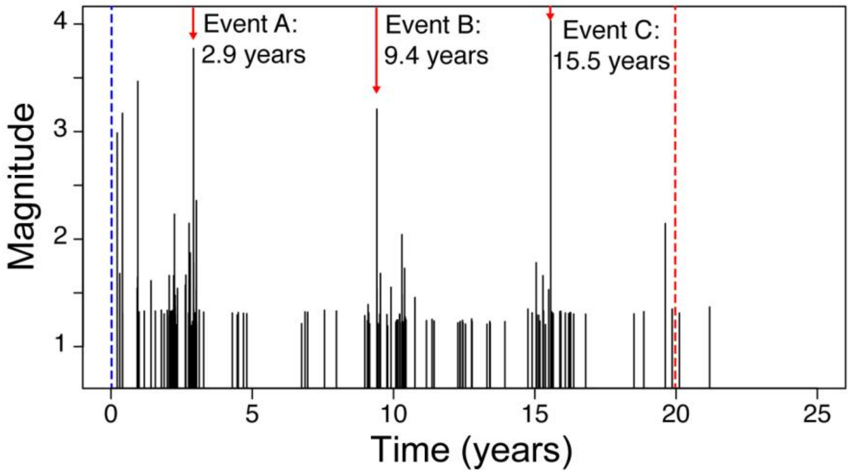
2) Delayed nucleation in the form of aftershocks to earlier induced events and the stress perturbation from injection.





Prevention by shut-in: Test of traffic light procedures

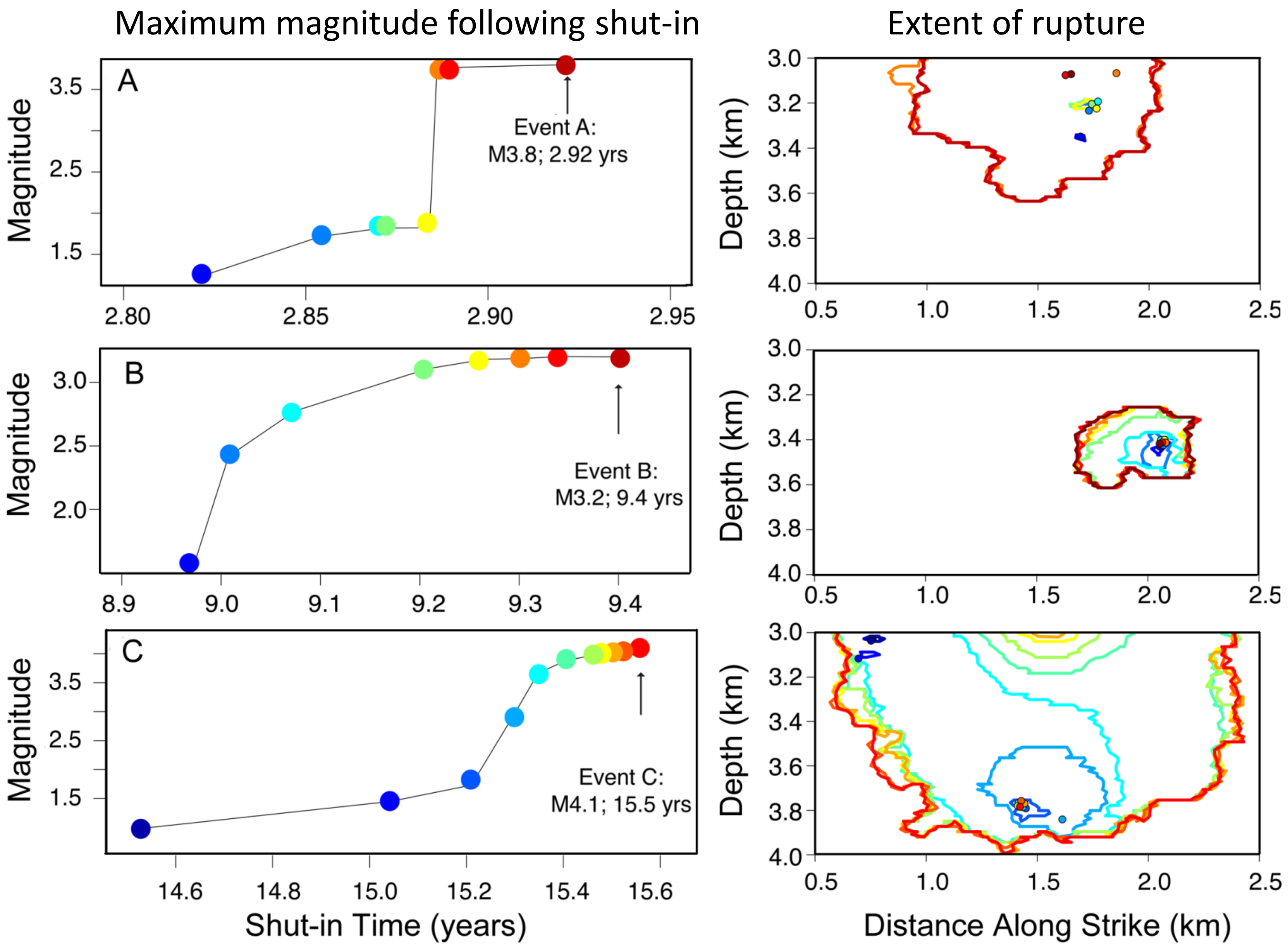




We first ran this simulation with injection for 20 years to establish base-line induced seismicity

Then we re-ran the simulation with different shut-in times to determine the latest shut-in times that prevented events A, B and C.

Effect of shut-in times on maximum magnitude



Maximum magnitude following shut-in

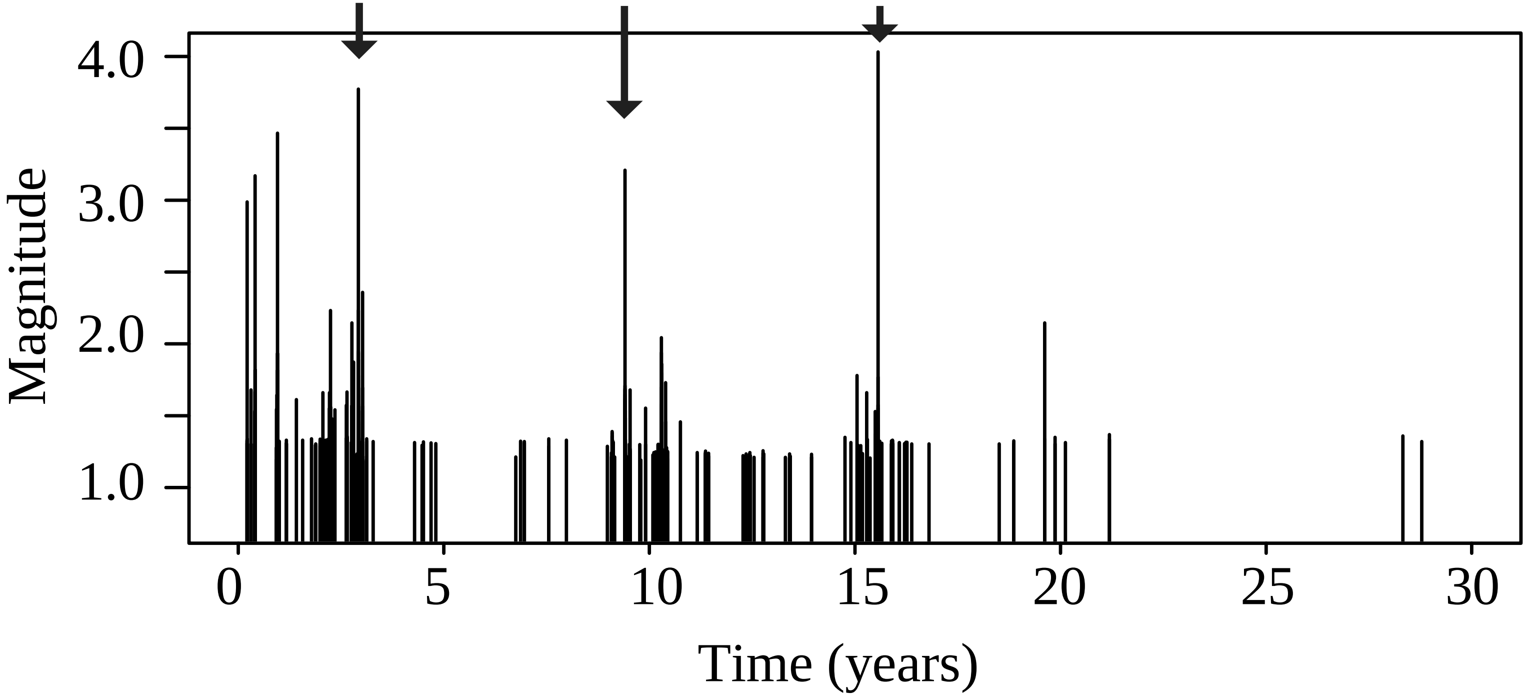
Extent of rupture

Event A: M3.8; 2.92 yrs

Event B: M3.2; 9.4 yrs

Event C: M4.1; 15.5 yrs

Shut-in following the first M>3.1 event would have prevented subsequent M>3 earthquakes,



Event A: M3.8; 2.92 yrs

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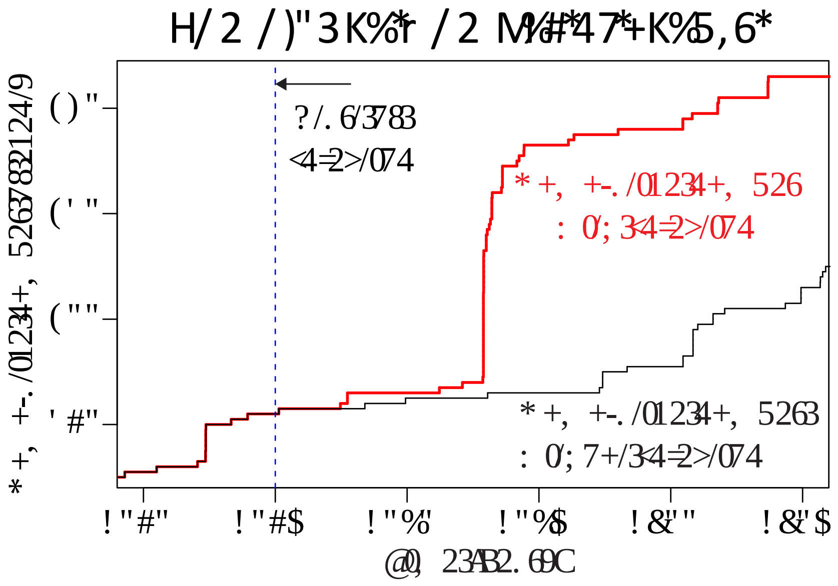
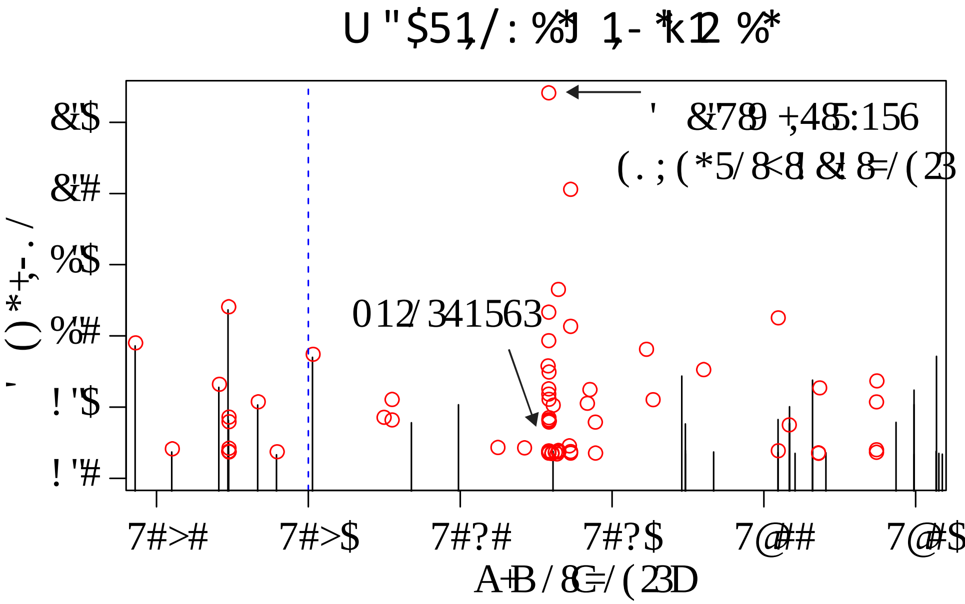
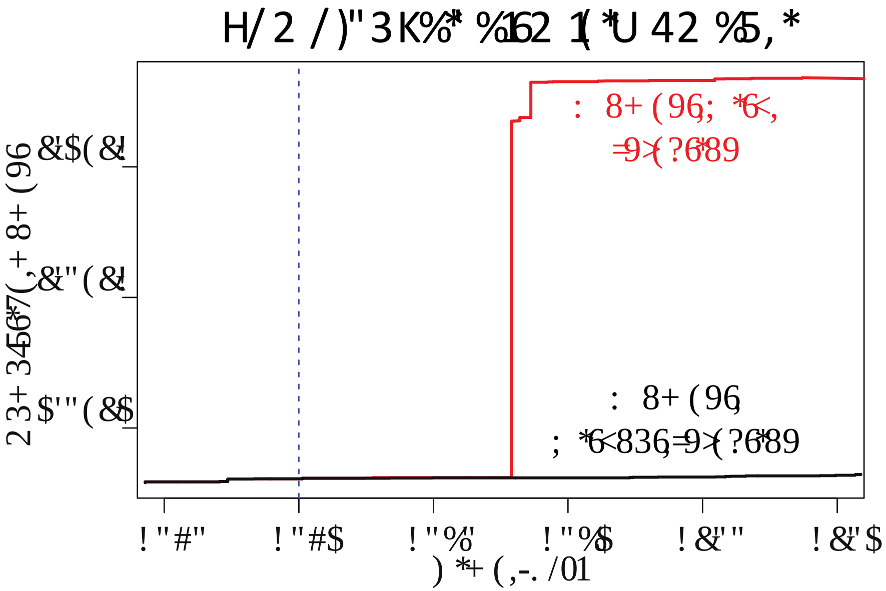
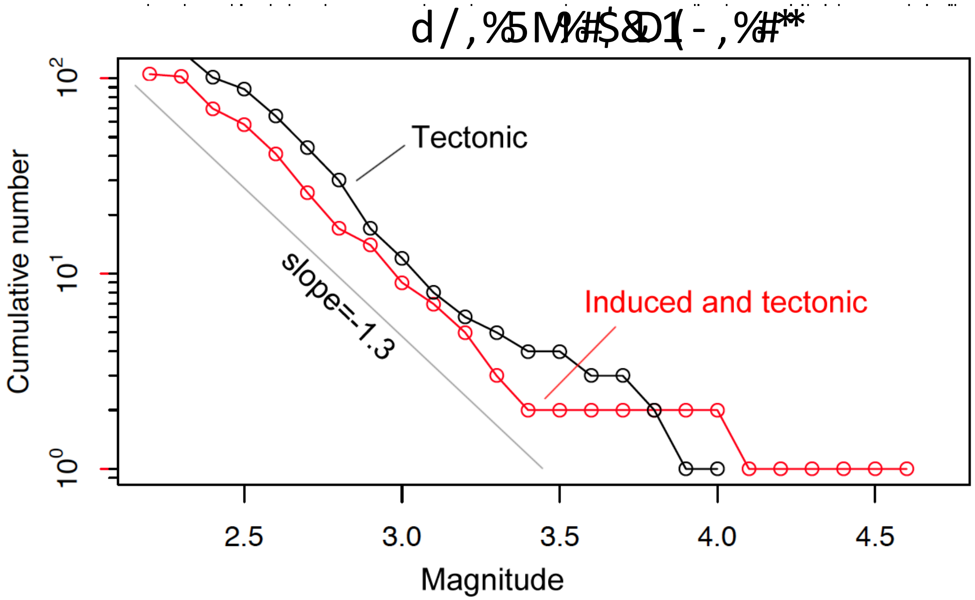
Tectonic stressing with fluid injection

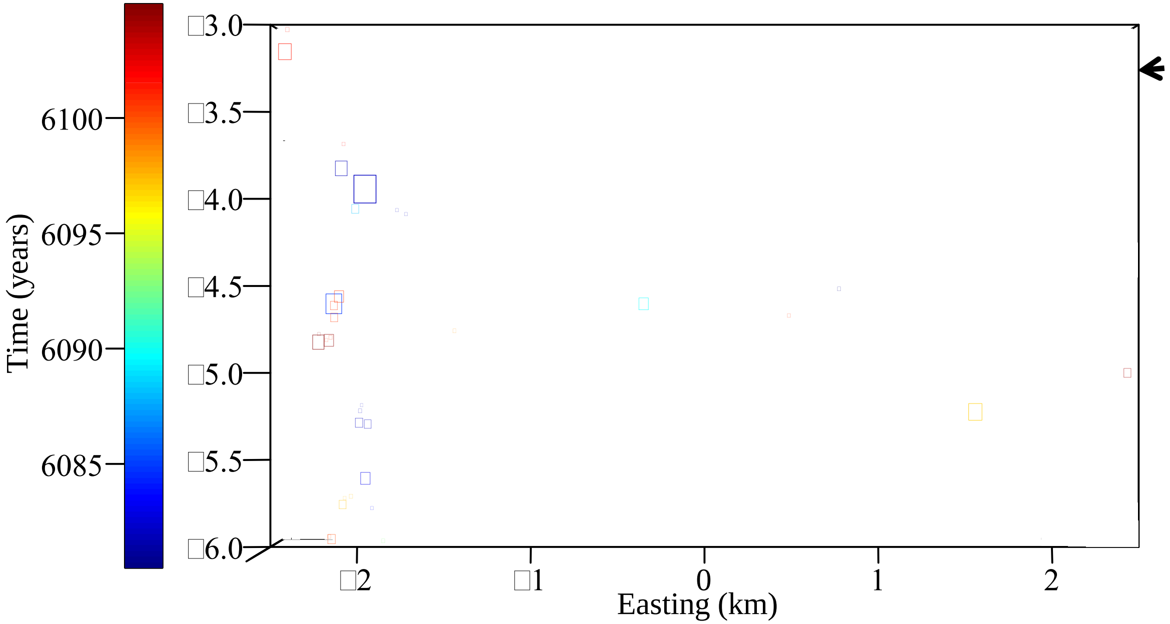






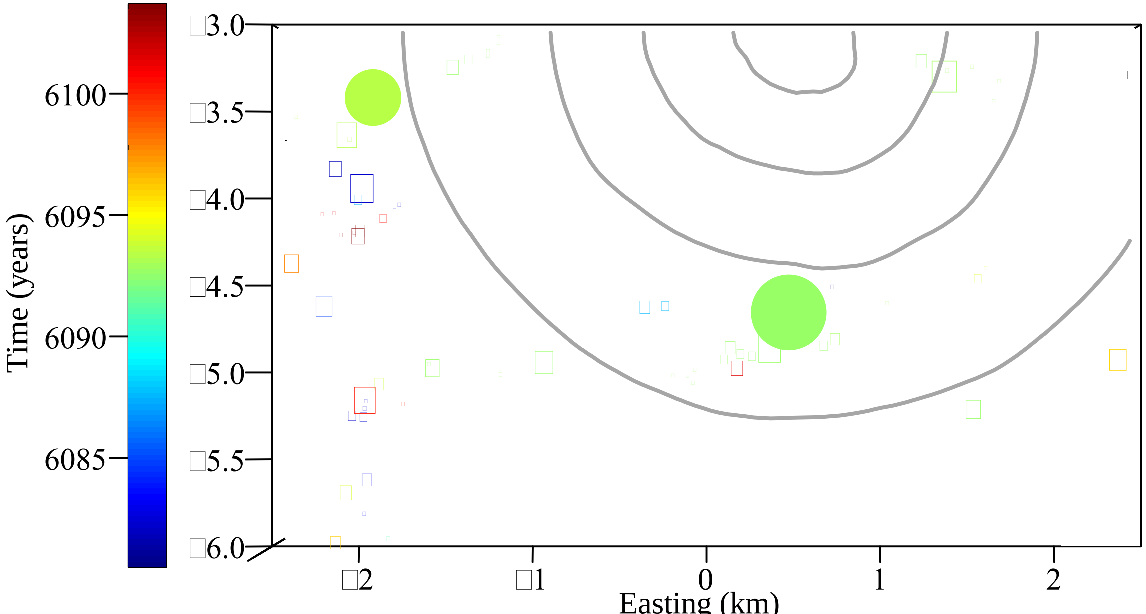


Tectonic stressing with fluid injection



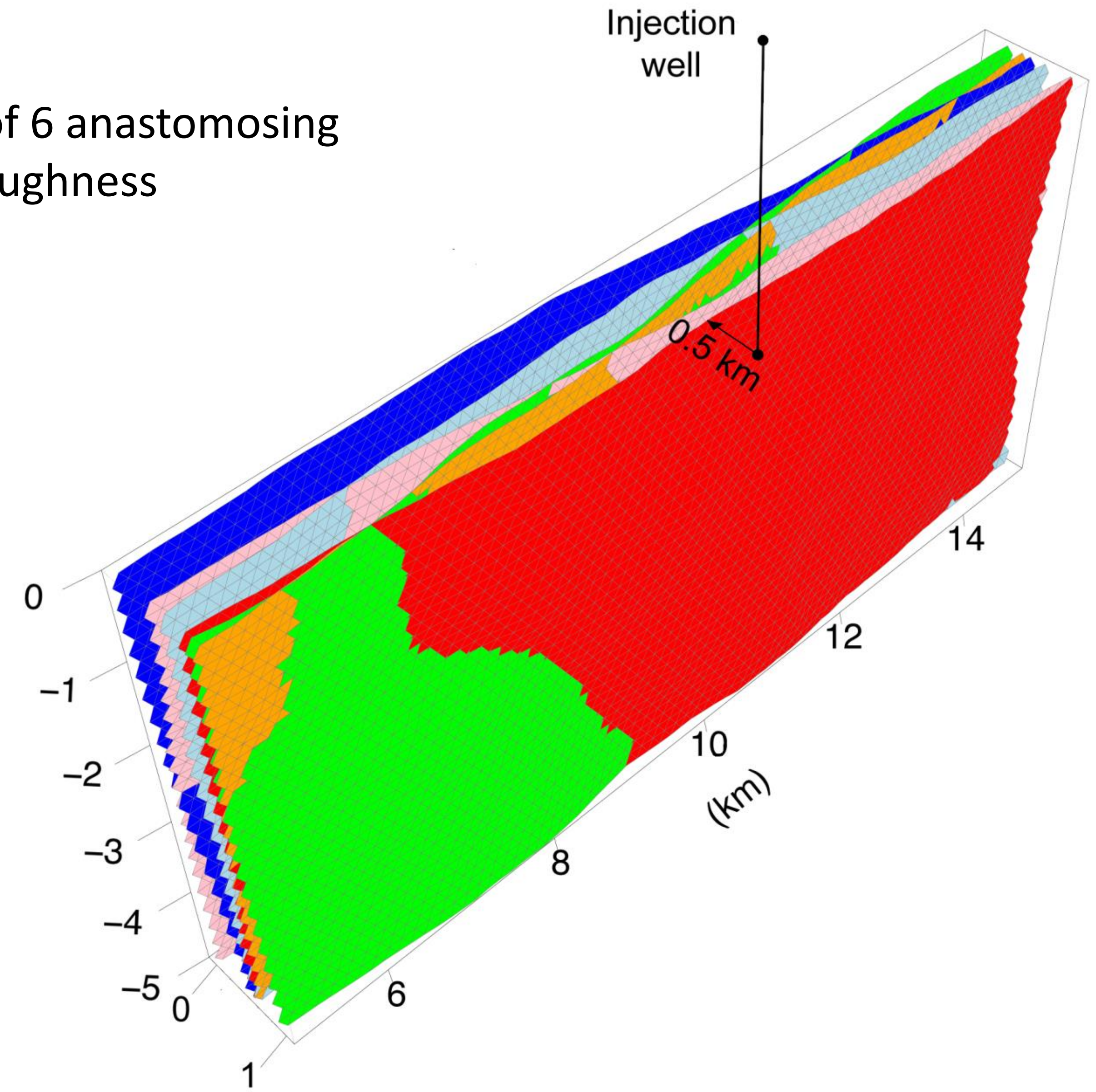
Without
injection

With
injection

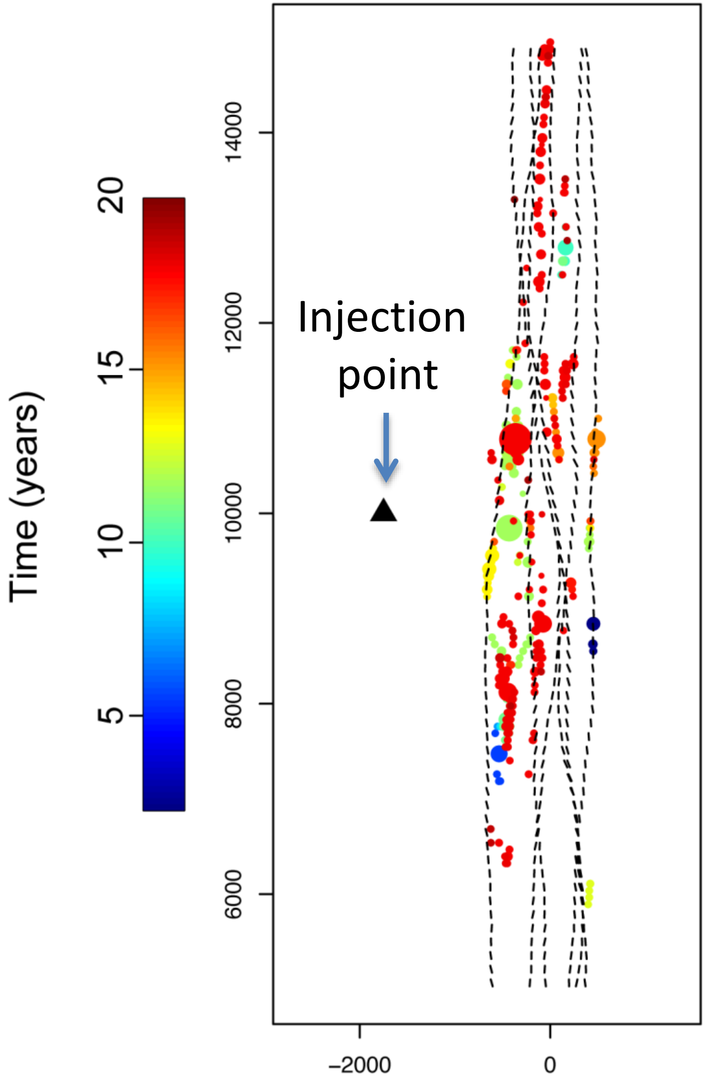


Induced seismicity from injection into a fault zone

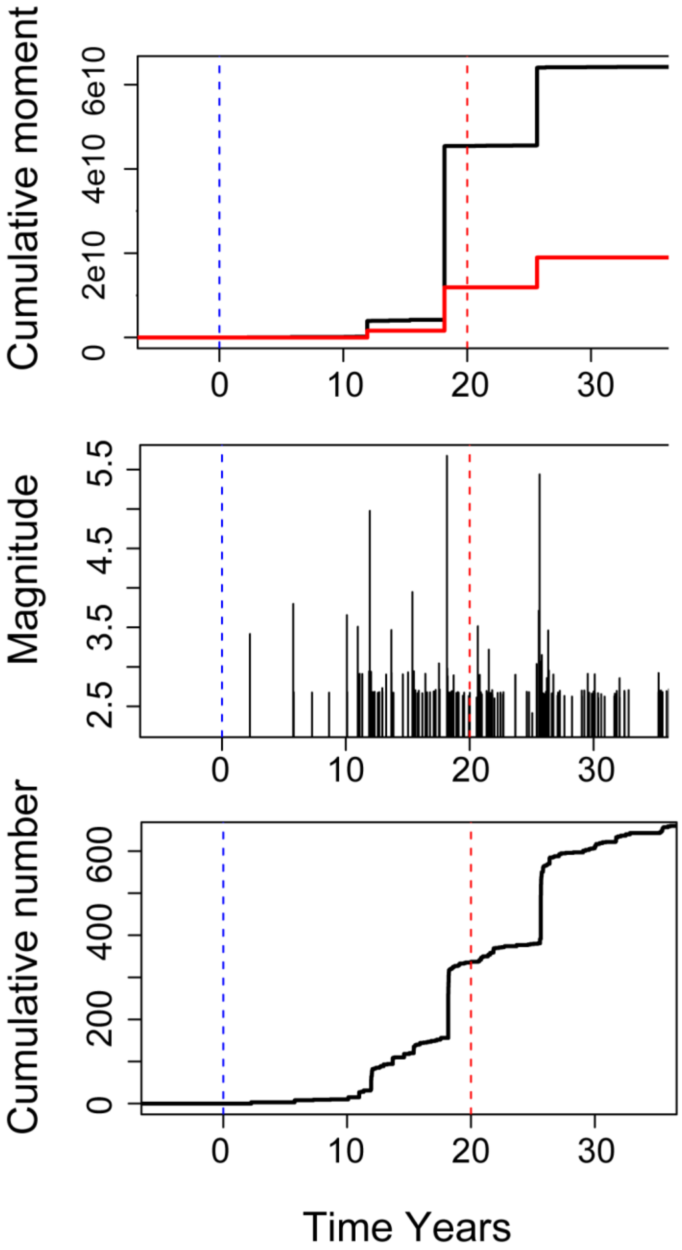
Fault zone consists of 6 anastomosing faults with fractal roughness



Induced seismicity from injection into a fault zone



Average initial shear stress 54MPa



Kayla Kroll PhD thesis)

Conclusions

1) Modeling
    - We have computational tools for quantitative virtual experiments
    - This includes models with highly complex fault systems – needed for case studies

2) Rate-state friction – Earthquake clustering can result in continuing seismicity long after P_{fluid} effects have dissipated.

3) Initial stresses strongly affect characteristics of induced seismicity

4) With qualifications, maximum earthquake magnitude should scale by injected volume. Slope depends on bulk vs (fault) fracture diffusion

5) Traffic light procedures – real-time hazard assessment and risk mitigation may be problematic because of the increasing time lag for pressure signals to more distant points.