Earthquake Rupture Behavior in EGS Settings

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Introduction

Injection-triggered earthquakes are usually thought to be caused by increased fluid pressure in fault zones. During fluid injection, several other physical mechanisms can promote an altered state of stress in the subsurface.


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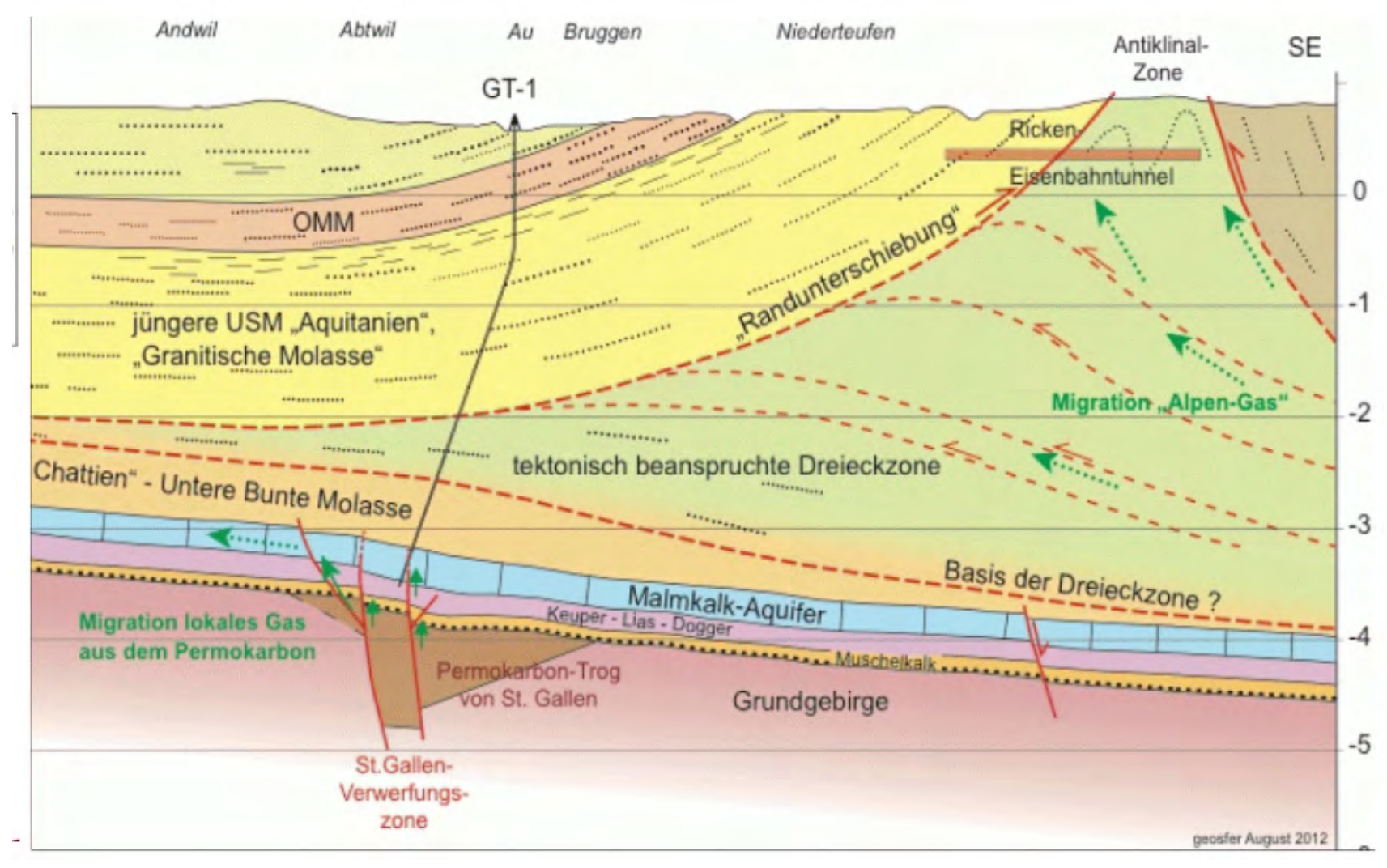


Moeck et al. (2015)

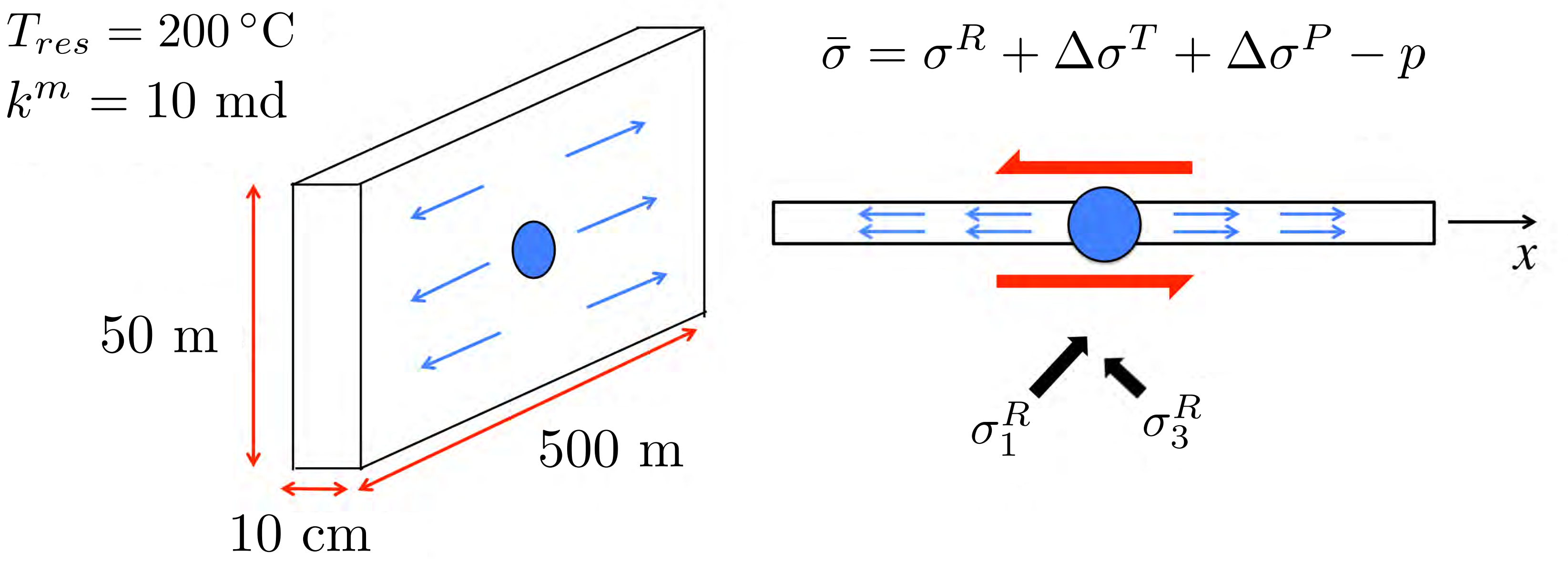
This work explores the earthquake rupture process, and investigates the relative influence of **fluid pressure changes**, **thermal stress**, and **poroelastic stress** on injection-triggered earthquake sequences. We considered a conceptual model of injection near a fault relevant to **Engineered Geothermal System (EGS) settings**.

Goals

- Determine whether the magnitudes of thermal stress and poroelastic stress can compete with fluid pressure changes
- Identify the role of each physical mechanism during the earthquake nucleation, rupture, and arrest processes

Model of Injection into a Fault

- The injection well has a direct hydraulic connection with the fault
- The fault is cricitally-stressed at a depth of roughly 4 km
- Cold water is injected at a constant rate of 50 kg/s for one day
- Matrix rock is permeable, so leakoff can occur


$T_{res} = 200\,^{\circ}\mathrm{C}$

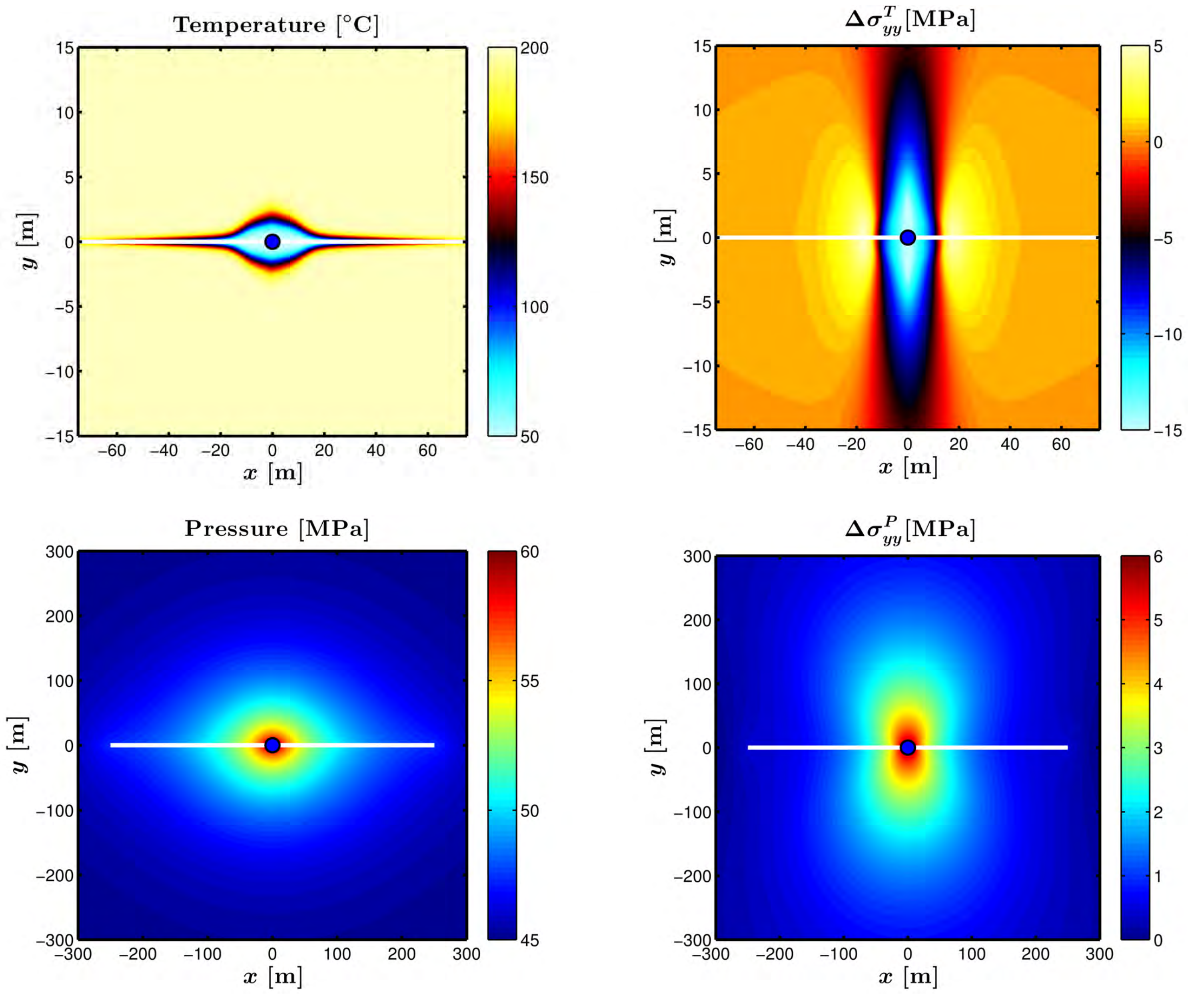
$k^m = 10$ md

$$\bar{\sigma} = \sigma^R + \Delta\sigma^T + \Delta\sigma^P - p$$

- Mass transfer, heat transfer, fault mechanics, and earthquake model are fully-coupled at every timestep
- "Embedded fracture" approach allows for a more realistic description of reservoir geology, but here we model a planar fault

Thermal and Poroelastic Stress

- As rock expands or contracts, stresses can be induced if deformation is constrained (by surrounding rock)



Earthquake Model

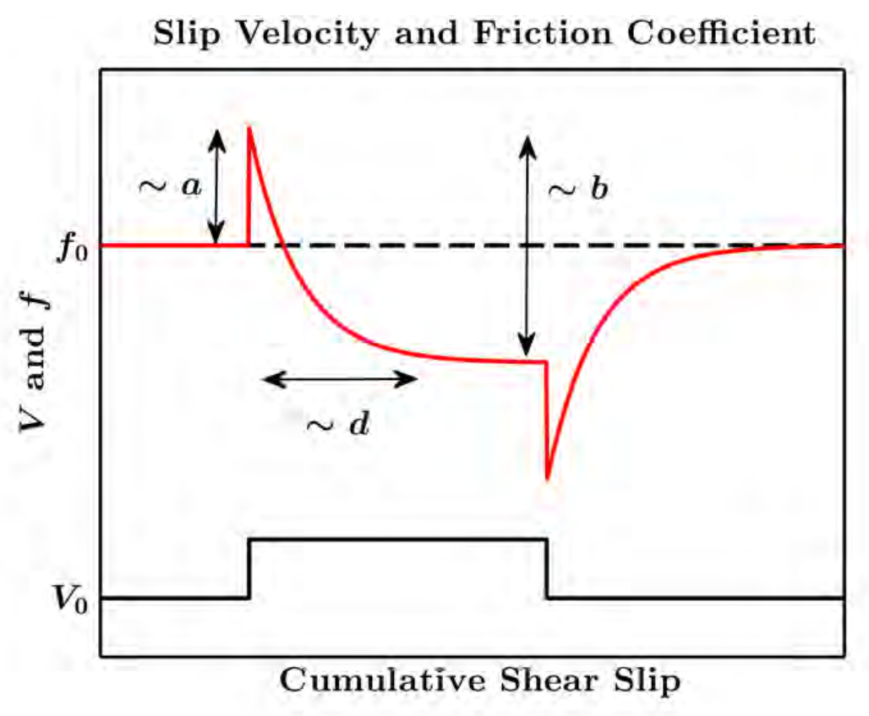
- Effective stress reflects combined effect of each mechanism

$$\bar{\sigma}(x,t) = \sigma^R + \Delta\sigma^T(x,t) + \Delta\sigma^P(x,t) - p(x,t)$$

- Elasticity equations expressed for mode-II shear problem

$$\tau(x,t) = \tau^R + \Theta(x,t) - \eta V(x,t)$$

- Rate-and-state friction evolution enables earthquake sequences to emerge (friction weakening and subsequent restrengthening)


Slip Velocity and Friction Coefficient

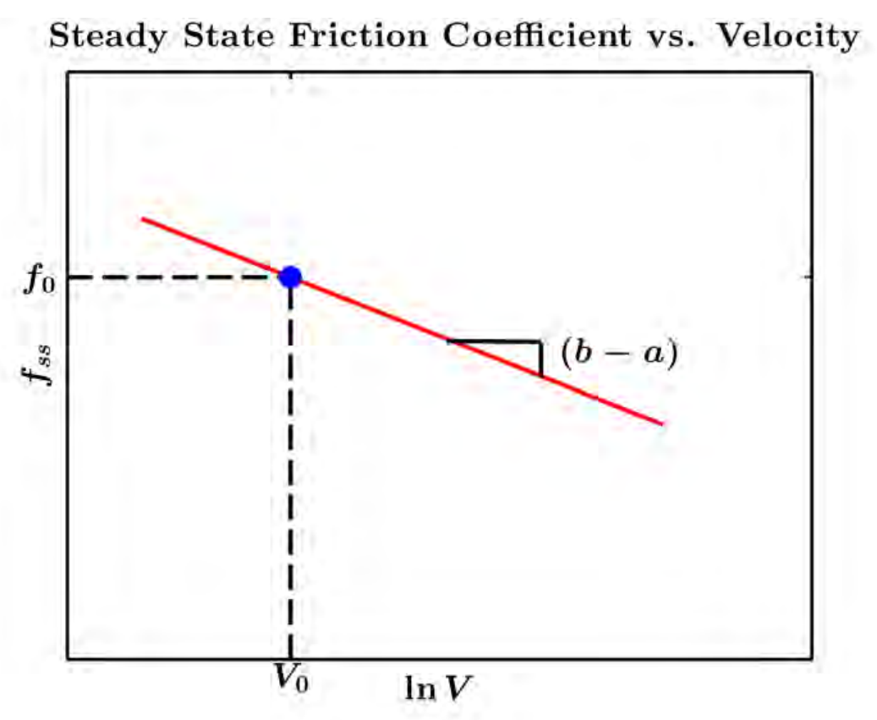
$$\frac{\partial\tau}{\partial t} = \bar{\sigma}\left[\frac{a}{V}\frac{dV}{dt} + \frac{\partial\Psi}{\partial t}\right]$$

$$f(V,\Psi) = a\ln\frac{V}{V_0} + \Psi$$

$$\Psi = f_o + b\ln\frac{V_0\theta}{d}$$

$$\frac{\partial\Psi}{\partial t} = -\frac{V}{d}\left[f(V,\Psi) - f_{ss}(v)\right]$$

$$f_{ss}(V) = f_0 - (b-a)\ln\frac{V}{V_0}$$


Steady State Friction Coefficient vs. Velocity

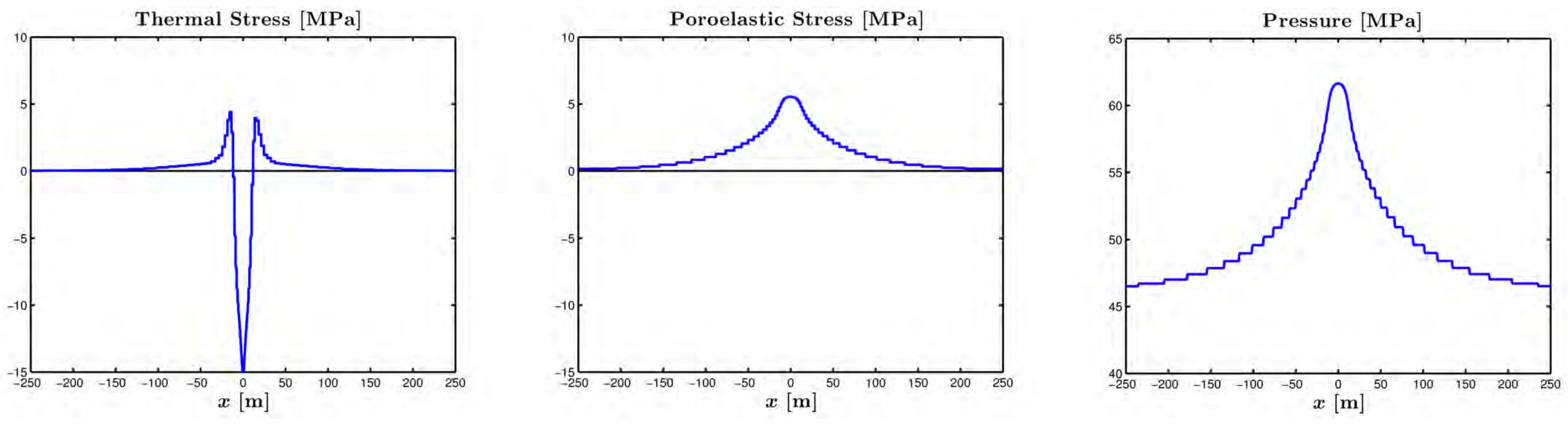
- Mechanical equilibrium is enforced and an explicit third order Runge-Kutta method is used to update slip, velocity, and friction

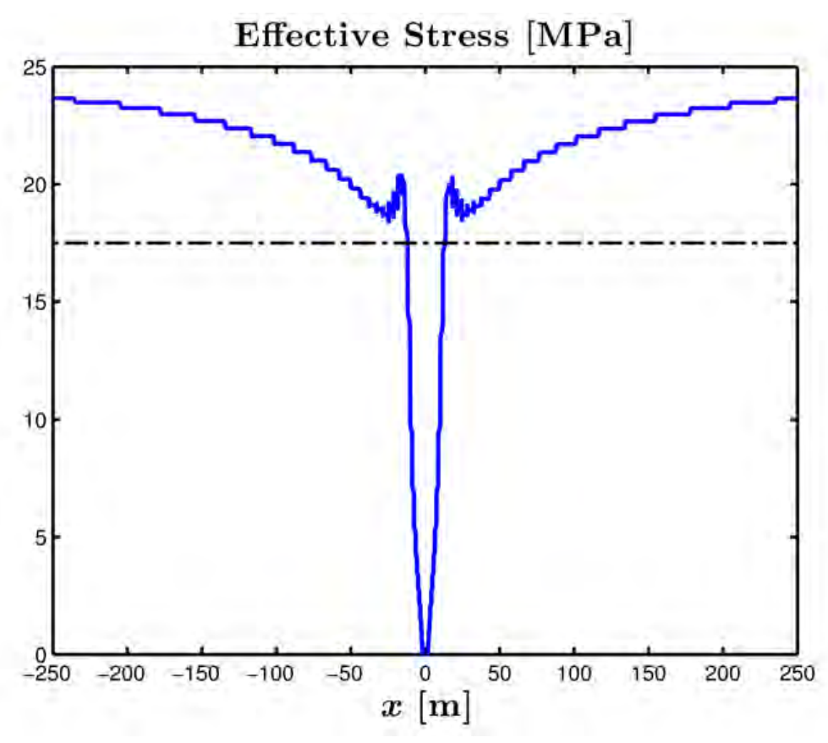
$$\tau^R + \Theta - \eta V = f\bar{\sigma} + S$$

Results

Relative Stress Magnitudes

destabilizing **stabilizing** **destabilizing**

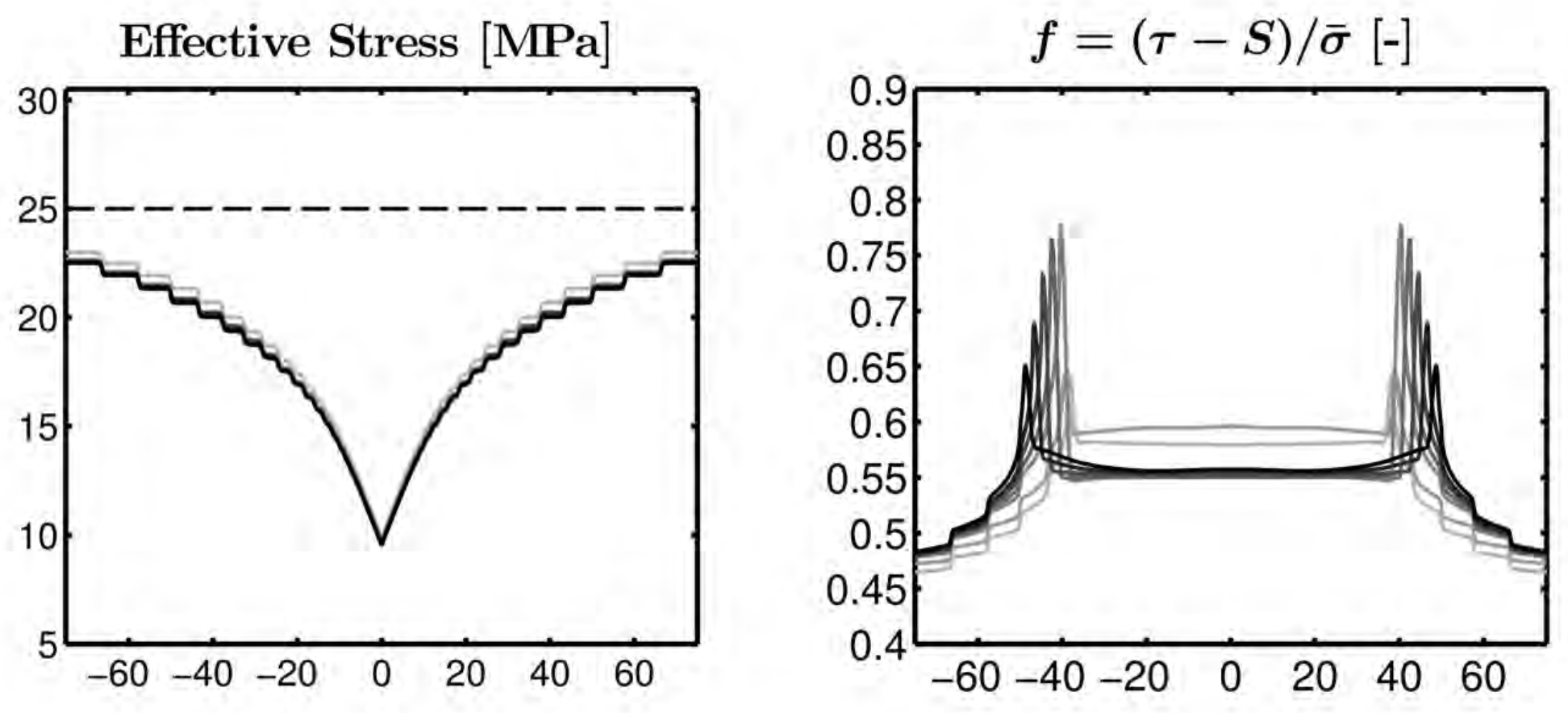




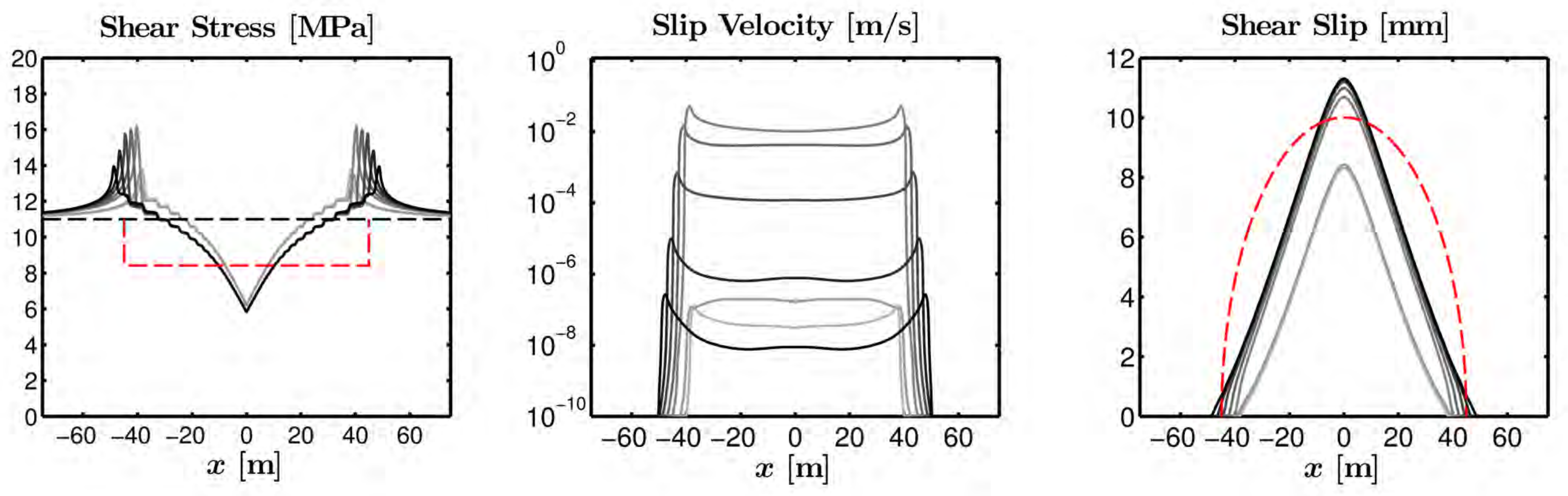
Case A: **p only**
Case B: **p** + **poro**
Case C: **p** + **thermal**
Case D: **p** + **poro** + **thermal**

	A	B	C	D
Total Number of Earthquakes [-]	4	0	8	2
Max Earthquake Magnitude [-]	1.9	N/A	1.5	0.7
Max Cumulative Shear Slip [cm]	2.8	0.7	3.7	2

Signature of Injection-Triggered Earthquakes



Effective normal stress and residual shear stress (stress drop) are not constants.



Conclusions

- Each of the three physical mechanisms considered affected the individual earthquake events and the overall earthquake sequences significantly
- Geologic and operational parameters will control whether certain processes dominate - further parametric study is warranted
- Rigourous coupling of flow, mechanics, and earthquake dynamics allowed us to identify behavior that may be unique to injection-triggered events

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SED-AGIS Induced Seismicity Workshop, 10-13 March, 2015