Rate- and State-based Simulations of Induced Seismicity and Coupling to Reservoir Processes

SIAM Geosciences

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NRAP National Risk Assessment Partnership

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LLNL-PRES-??????

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Simulation Goals

- Perform simulations of induced events
- Develop a method to determine safe injection practices
- Inform regulatory agencies
- Simulations must produce realistic results
    - Power law FMD
    - Migration of events away from well with time
    - Small events that lead to larger events
    - M_{max} scales with injected volume (?)
    - Low stress drops
    - Rupture speeds on the order of traditional VEQ

What information is necessary to simulate induced earthquakes?

1. Fault geometry and **rate-state constitutive** parameters
2. Reservoir characterization
3. External stressing history
   - Analytical solution for pore-fluid diffusion (Wang, 2002)
   - NUFT (Nitao, 1998; Hao et al., 2012)
4. Tectonic driving stress (perhaps neglect this in relatively aseismic regions)
5. **Pre-existing shear stress conditions:**
   - *In situ* stress measurements - regional average (from global stress maps)
   - Projection of the regional stress tensor (from global stress maps)
   - Randomly generated heterogeneous field (some fractal distribution)
6. **Earthquake simulation method**
   - **RSQSim**
7. Well located seismicity catalog with low magnitude of completeness

Earthquake Time-dependency: Rate- and State-dependent Friction

$$\tau = \mu(\sigma - p)$$

(1) Modified Coulomb Criterion

$$\mu = \mu_0 + a\ln\left(\frac{V}{V^*}\right) + b\ln\left(\frac{\theta V^*}{D_c}\right)$$

(2) Rate- and State-dependent friction

$$\tau = (\sigma - p)\left[\mu_0 + a\ln\left(\frac{V}{V^*}\right) + b\ln\left(\frac{\theta V^*}{D_c}\right)\right]$$

(3) Constitutive Law

Rate-term State-term

μ_0= Nominal coefficient of friction

V^*: Reference slip rate

V: Earthquake slip rate

θ: State variable

D_c: Characteristic slip distance

***a* and *b*: Constitutive parameters describing the material**

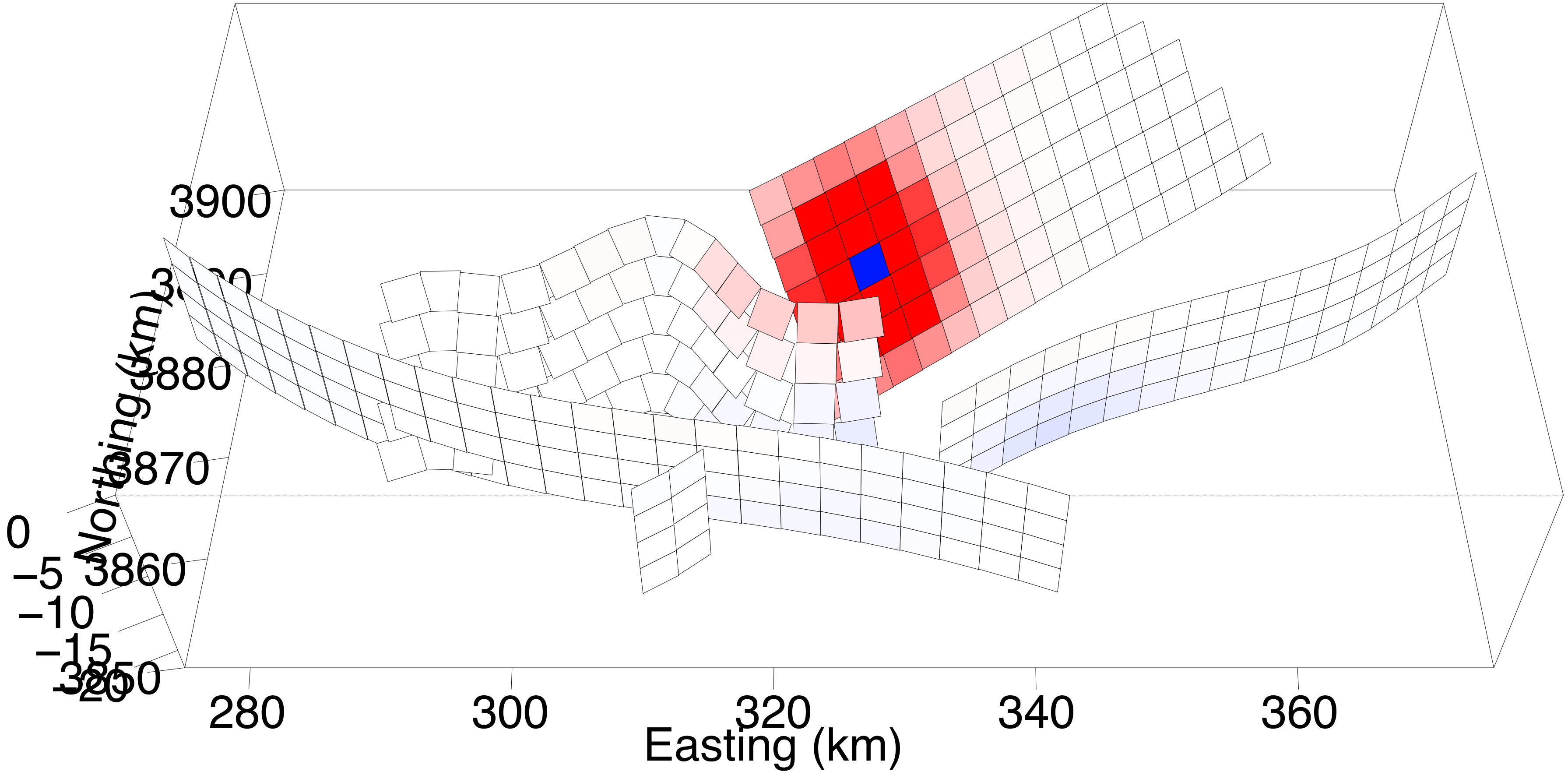
Dieterich, 1978, 1979; Ruina 1983

RSQSim: Governing equations

- Constitutive relation: $$\tau_i^{\text{fric}} = \sigma_i \left[\mu_0 + a \ln \left(\frac{\dot{\delta}_i}{\dot{\delta}^*} \right) + b \ln \left(\frac{\theta_i \dot{\delta}^*}{D_c} \right) \right]$$
- State evolution: $$\dot{\theta}_i = 1 - \frac{\theta_i \dot{\delta}_i}{D_c} - \frac{\alpha \theta_i}{b \sigma_i} \dot{\sigma}_i$$
- Applied stress evolution: $$\dot{\tau}_i = \dot{\tau}_i^{\text{tect}} + K_{ij}^{\tau} \dot{\delta}_j$$ $$\dot{\sigma}_i = \dot{\sigma}_i^{\text{tect}} + K_{ij}^{\sigma} \dot{\delta}_j$$

- Terms in red are additional ones due to normal stress variations (Linker and Dieterich, 1992)
- Interaction coefficients, *K*, calculated from the dislocation solutions of Okada, 1992
- Tectonic stressing rates derived from backslipping the model
- Numerical integration too slow for the scale of problems we would like to address

Coulomb stress change from unit slip on one element



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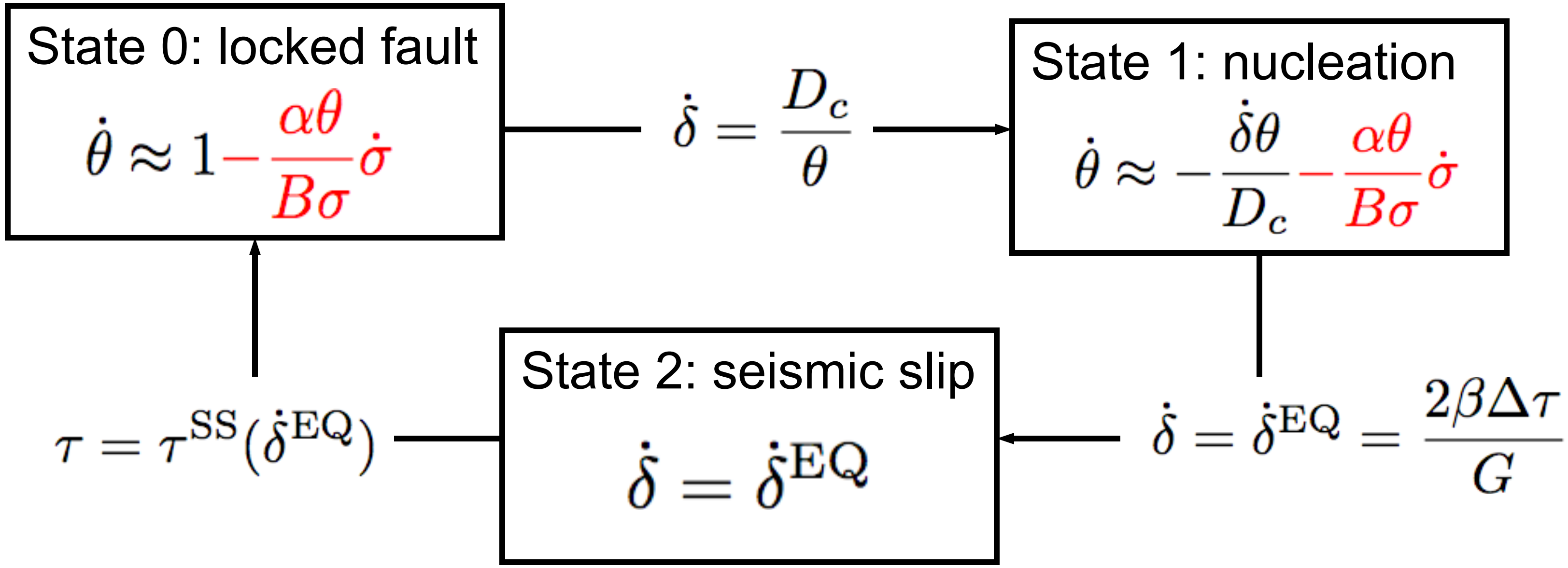
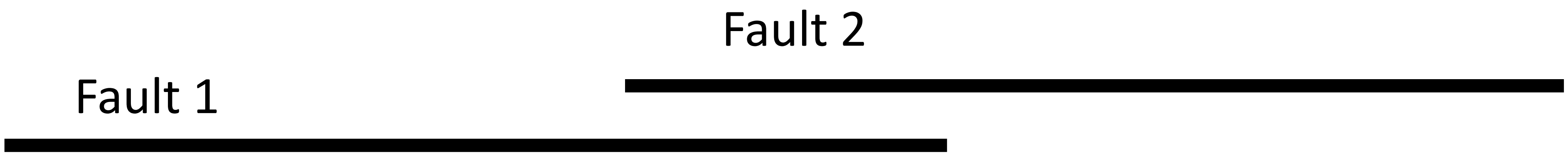
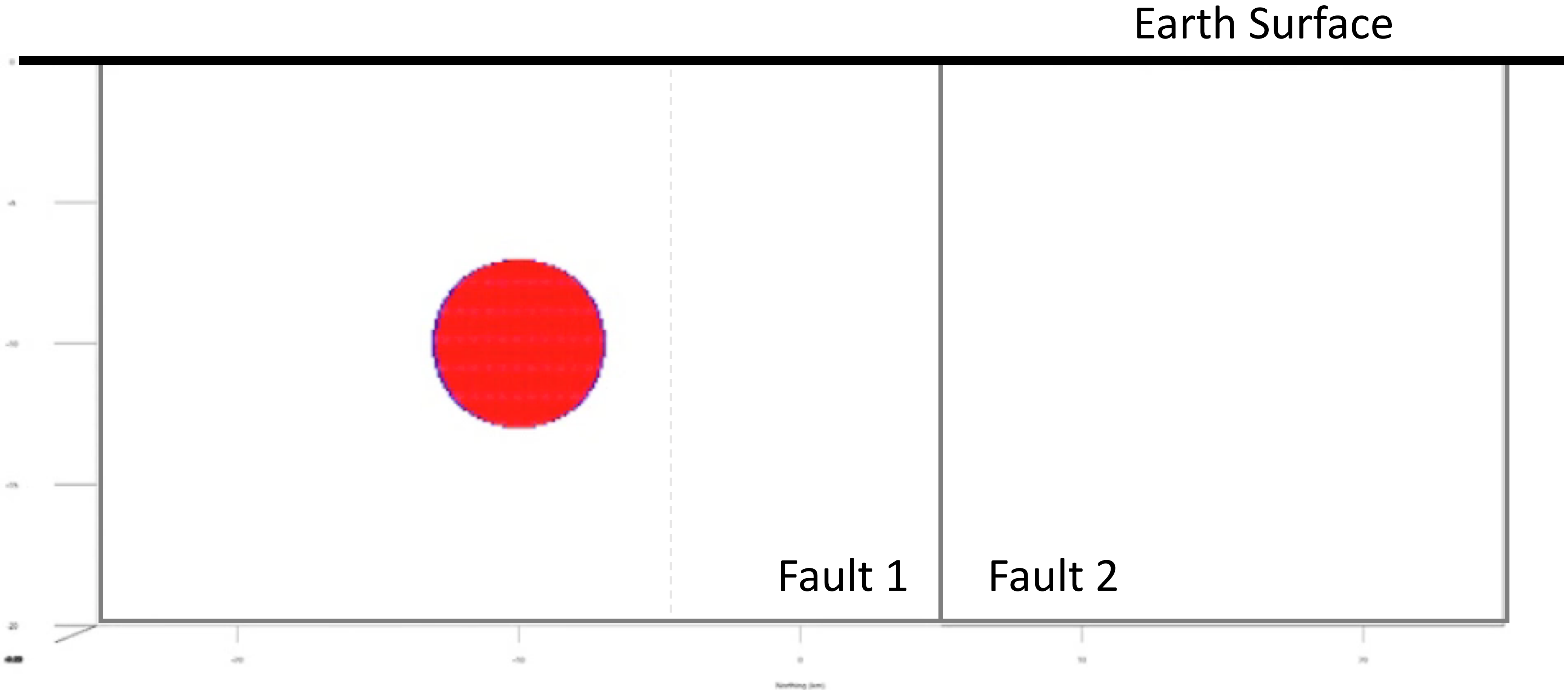
- State evolution: $$\dot{\theta}_i = 1 - \frac{\theta_i \dot{\delta}_i}{D_c} - \frac{\alpha \theta_i}{b \sigma_i}\dot{\sigma}_i$$
- Stress evolution: $$\dot{\tau}_i = \dot{\tau}_i^{\text{tect}} + K_{ij}^{\tau}\dot{\delta}_j \qquad \dot{\sigma}_i = \dot{\sigma}_i^{\text{tect}} + K_{ij}^{\sigma}\dot{\delta}_j$$

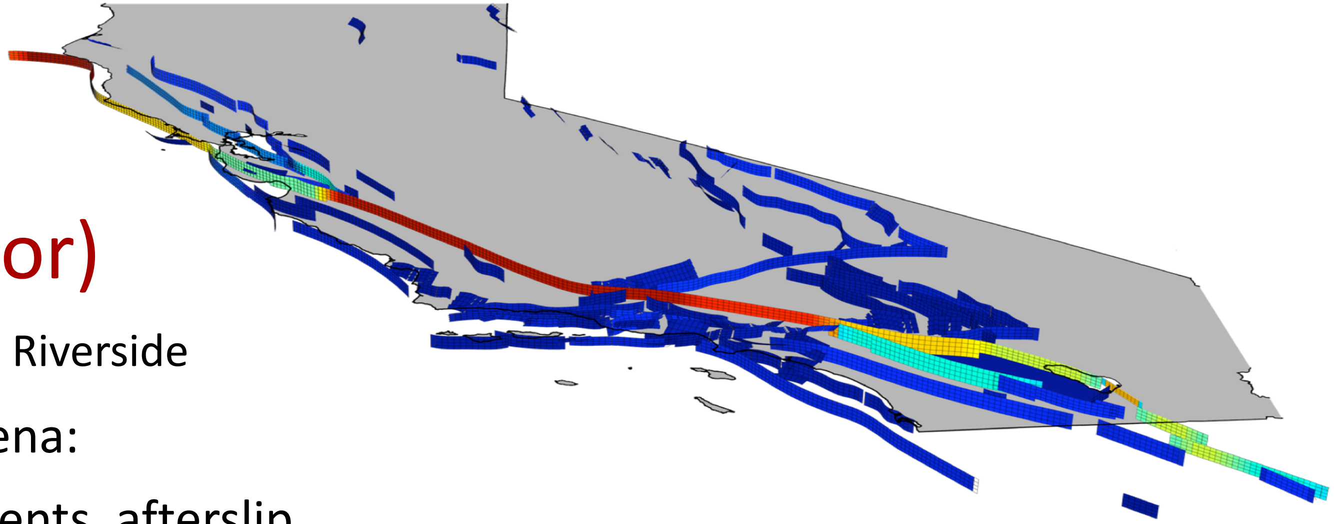


M=7.0 Multi-fault earthquake rupture simulation



Red shows areas that are actively slipping in the earthquake



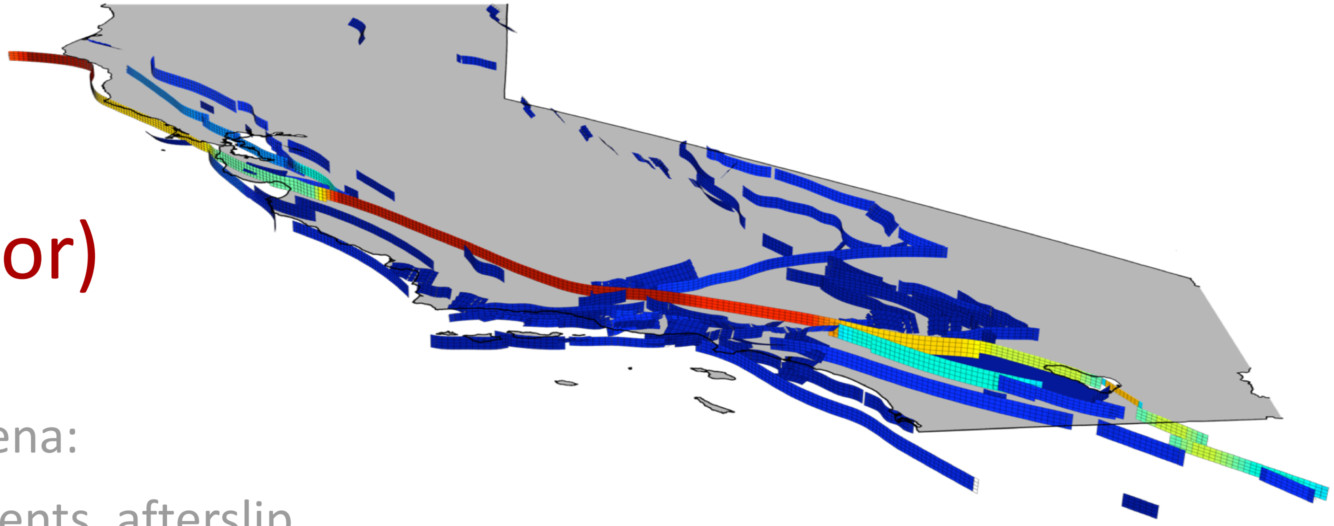


RSQSim
(**R**ate-**S**tate earth**Q**uake **Sim**ulator)

Developed by Jim Dieterich and Keith Richards-Dinger at UC Riverside

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

RSQSim
(Rate-State earthQuake Simulator)



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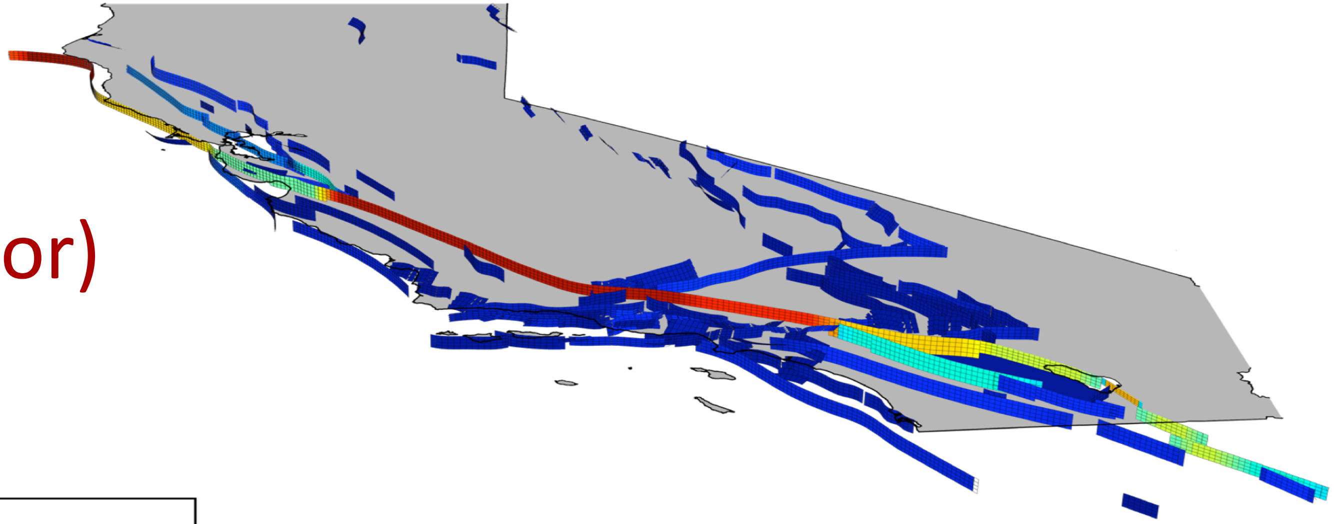

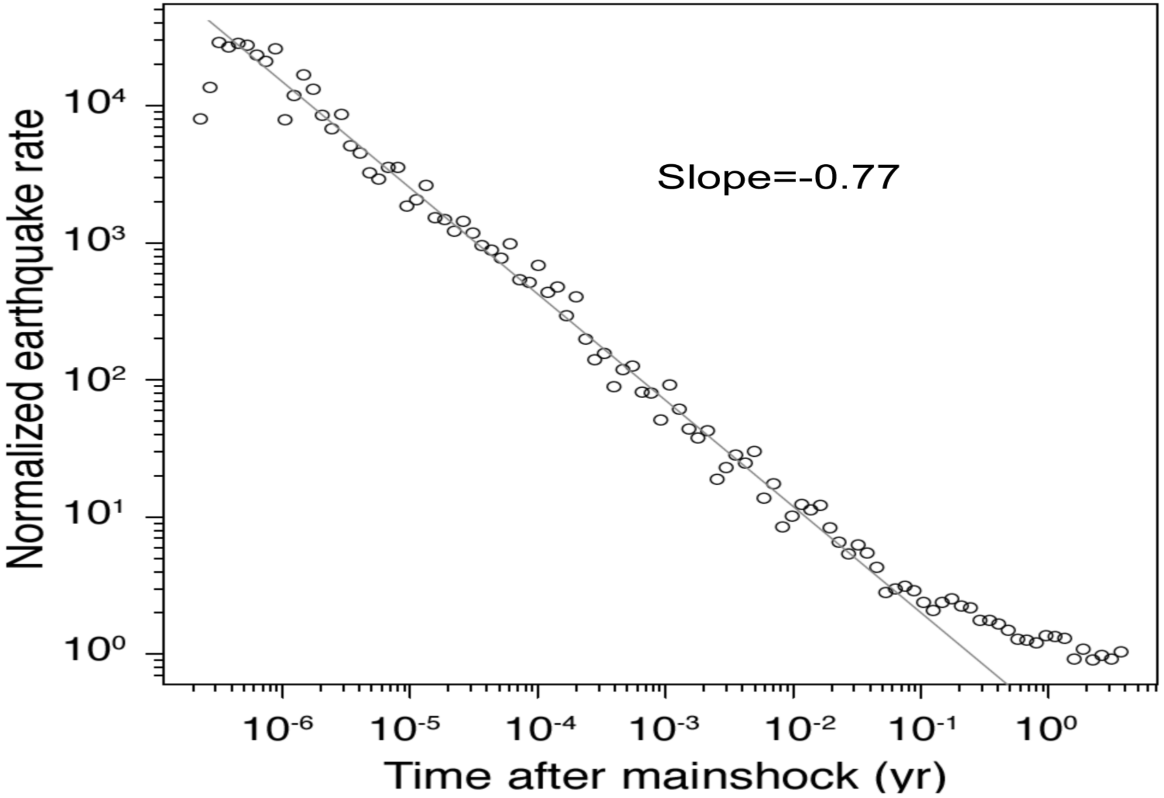

All-California simulation
Aftershocks follow the Omori Law
for aftershock decay with time

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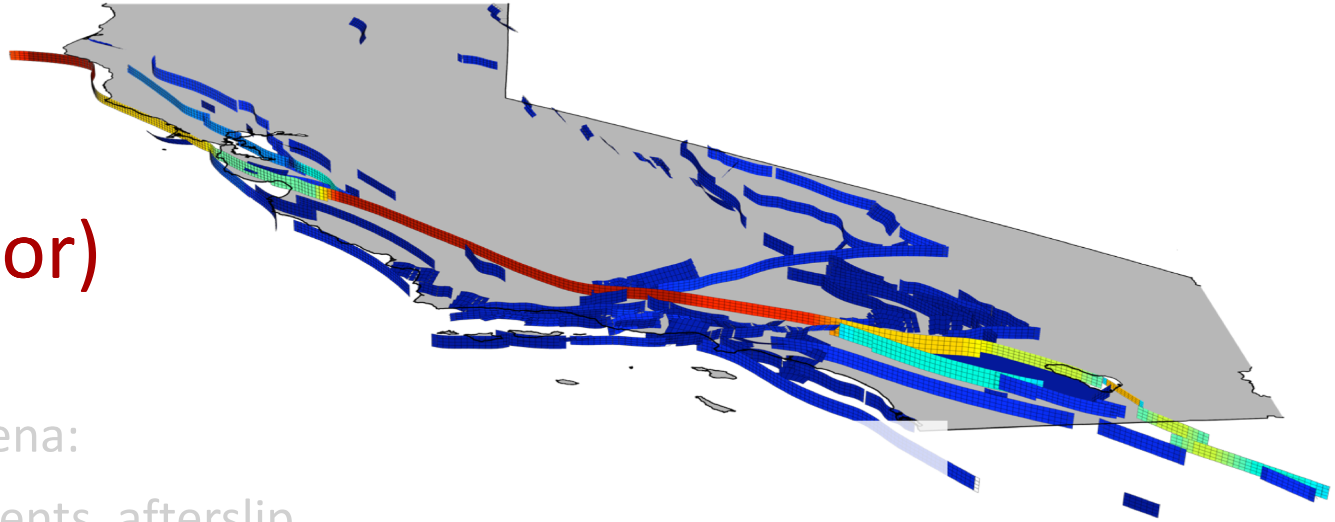

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  - → Up to 10^6 fault elements
  - → Range of earthquake magnitudes M=3.5 to M=8 (for 1 km^2 triangular elements)

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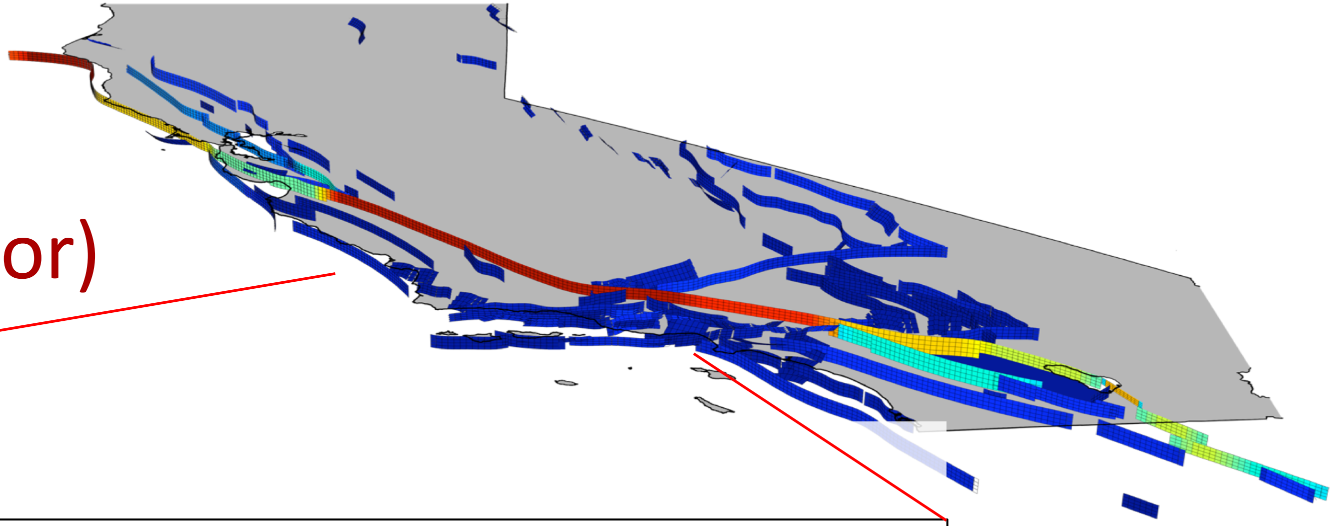

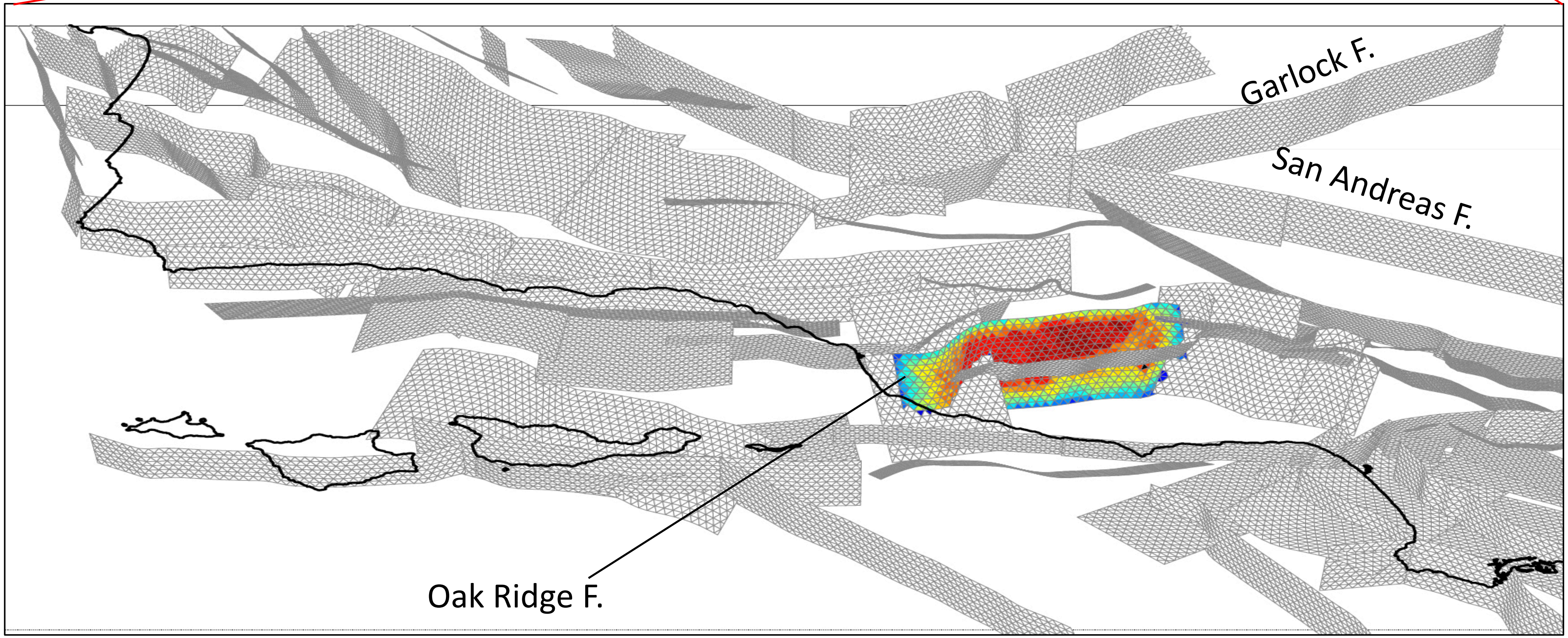

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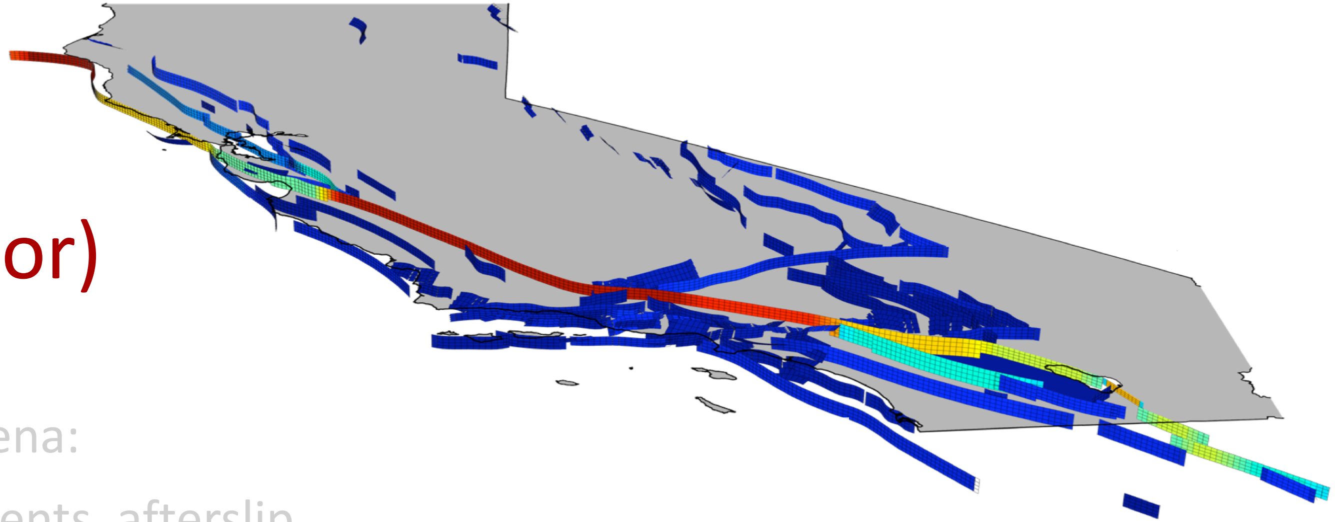

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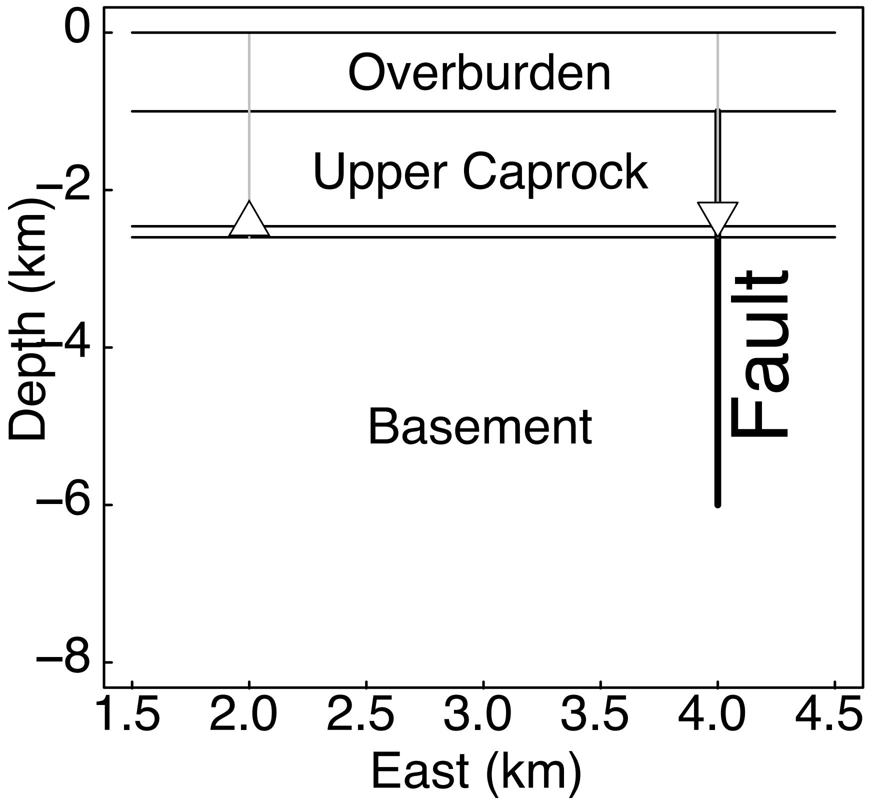
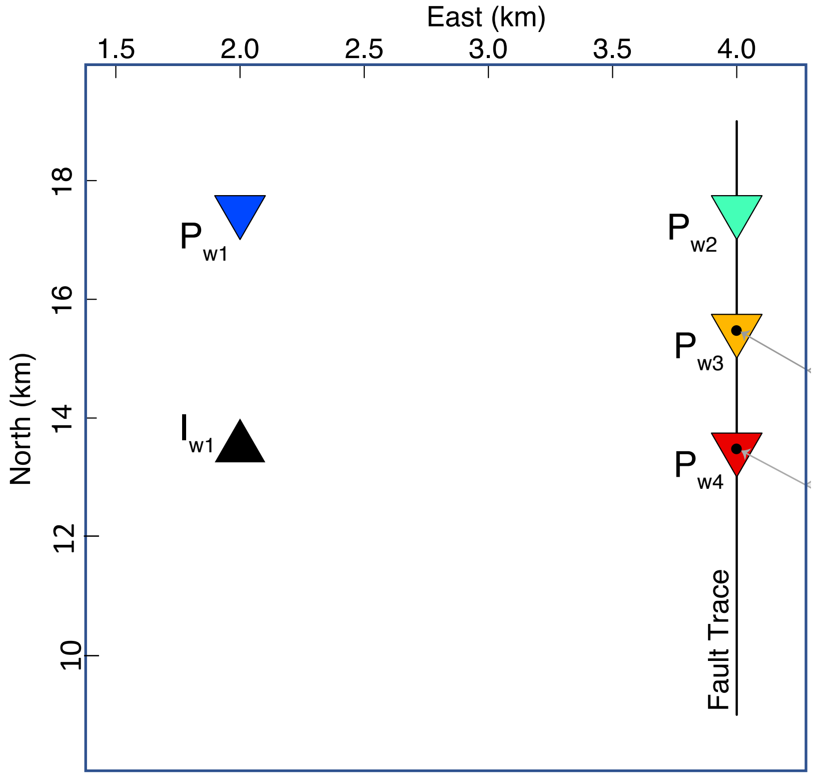
- High resolution models of geometrically complex fault systems
  - → Up to 10^6 fault elements
  - → Range of earthquake magnitudes M=3.5 to M=8 (for 1 km^2 triangular elements)
- Highly efficient code
  - → Good statistical characterizations from long simulations of 10^6 earthquakes
  - → Repeated simulations to explore parameter space

Model Geometry





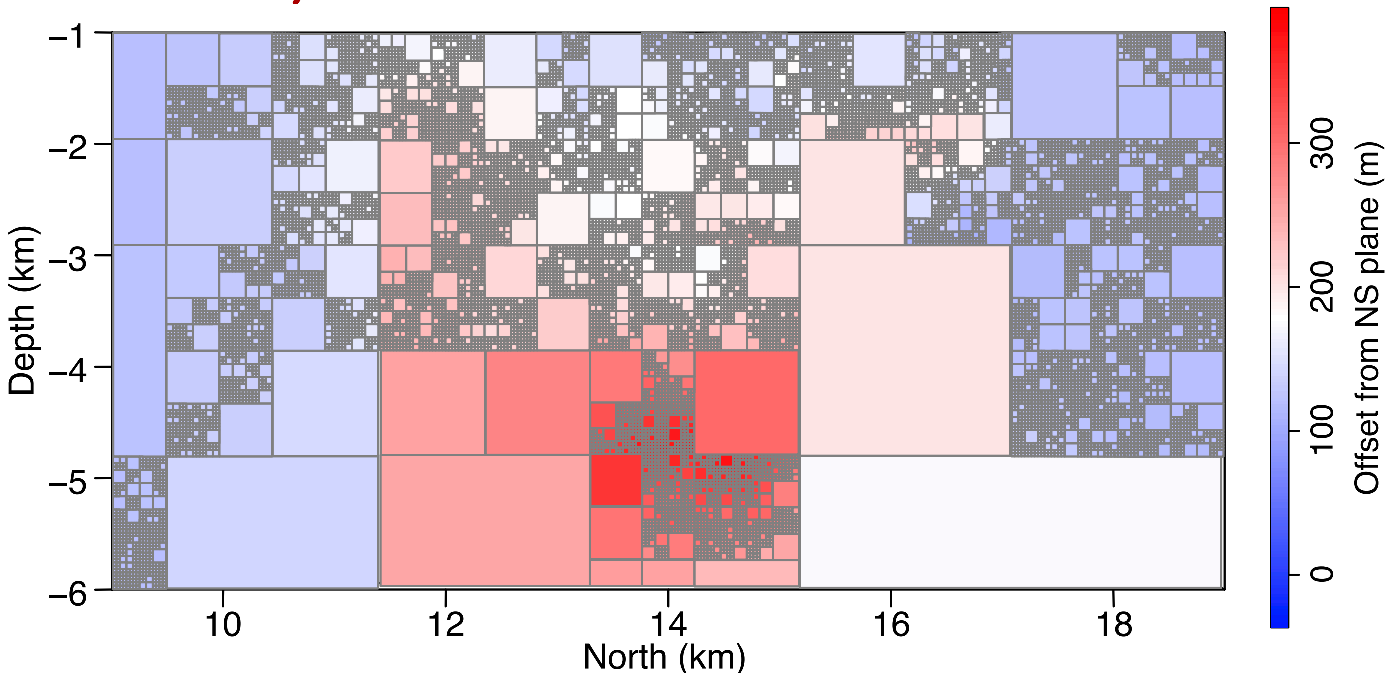
Injection and Co-production (various volumes)

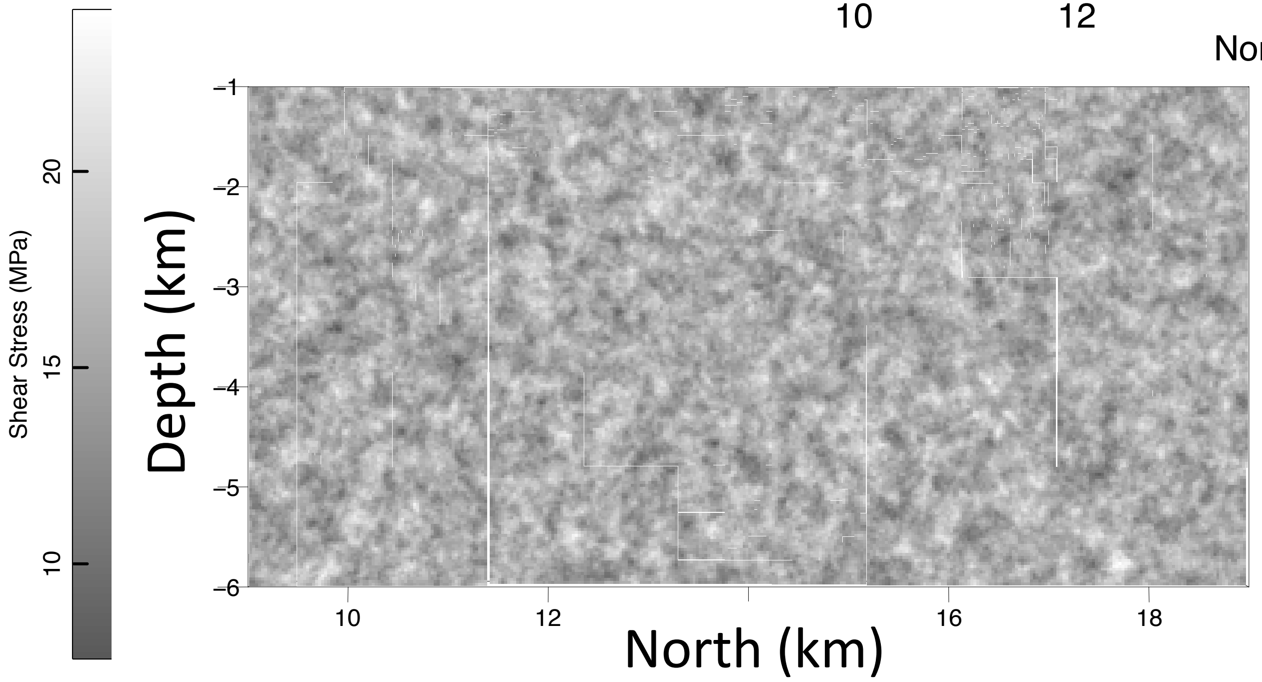
- 25 % (14.25 Mt CO2)
- 50% (28.50 Mt CO2)
- 75% (42.75 MT CO2)
- 100% (57 Mt CO2)

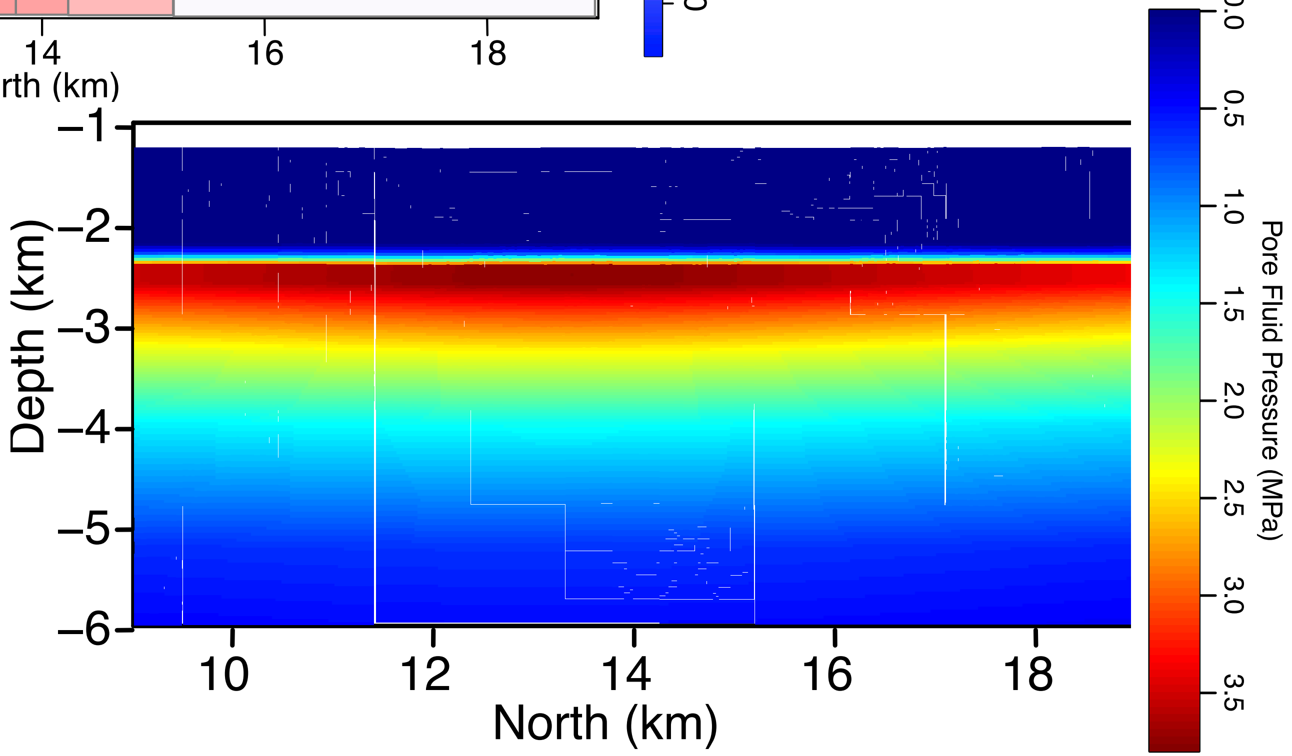
- Injection for 30 years (~0.6 m^3/s)
- Co-production
  - 30 years at fractional rate

*Net injection volume = injected volume – production volume

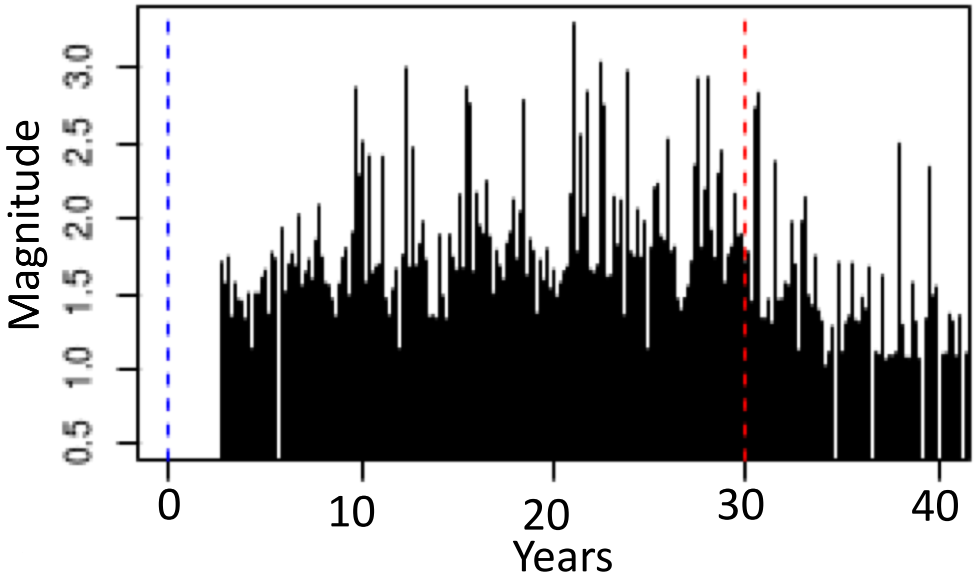
Fault Geometry, Pre-stress, and Pressure

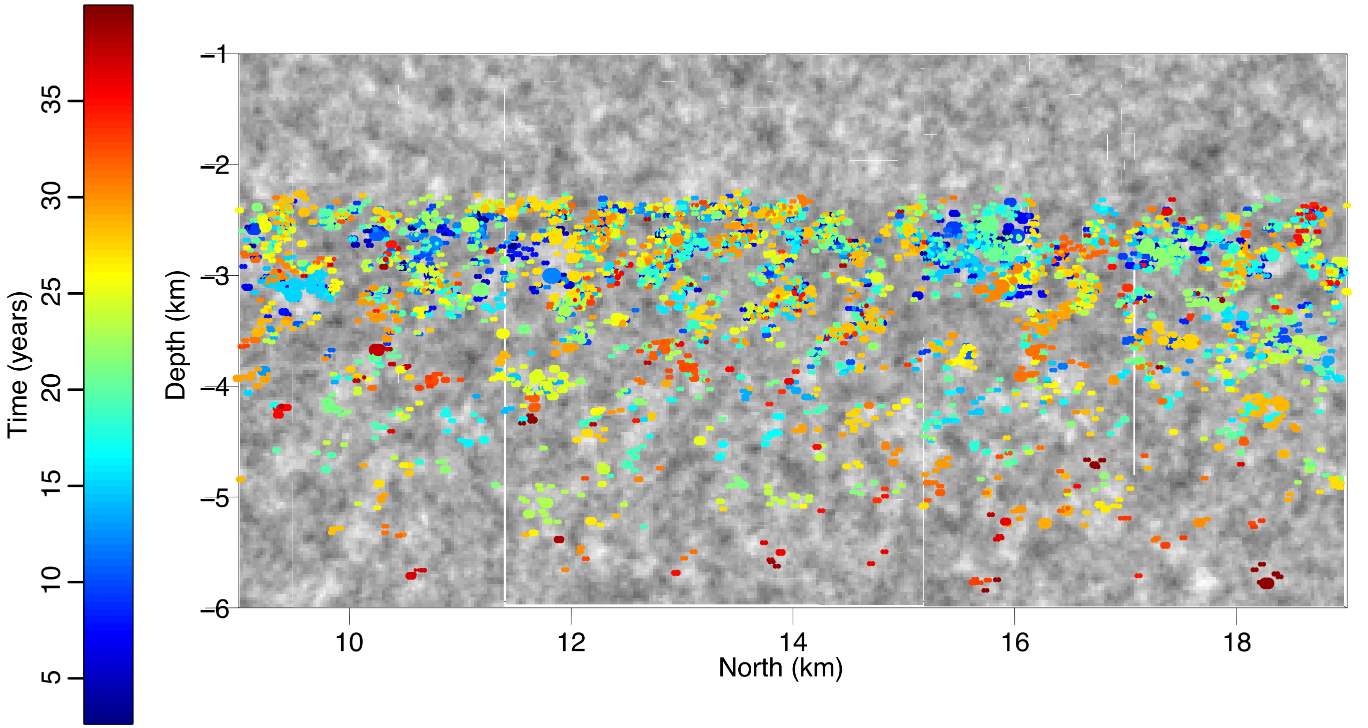


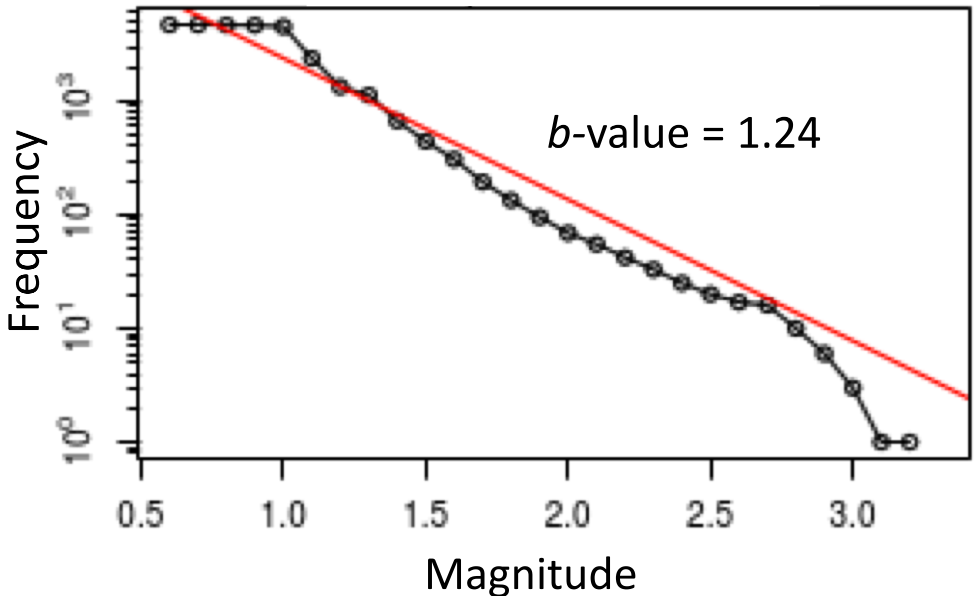


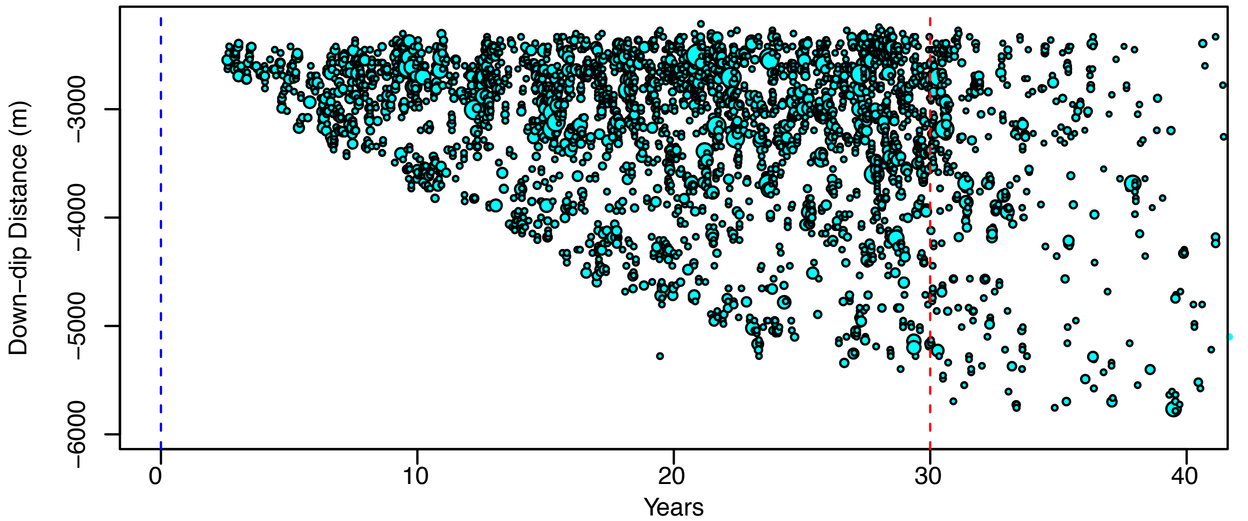


Resulting Seismic Catalog (Injection Only)

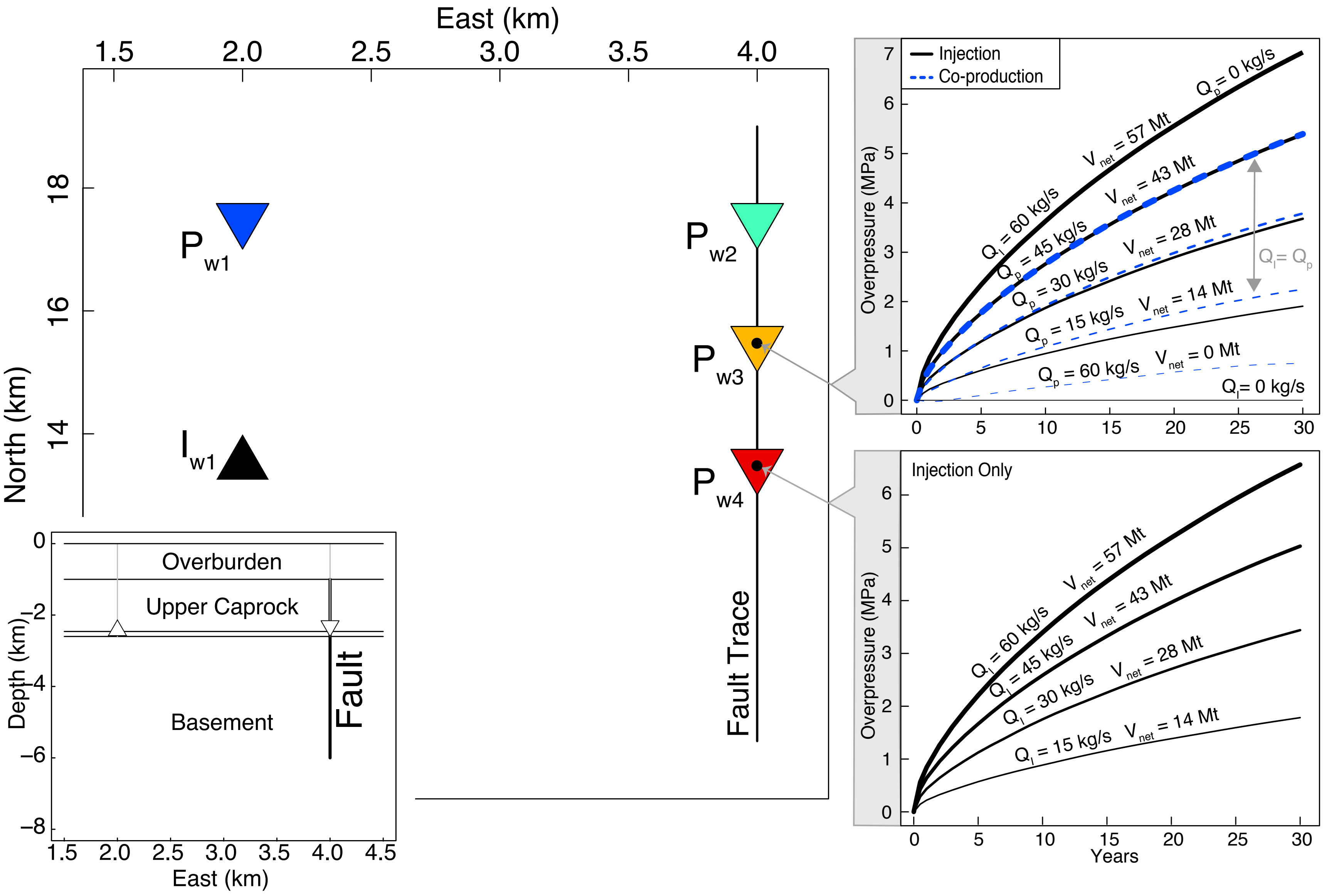




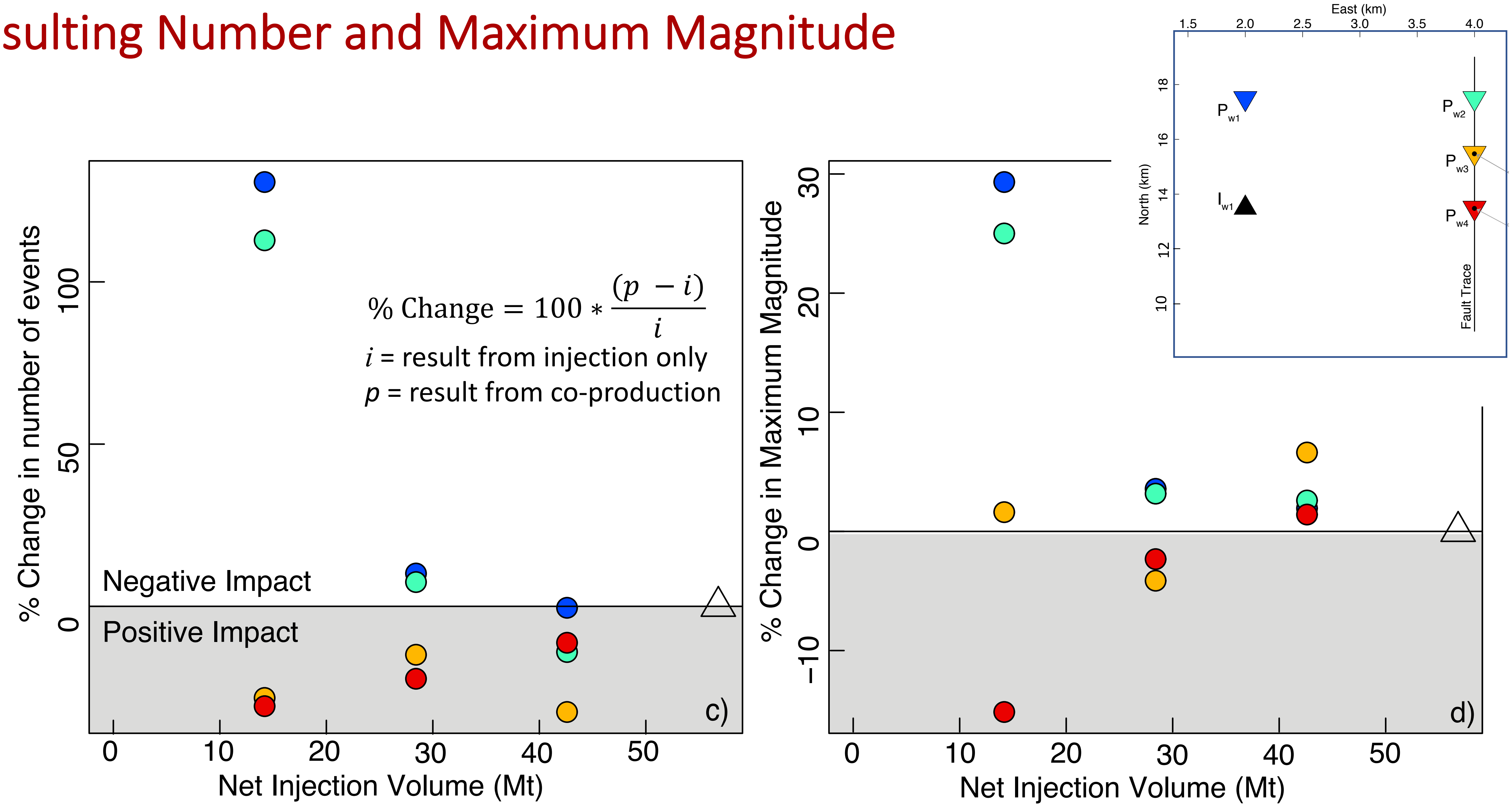




Pore-fluid Pressure On Fault



Resulting Number and Maximum Magnitude



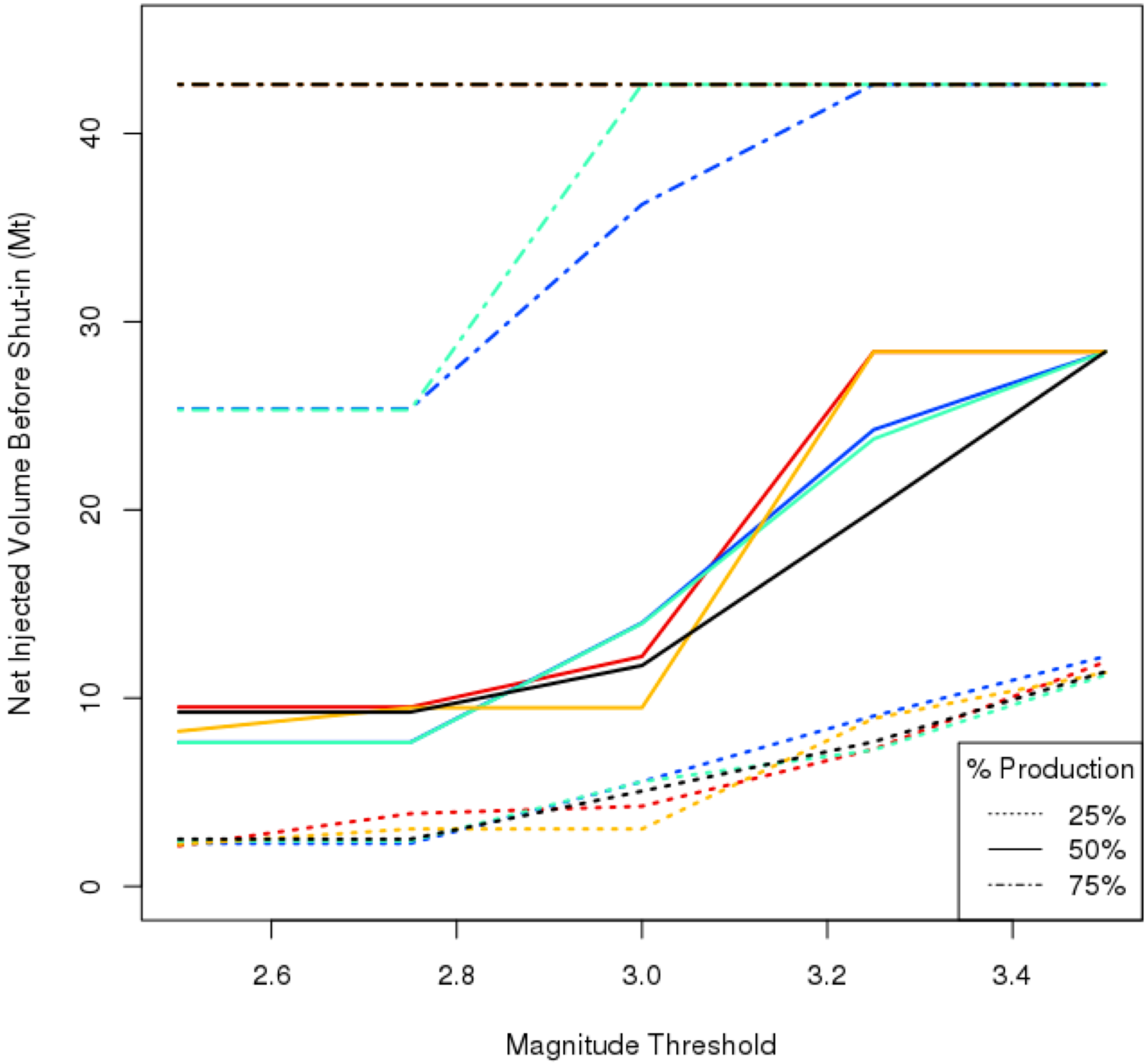
$$\% \text{ Change} = 100 * \frac{(p - i)}{i}$$

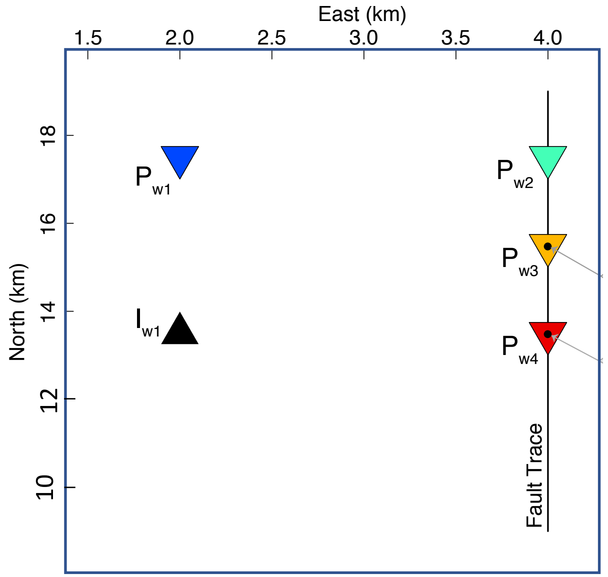
i = result from injection only

p = result from co-production

*Net injection volume = injected volume – production volume

Selection of Preferred Injection Scenario?





Conclusions

- Active pressure management ***might*** be a useful mitigation strategy
  - May actually cause more (but smaller?) earthquakes
  - Highly dependent upon knowledge of fault location, well/fault configuration, reservoir characteristics, the pre-stress conditions, fault interaction and permeability structure
- Most advantageous when co-produced fluids can be managed and potentially dangerous faults are known
- Perhaps more applicable to carbon storage settings?
  - Replace low-risk brine with high-risk CO2
  - Fewer coordination logistics