THE UNIVERSITY OF TEXAS AT AUSTIN
Petroleum and Geosystems Engineering
Cockrell School

PREDICTIVE MODELING OF INDUCED SEISMICITY: NUMERICAL APPROACHES, APPLICATIONS, AND CHALLENGES

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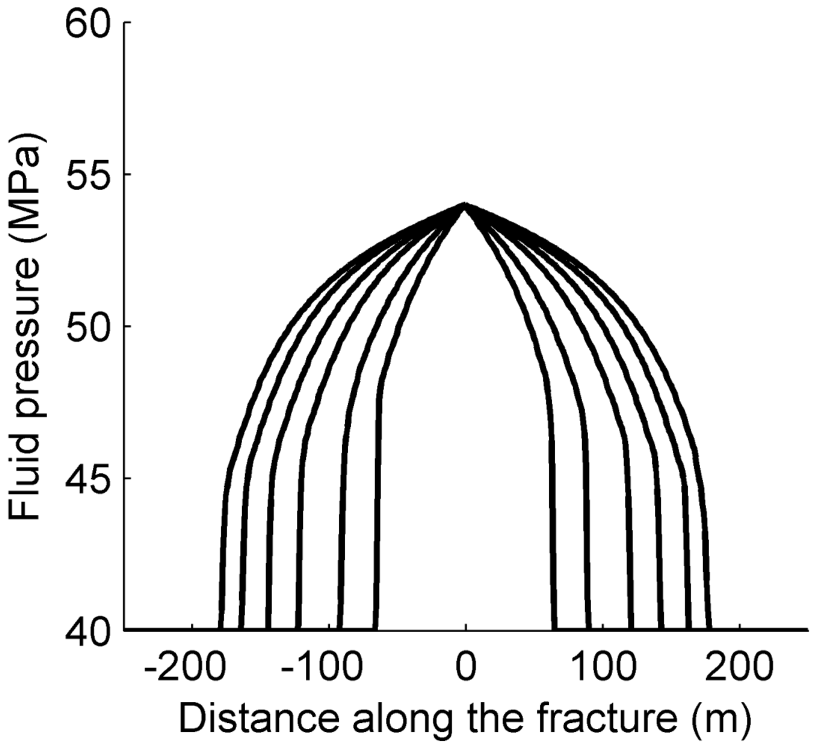
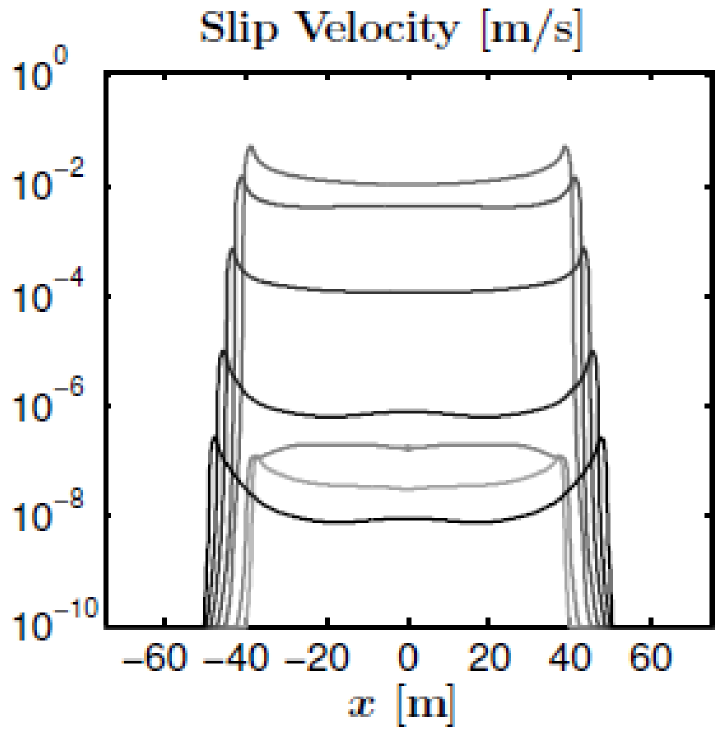
Overview of this talk

- Discussion of different modeling approaches
- Opportunities and challenges
- My work with CFRAC
  - Coupling fluid flow with rate/state friction earthquake simulation
  - Post-injection seismicity and a strategy for minimization
- Other investigators using and extending CFRAC

Forward simulations of earthquake rupture

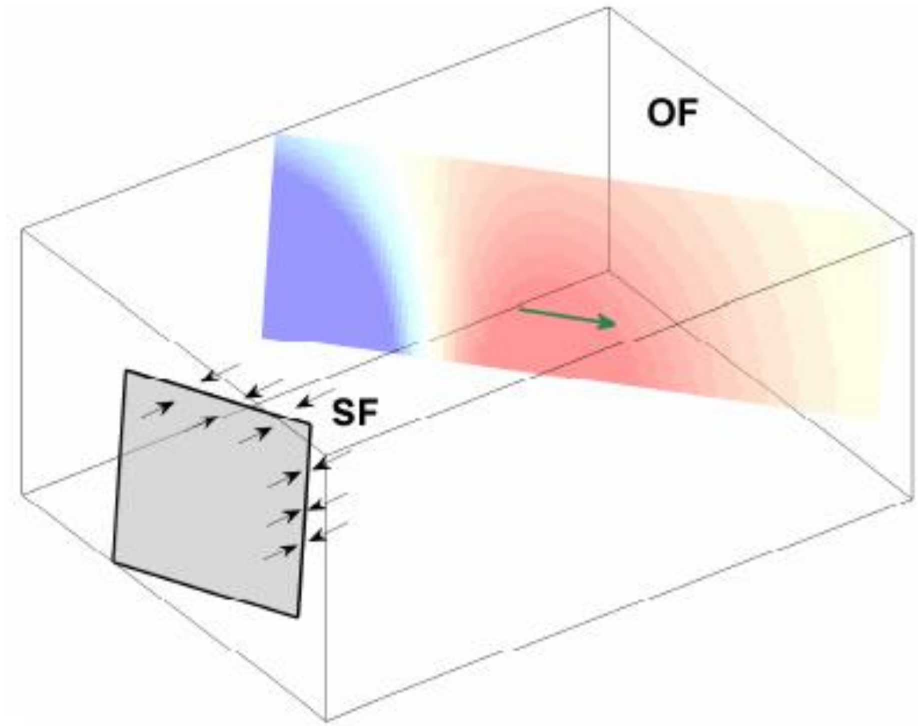


McClure and Horne (2011)

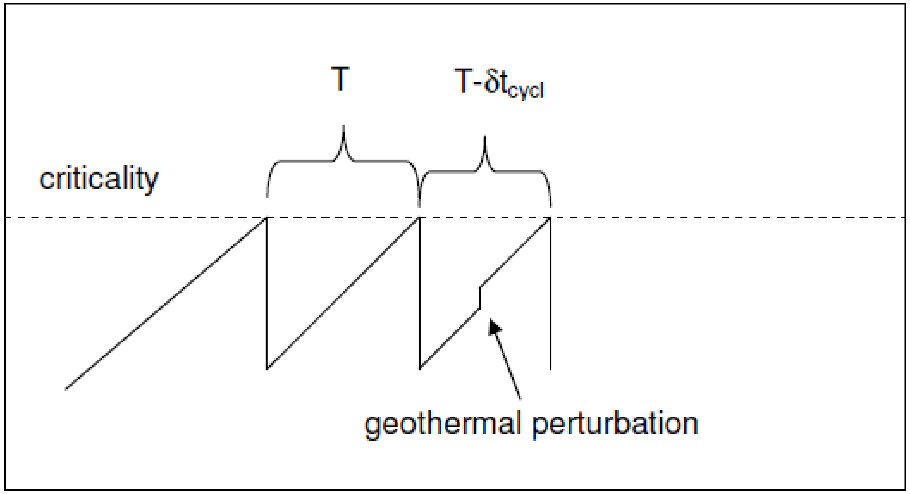


Norbeck and Horne (2015)

Heuristics for predicting earthquake occurrence



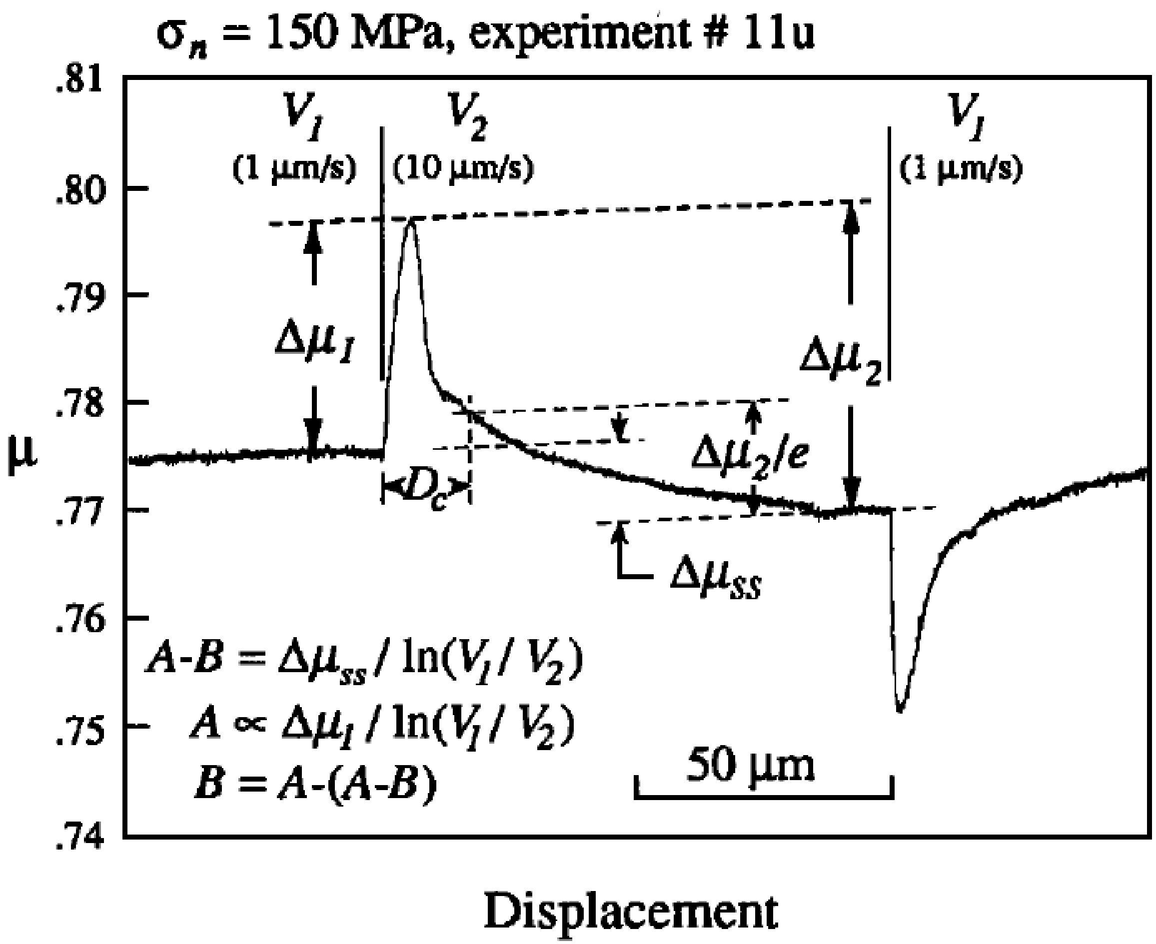
Coulomb stress versus time



Vörös and Baisch (2009)

Serianex report on induced seismicity hazard at Basel

Rate and state friction in earthquake modeling



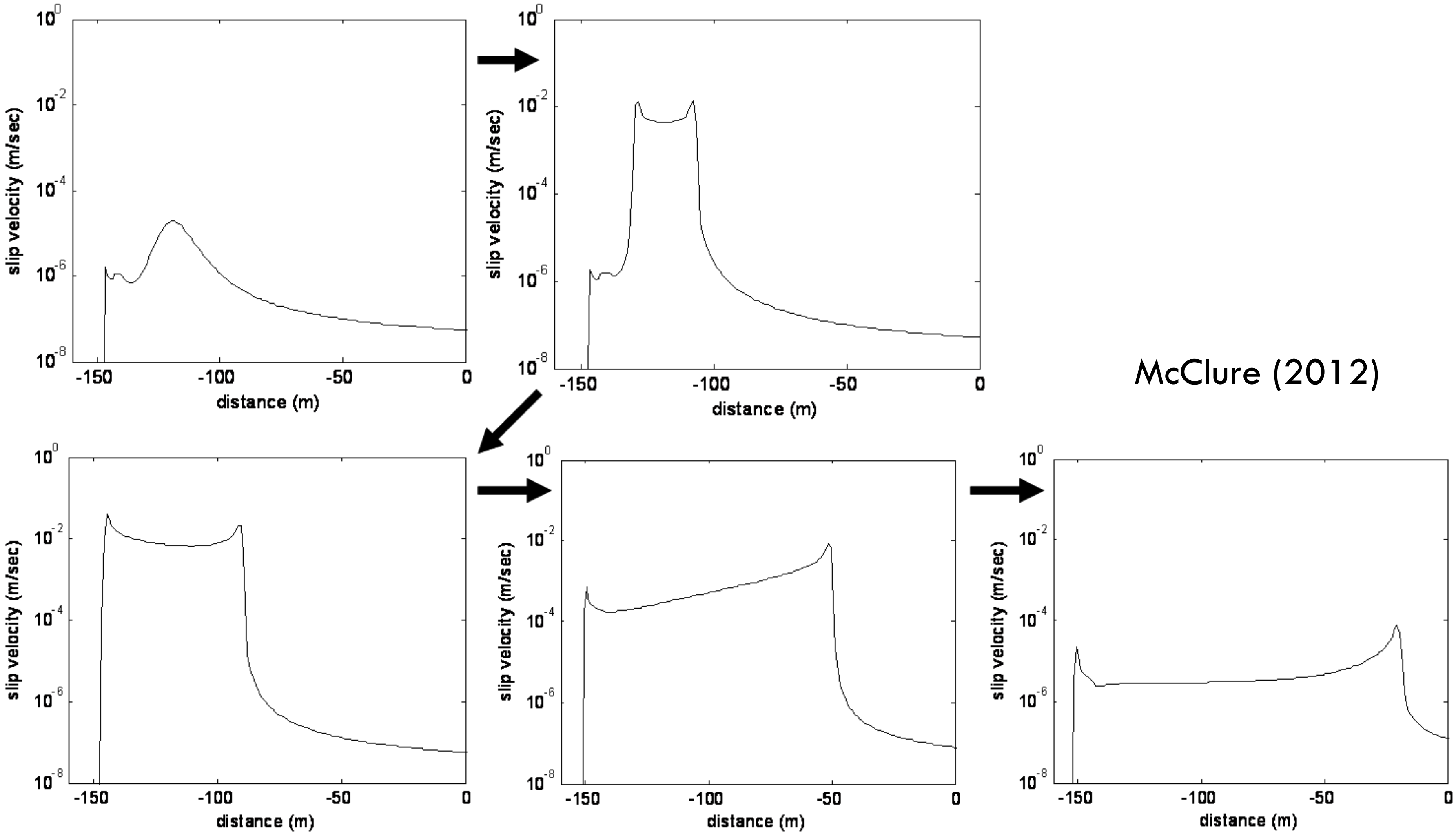
Kilgore et al., 1993

$$|\tau - \eta v| \leq \mu(\sigma_n - P)$$

$$\mu = f_0 + a\log(v/v_0) + b\log(v_0\theta/d_c)$$

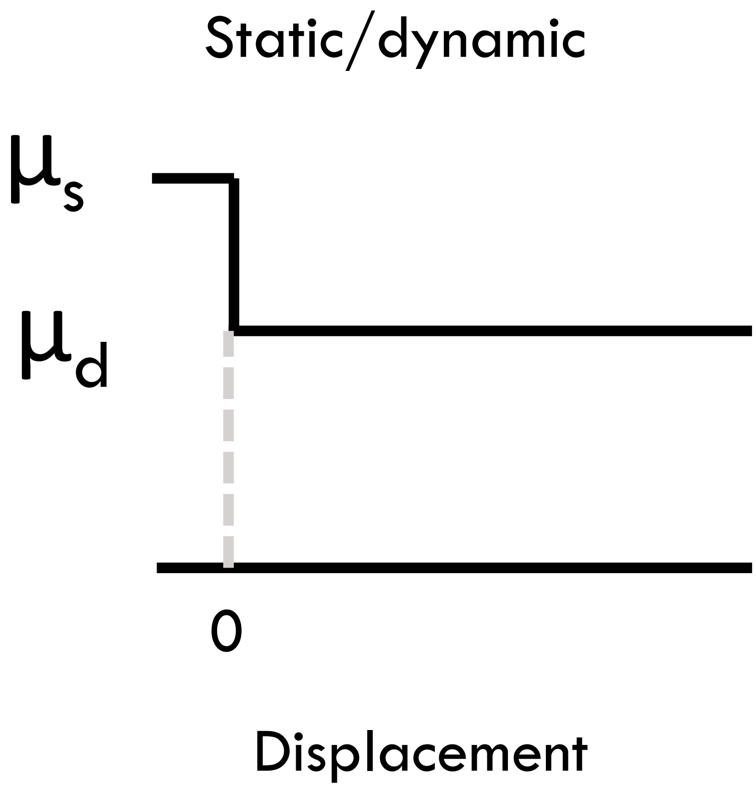
$$\frac{d\theta}{dt} = 1 - \frac{v\theta}{D_c}$$

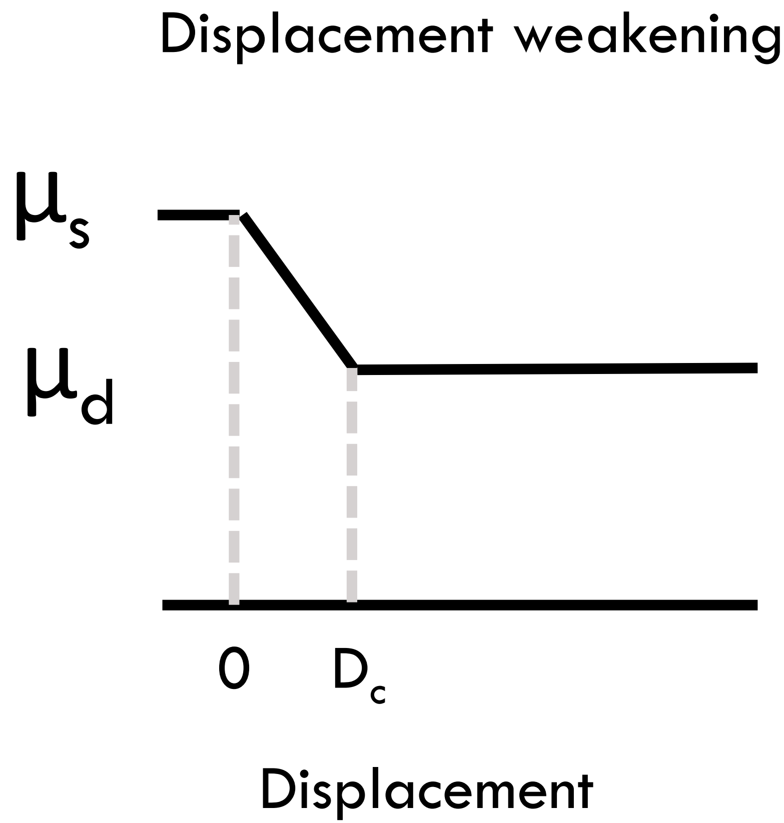
Example of rate/state earthquake simulation



McClure (2012)

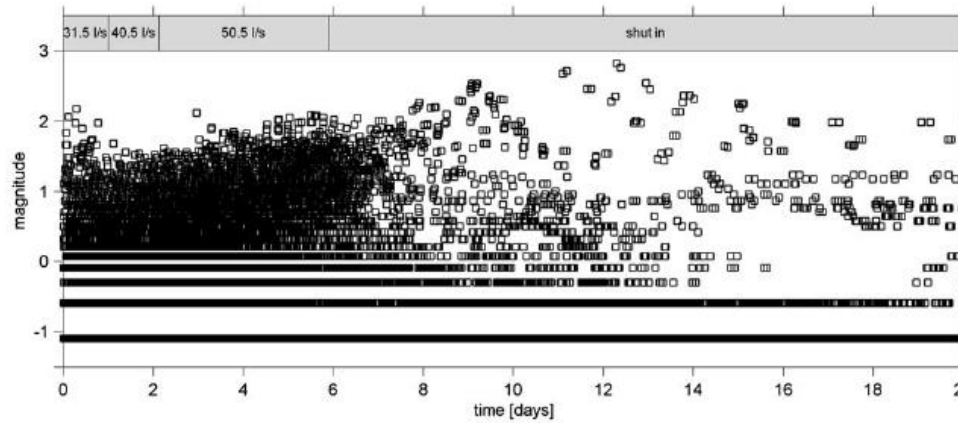
Treatments of friction in earthquake modeling



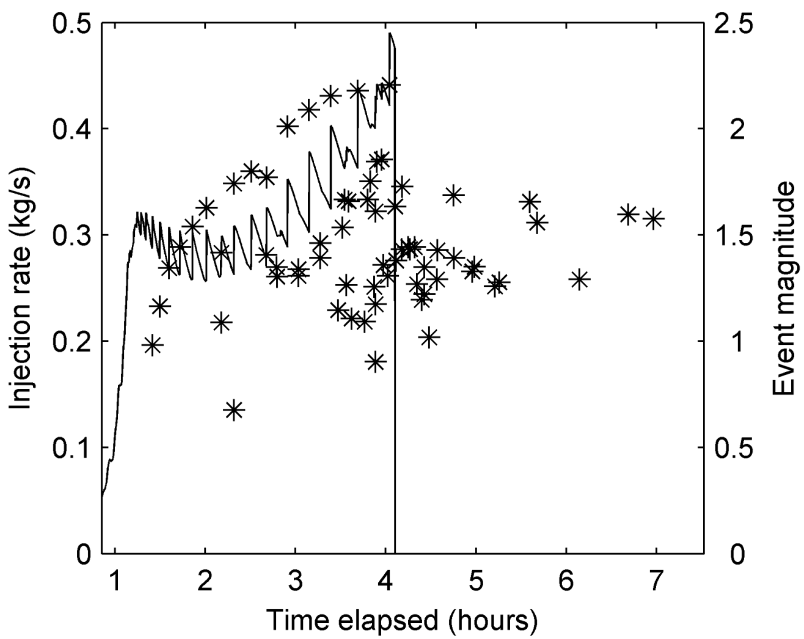


*Constant stress drop can be imposed instead of a drop in friction.

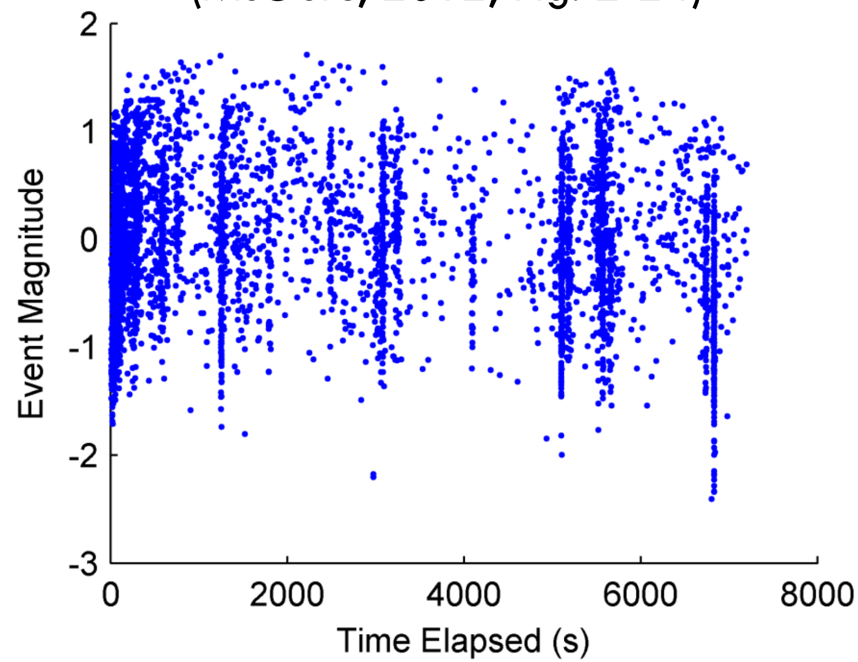
Static/dynamic (Baisch et al., 2010)



Rate/state (McClure and Horne, 2011)



Static/dynamic (McClure, 2012; Fig. 2-24)



Role of heterogeneity

- Heterogeneity exists in:
  - Fault shape/geometry
  - Elastic properties
  - Frictional properties
- Numerical models include less heterogeneity than reality
- Stochastic realizations can help handle uncertainty and heterogeneity

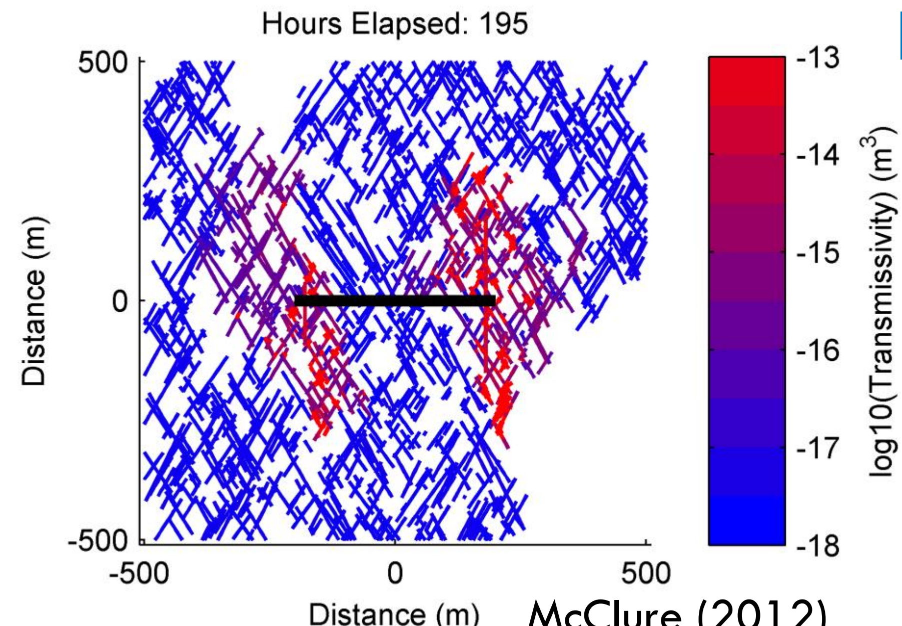
Opportunities and challenges

- Generic simulations for sensitivity analysis
  - Develop physical insight
  - Impact of variables and uncertainties
  - Prompt further investigation
  - Investigate processes
- Site-specific for hazard analysis
  - Site specific modeling will *always* be fraught with uncertainty from physics and from uncertain model inputs
  - For example: how can we relate calculated stress changes to observed seismicity?
  - Integrate physics and heterogeneity and uncertainty in a balanced way

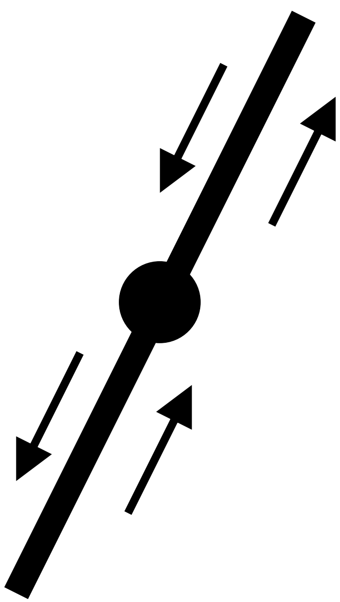
CFRAC (Complex Fracturing ResеArch Code)

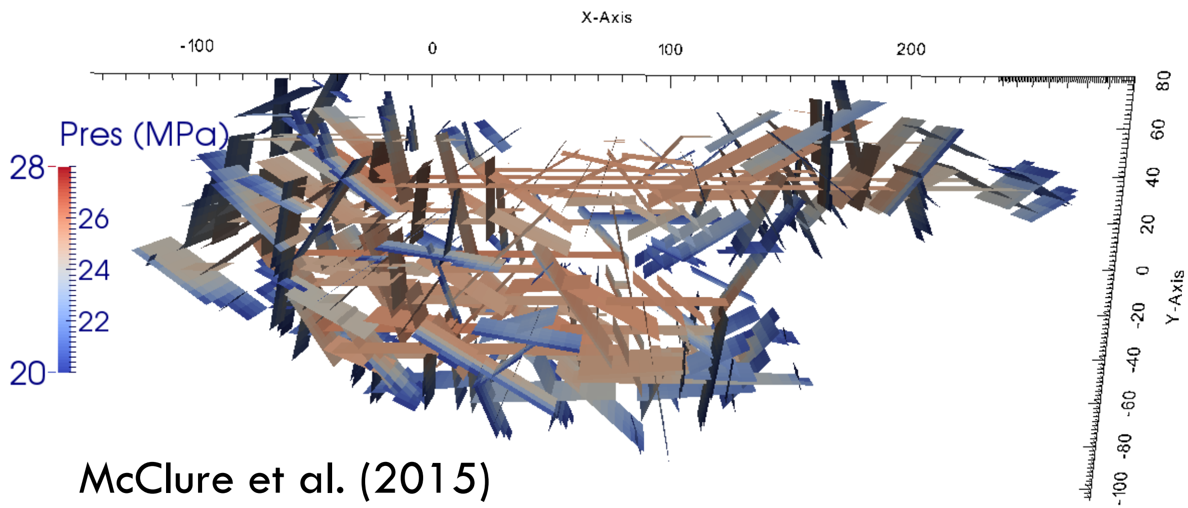
Full coupling of fluid flow with deformation in discrete fractures.

Hmmvp (Bradley, 2012) key for efficiency.



McClure (2012)





McClure et al. (2015)

$$\frac{\partial(\rho\phi)}{\partial t} = \nabla \cdot (\frac{k\rho}{\mu} \nabla P)$$

Mass balance

$$| \tau - \eta v | \leq \mu(\sigma_n - P)$$

Frictional equilibrium

$$\mu = f_0 + a \log(v / v_0)$$
$$+ b \log(v_0 \theta / d_c)$$

Rate and state friction

$$\frac{d\theta}{dt} = 1 - \frac{v\theta}{D_c}$$

"Aging" law

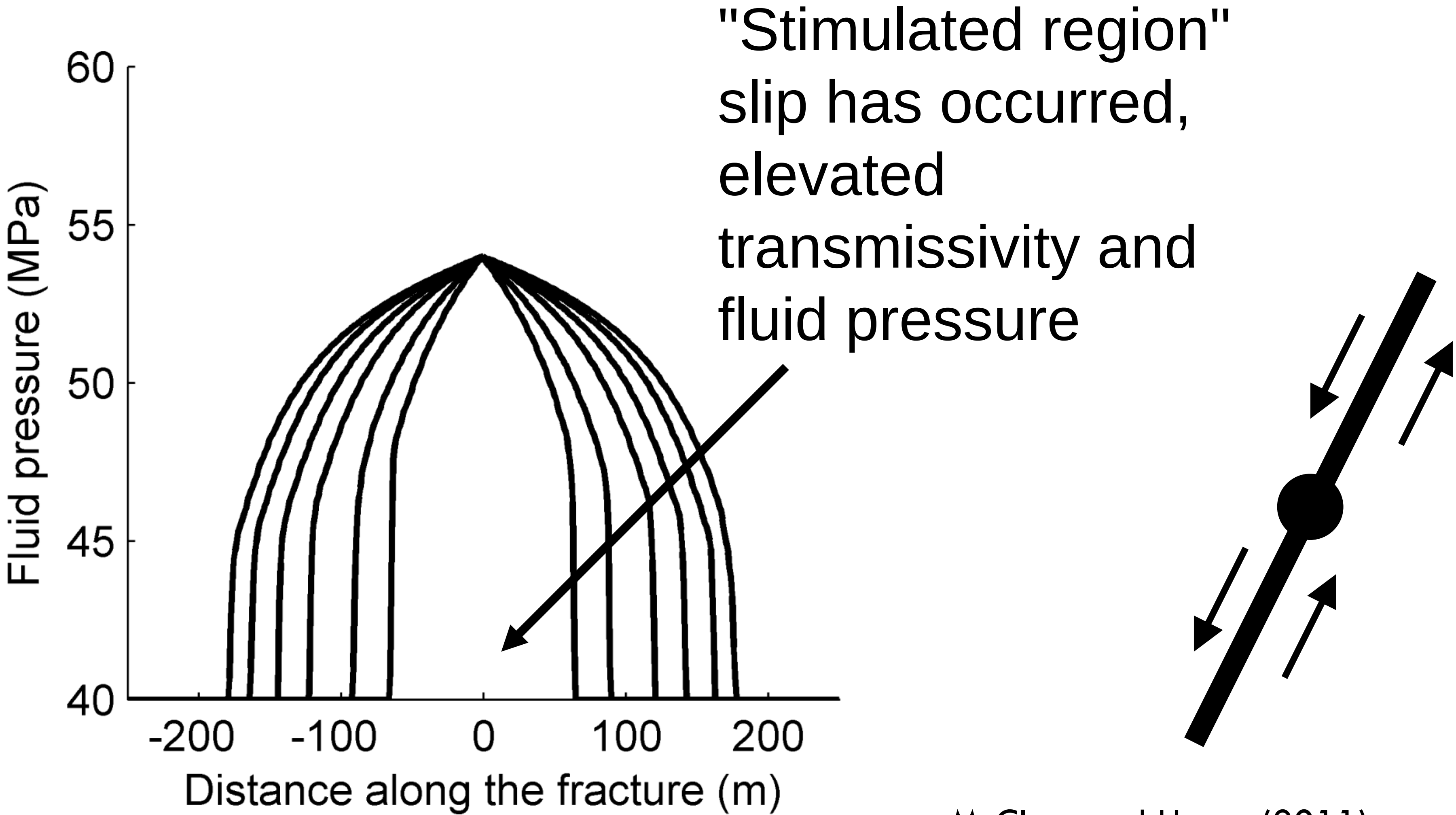
$$e = \frac{e_0}{1 + \frac{9(\sigma_n - P)}{\sigma_n}} + D * \tan\left(\frac{\phi_{dil}}{1 + \frac{9(\sigma_n - P)}{\sigma_n}}\right)$$

Willis-Richards et al. (1996)

$$T = \frac{e^3}{12}$$

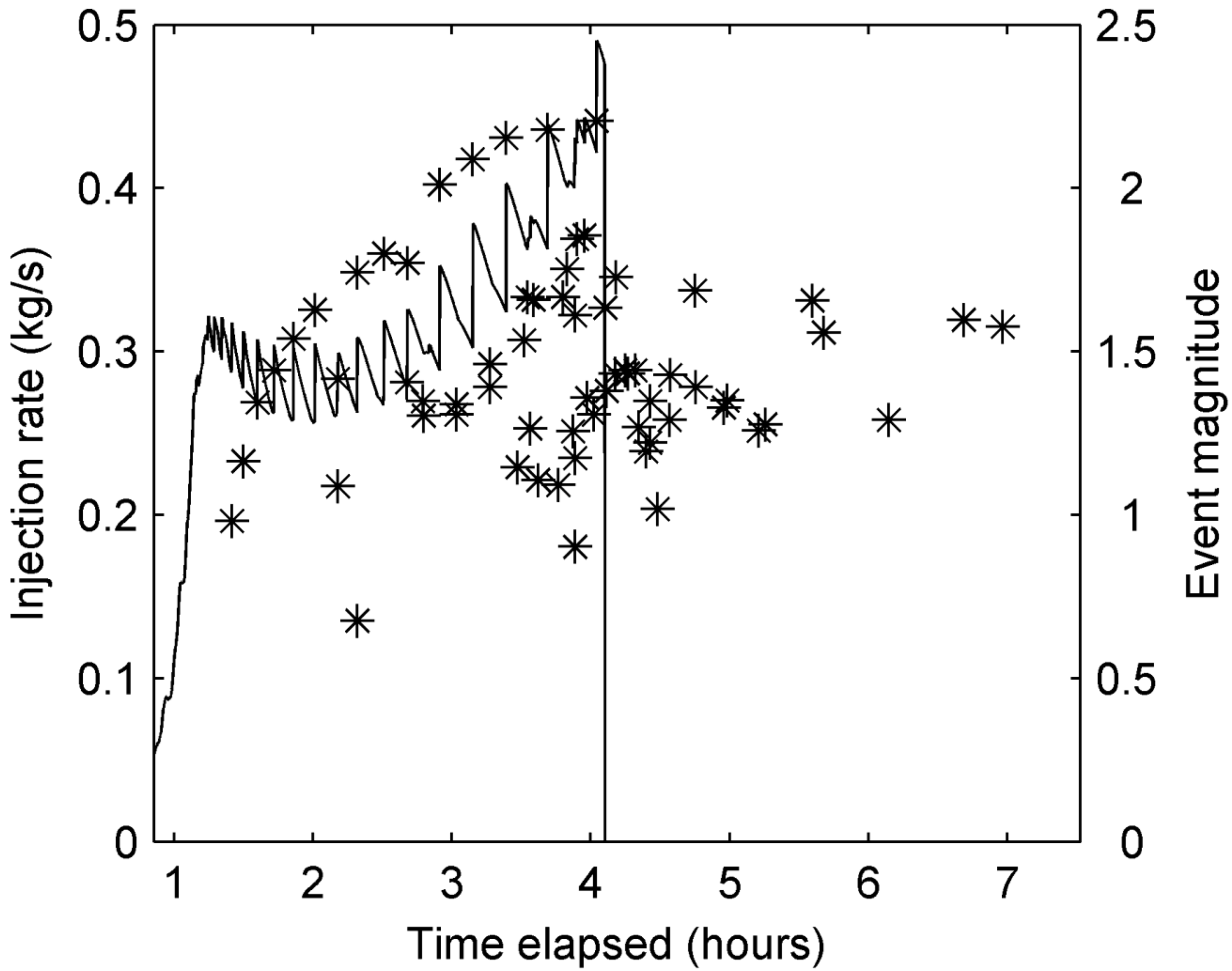
Witherspoon et al. (1980)

Injection into a single fault
Similar to some EGS projects
(Soultz, Basel, Cooper Basin...)



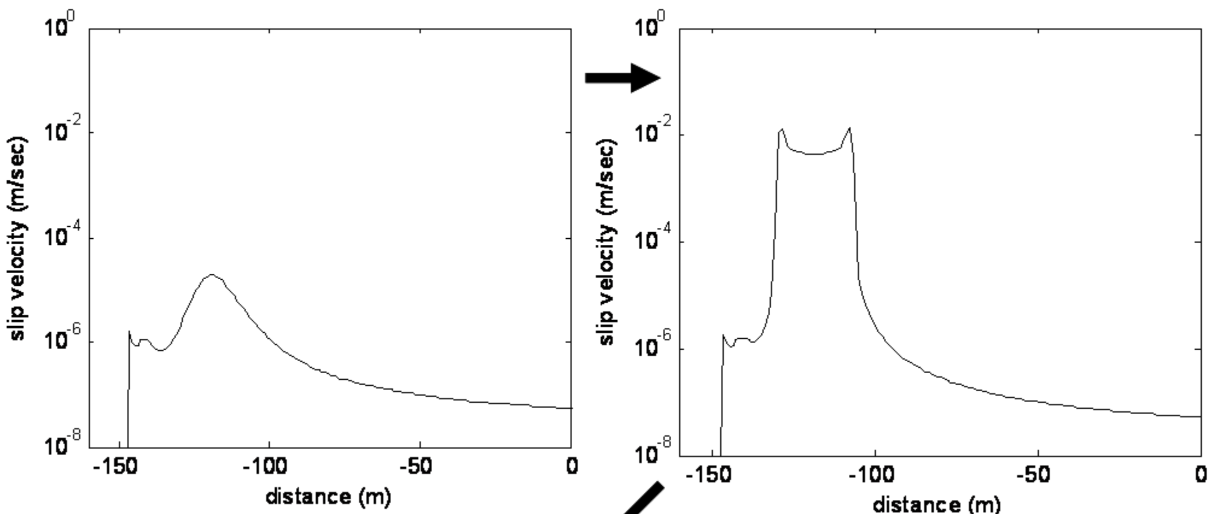
McClure and Horne (2011)

Injection into a single fault

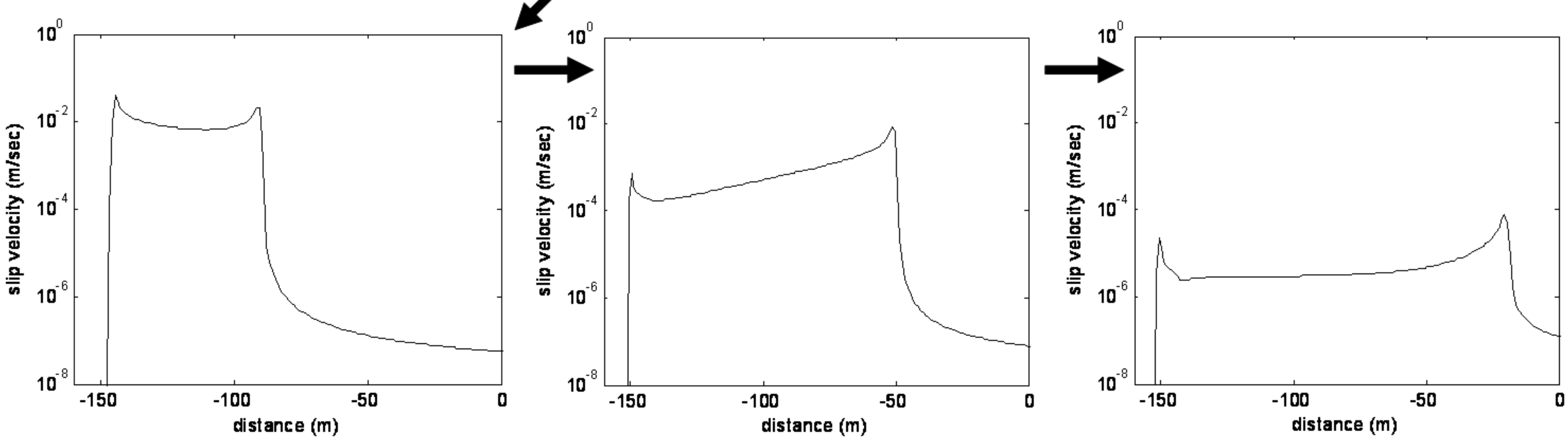


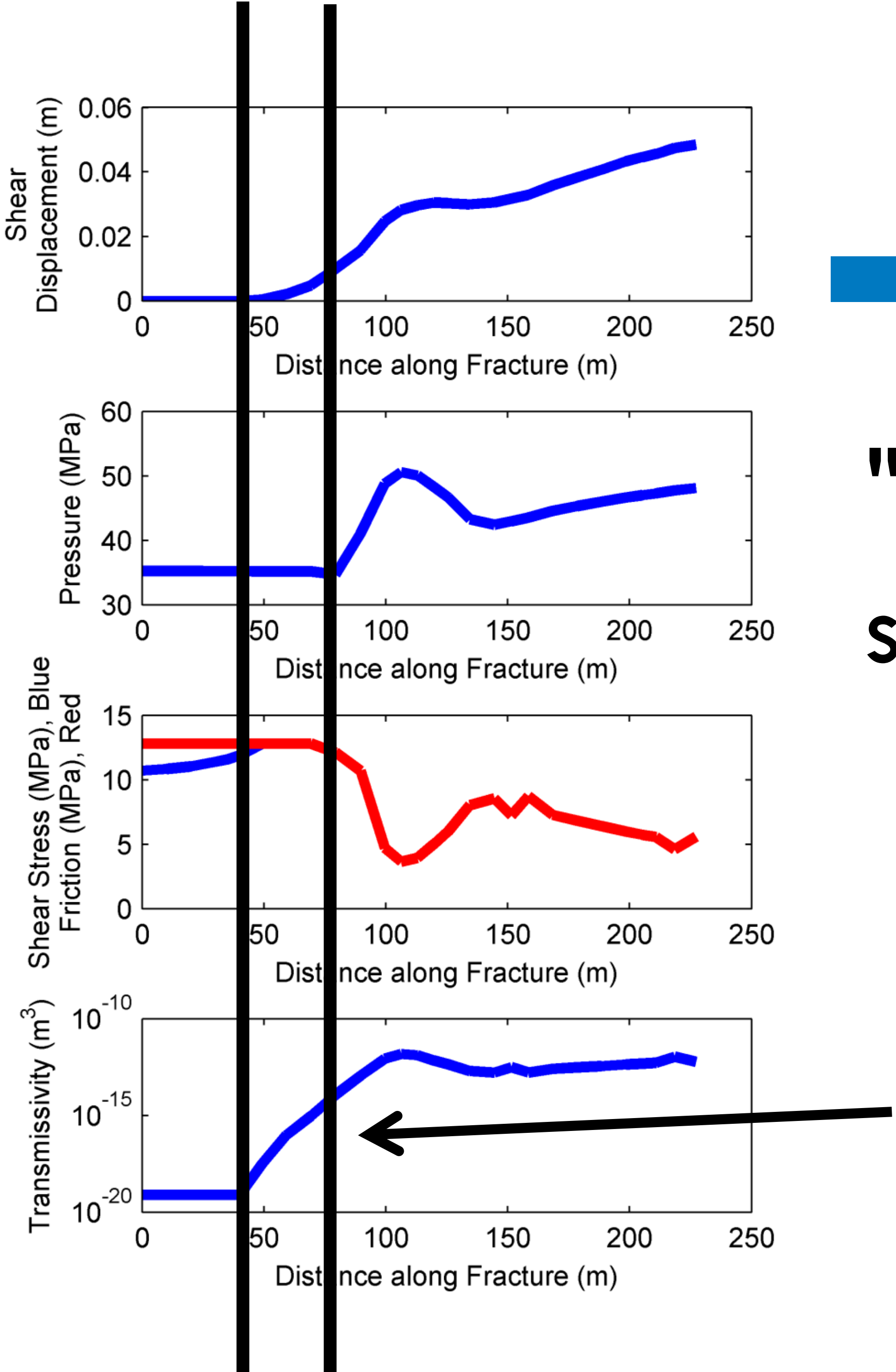
McClure and Horne (2011)

Example of rate/state rupture simulation



Ability of rupture to extend into previously unslipped region depends on stress state.



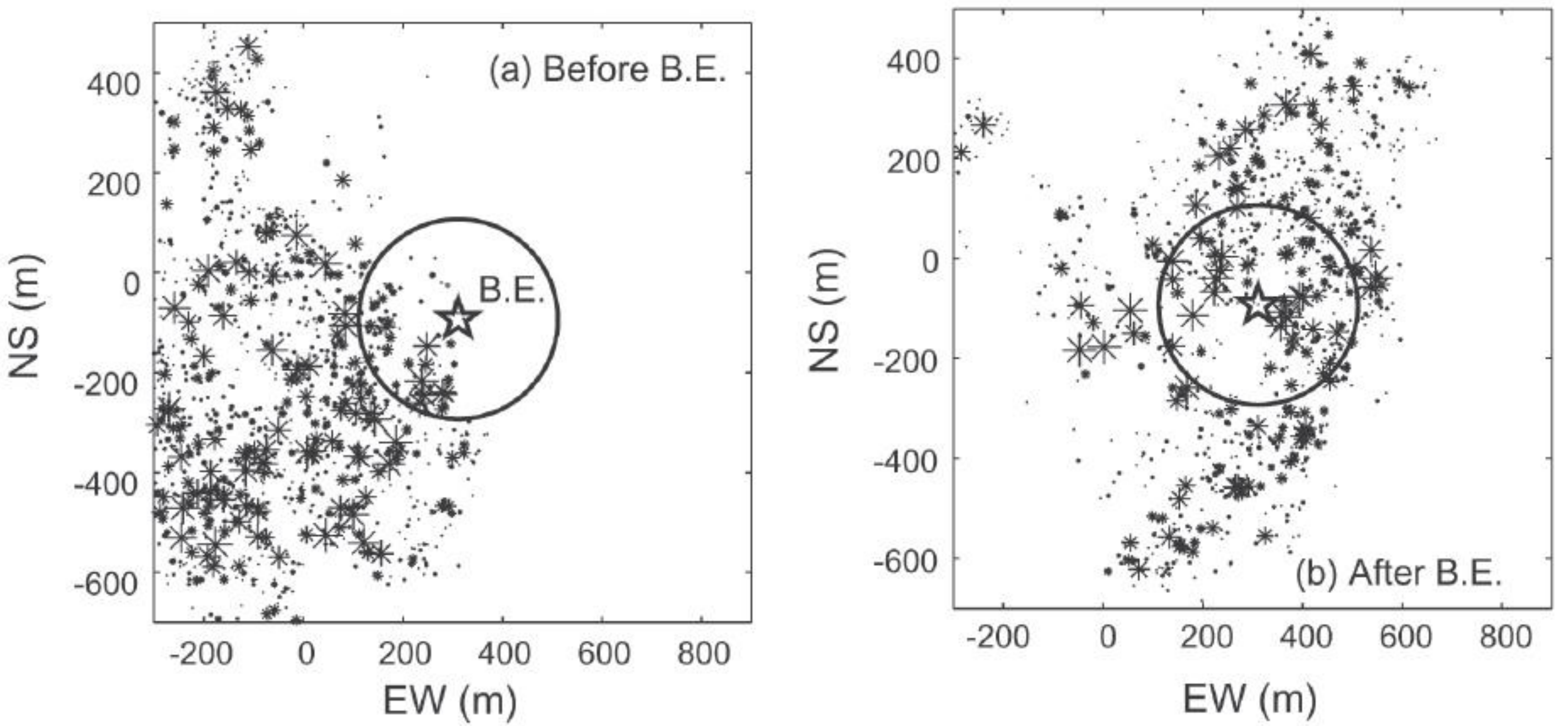


"Crack-like" shear stimulation

Sliding and shear stimulation occur ahead of the fluid pressure front.

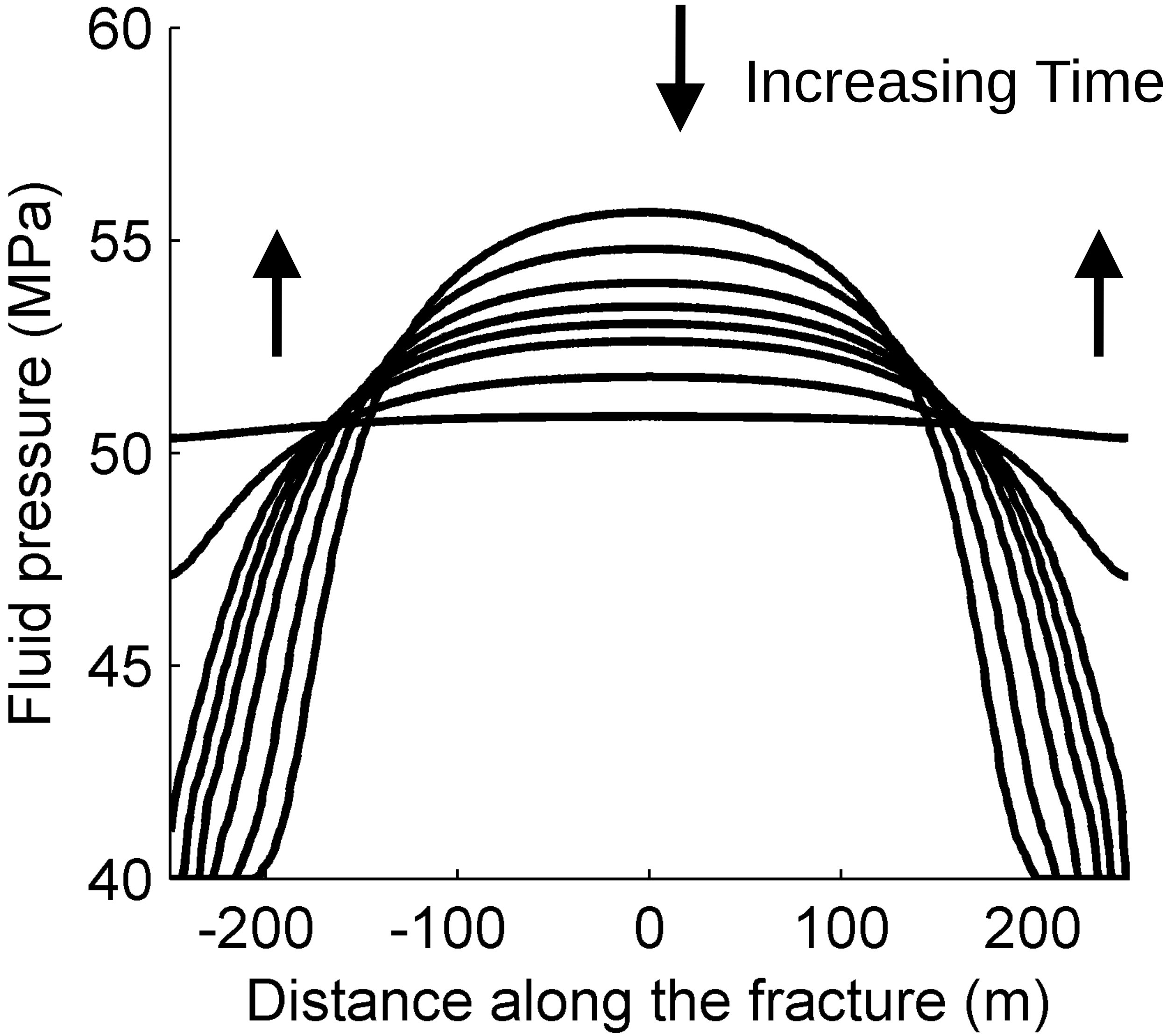
McClure (2012)

Cooper Basin example of episodic "crack-like" shear stimulation

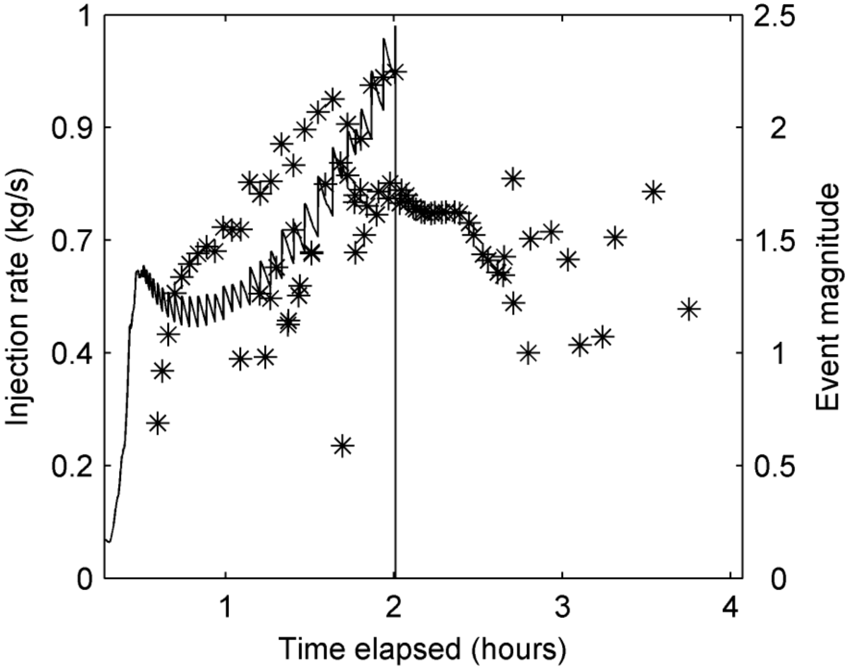


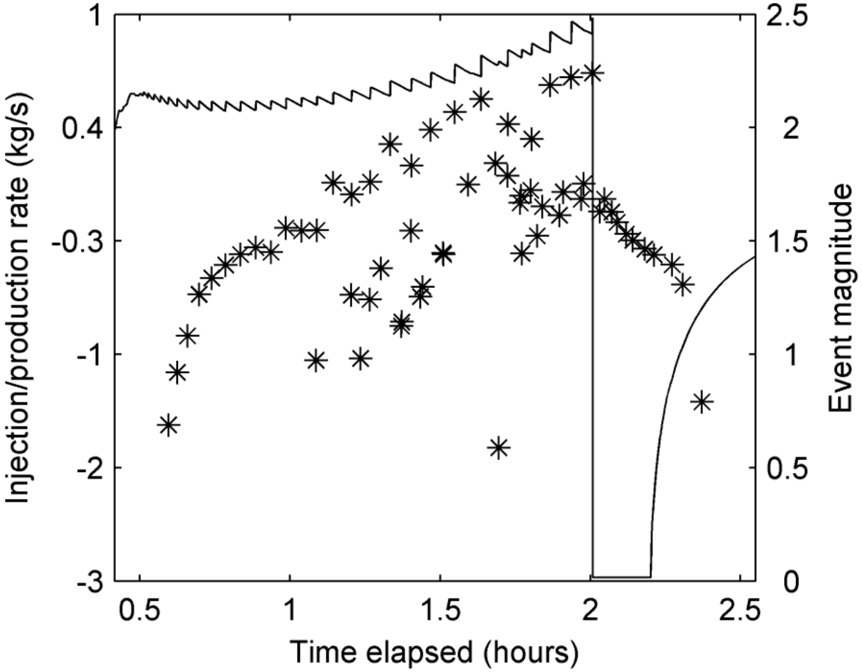
Asanuma et al. (2005)

Post-injection seismicity



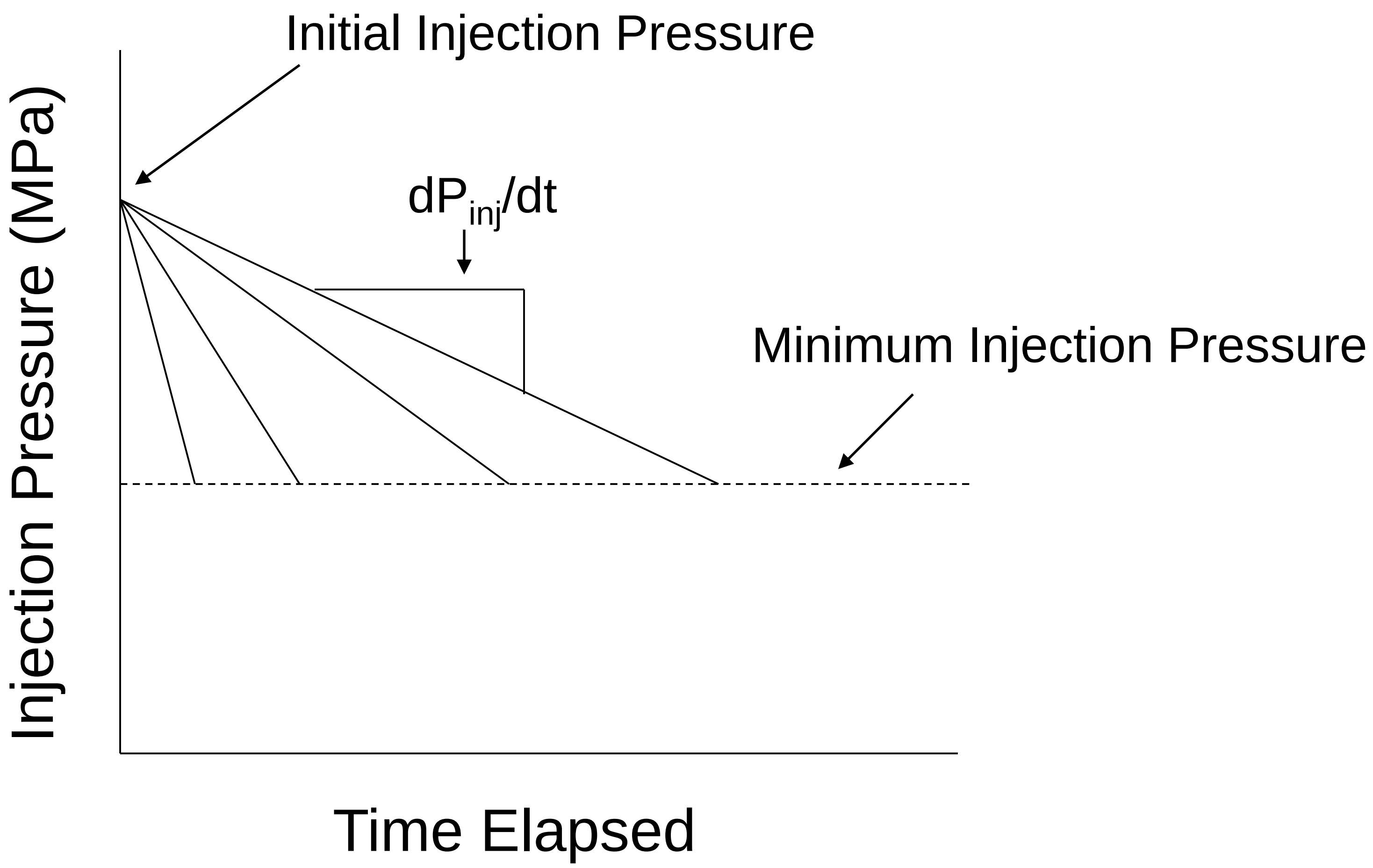
Flowback after injection



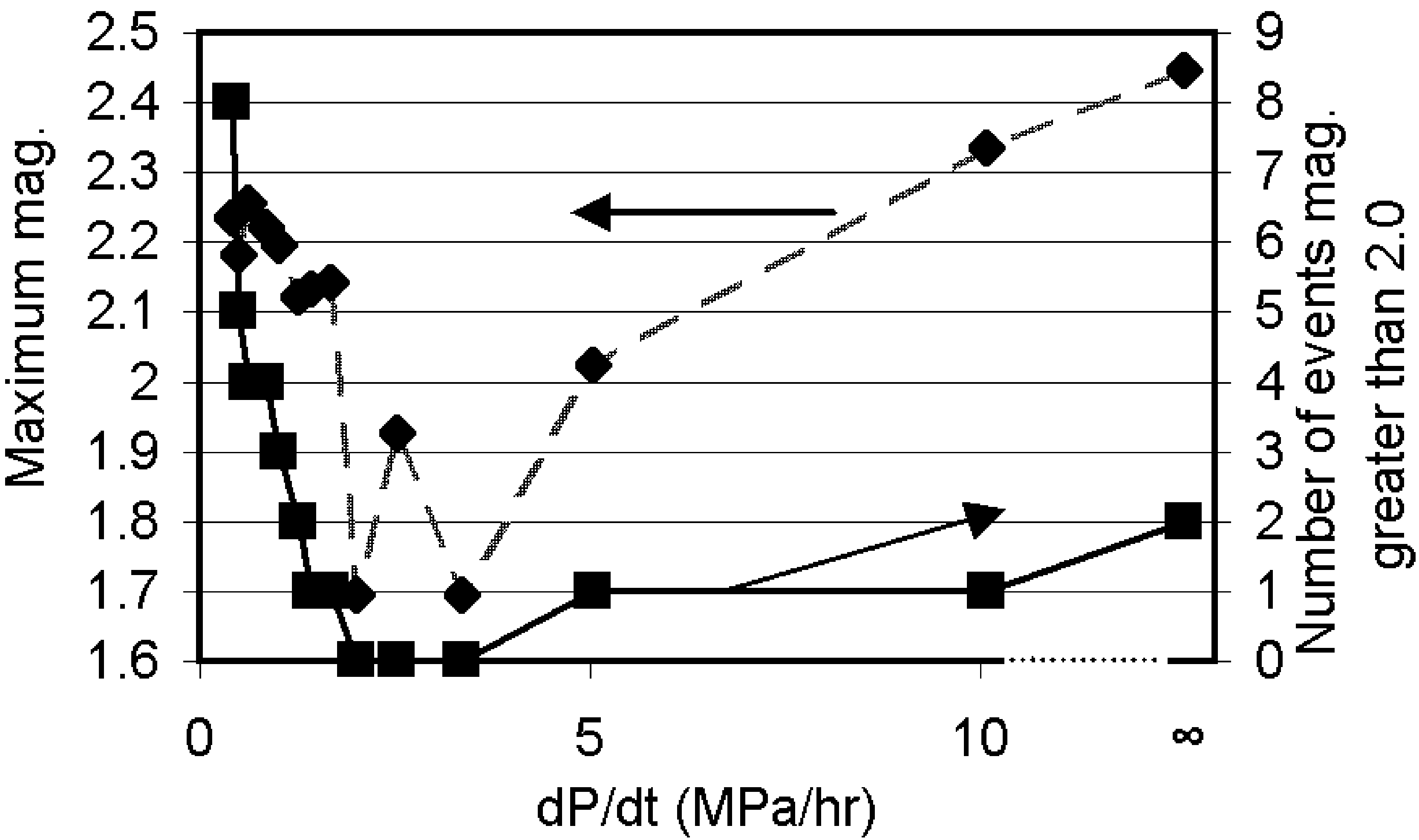


Producing fluid back after injection decreases post-injection seismicity

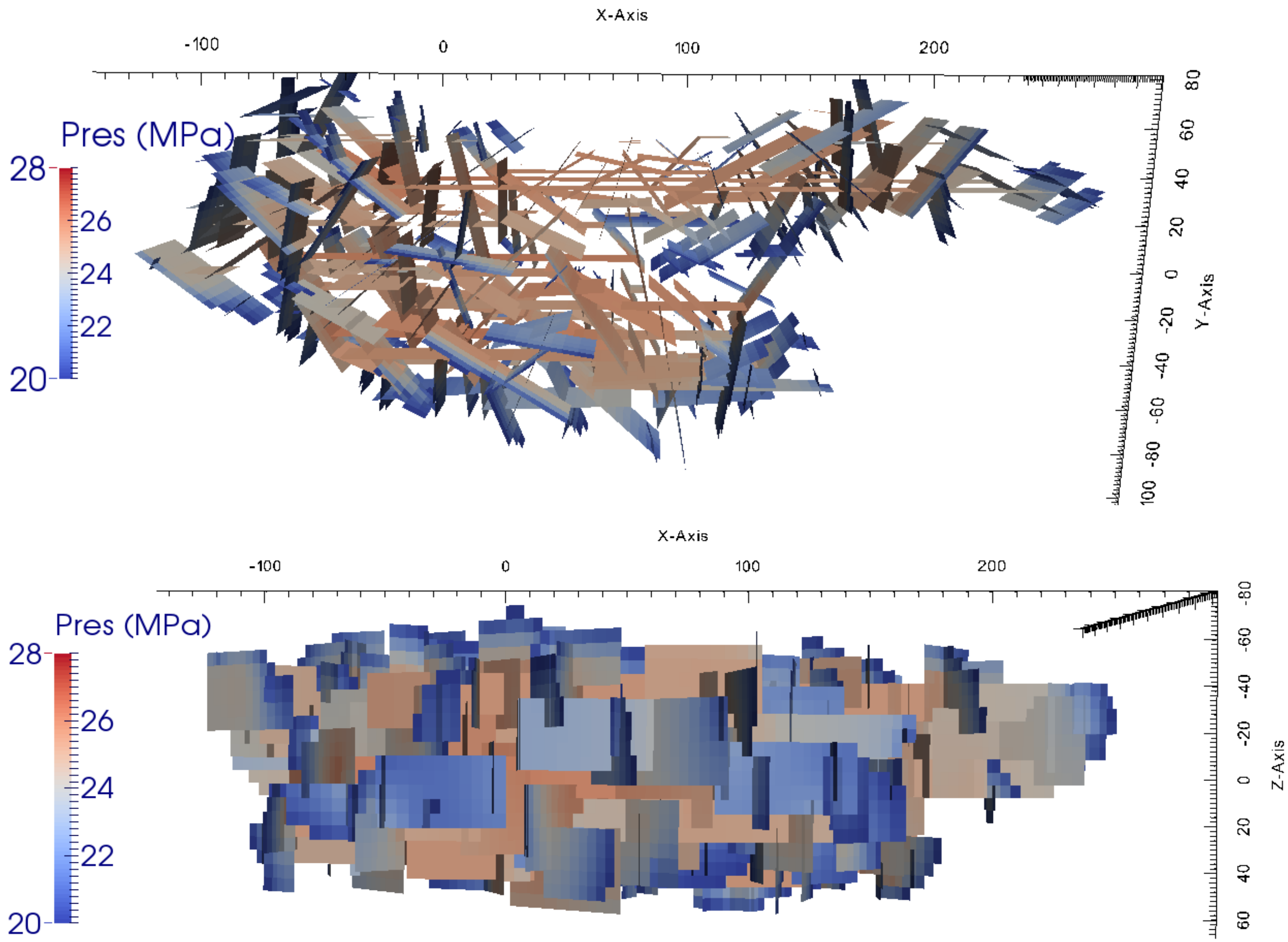
Gradually tapering injection pressure



Gradually tapering injection pressure

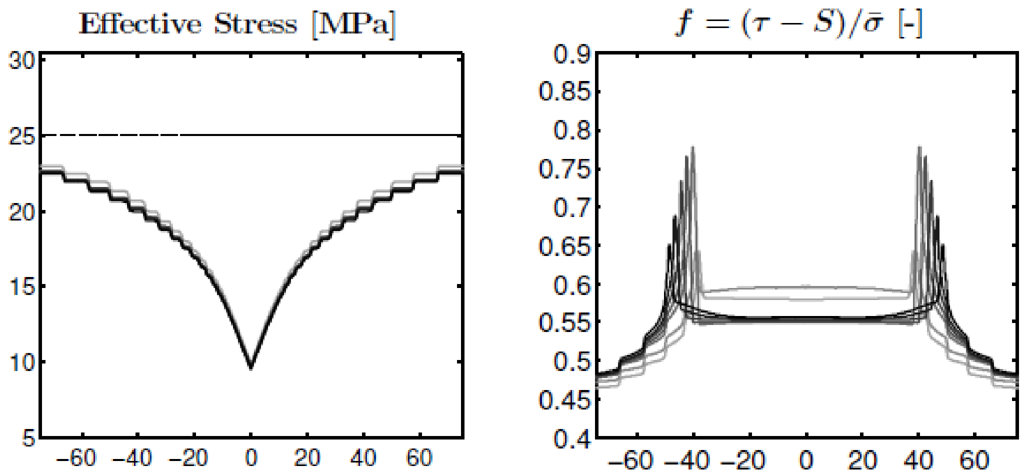


3D simulations with CFRAC

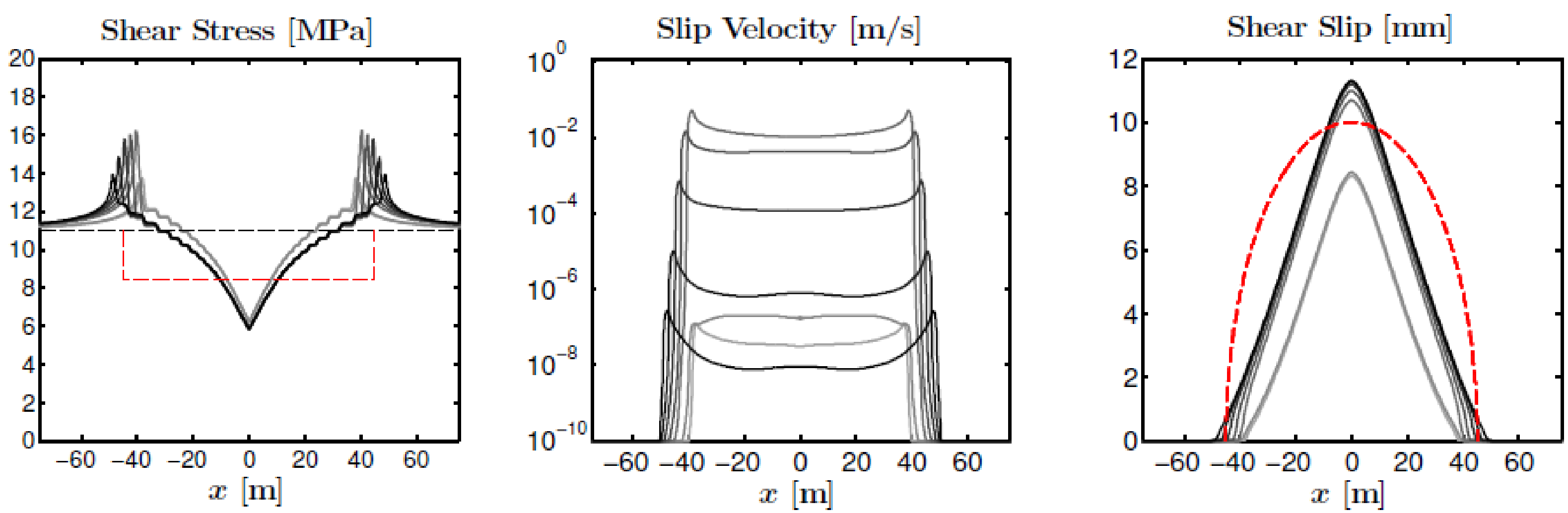


McClure et al. (2015)

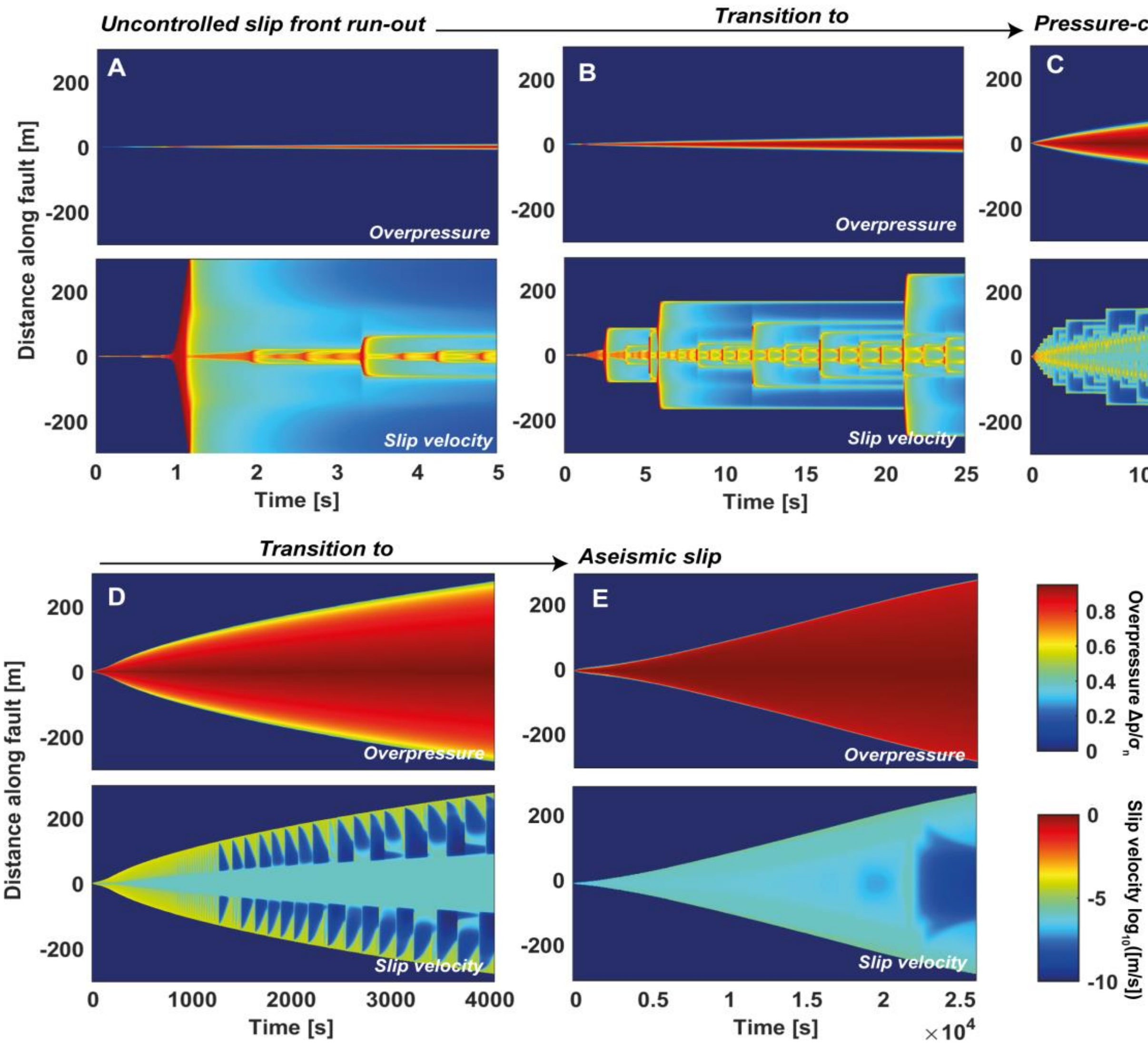
Jack Norbeck and Roland Horne



Norbeck and Horne have been adding thermal and poroelastic stresses into CFRAC and investigating their effects.



Valentin Gischig



Valentin Gischig has been using CFRAC to look at the relationship between stress state and aseismic/seismic slip.

Conclusions

- Simulations with more realistic physics are very useful for generic investigation of processes
- For site specific assessment, we need to move towards integrating physical models and statistical approaches in a balanced way
- CFRAC simulations investigated post-injection seismicity, "crack-like shear stimulation," and mitigation strategies
- Research with CFRAC is ongoing (including other researchers), and it continues to gain capability over time

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