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Simulating Injection Induced Earthquakes: The Effects of Rate-and State-dependent Friction and Injection History

K. A. Kroll, K. B. Richards-Dinger, J. H. Dieterich, J. A. White

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Simulating Injection Induced Earthquakes:

The Effects of Rate-and State-dependent Friction and Injection History

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What Are Earthquake Simulators?

- Computer codes which
  - Solve simplified forms of the physical equations
  - Typically boundary elements
  - Quasi-static with some approximation to inertia
  - Group the resulting time histories of slip across the elements into earthquake events
  - Multiple earthquake cycles

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

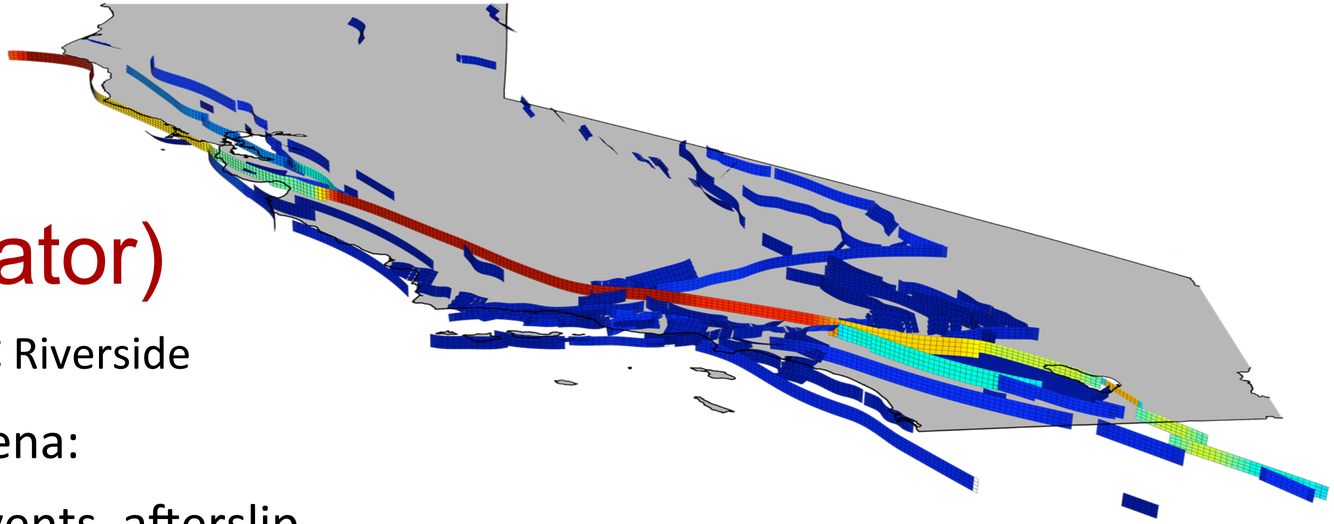
V: Earthquake slip rate

θ: State variable

D_c: Characteristic slip distance

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

Dieterich, 1978, 1979; Ruina 1983

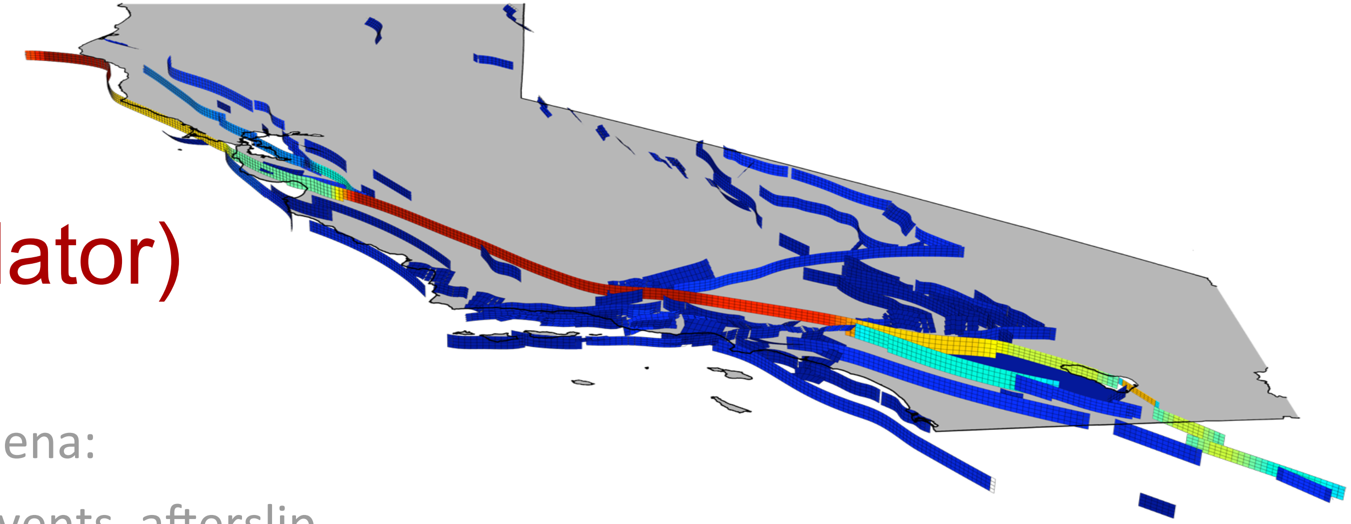


RSQSim
(Rate-State earthQuake Simulator)

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



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- Implement rate- and state-dependent friction effects
  - → Earthquake clustering effects (aftershocks and foreshocks)

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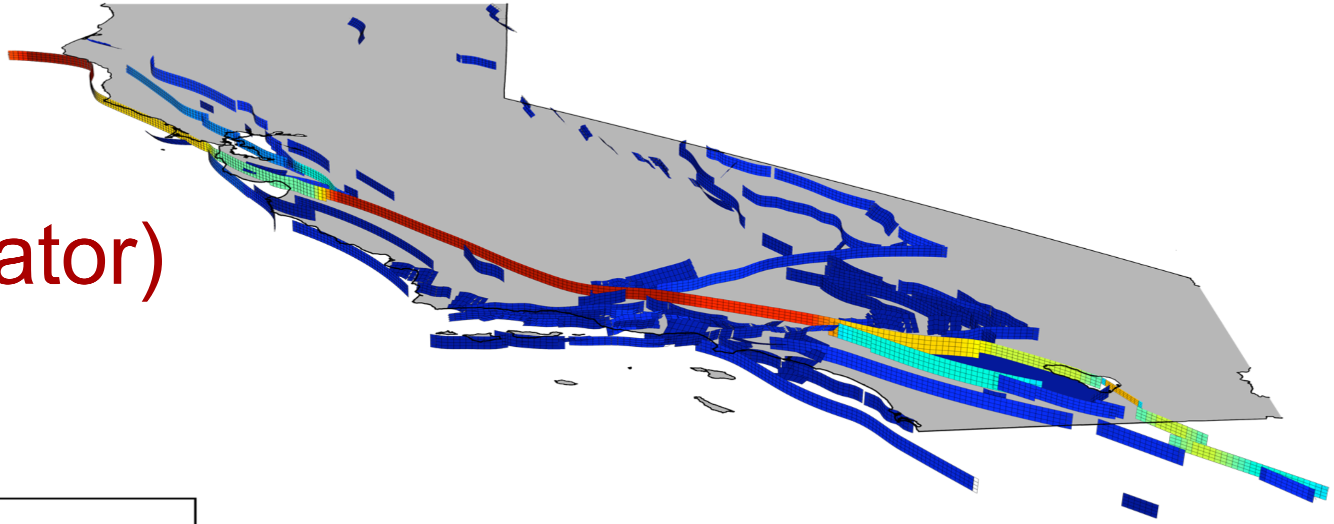

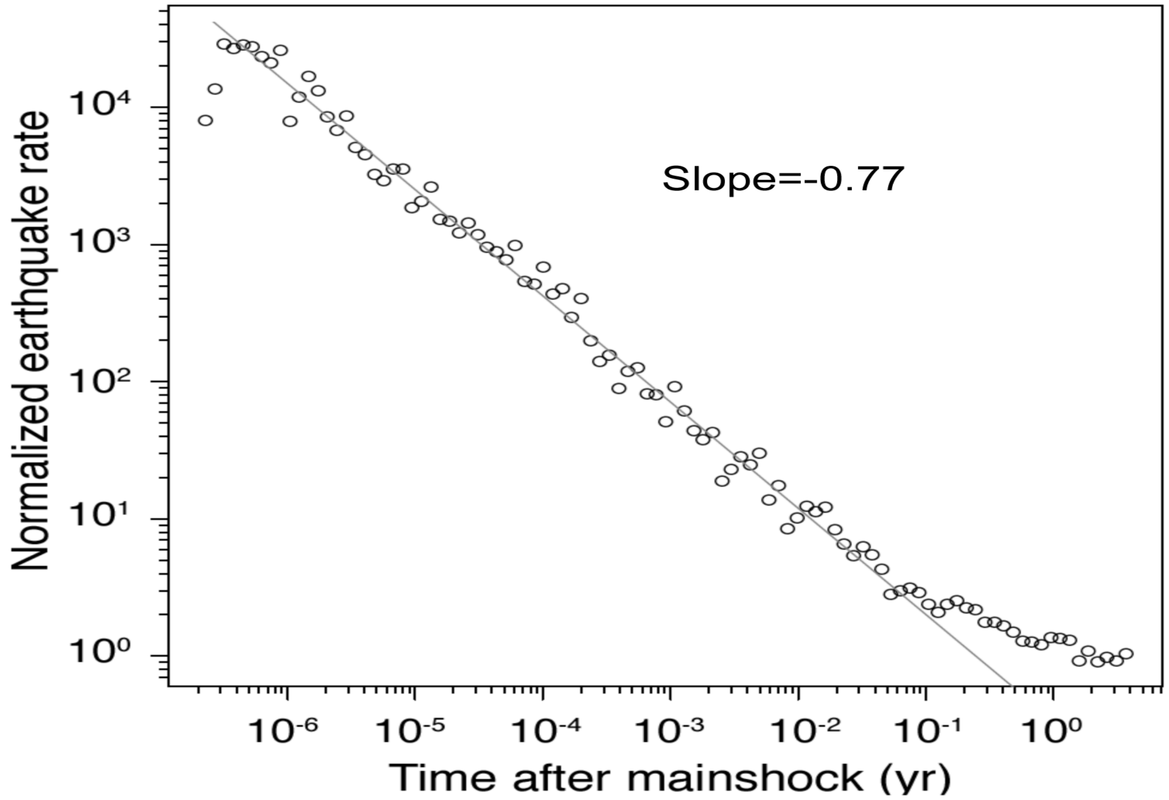

All-California simulation
Aftershocks follow the Omori Law for aftershock decay with time

RSQSim
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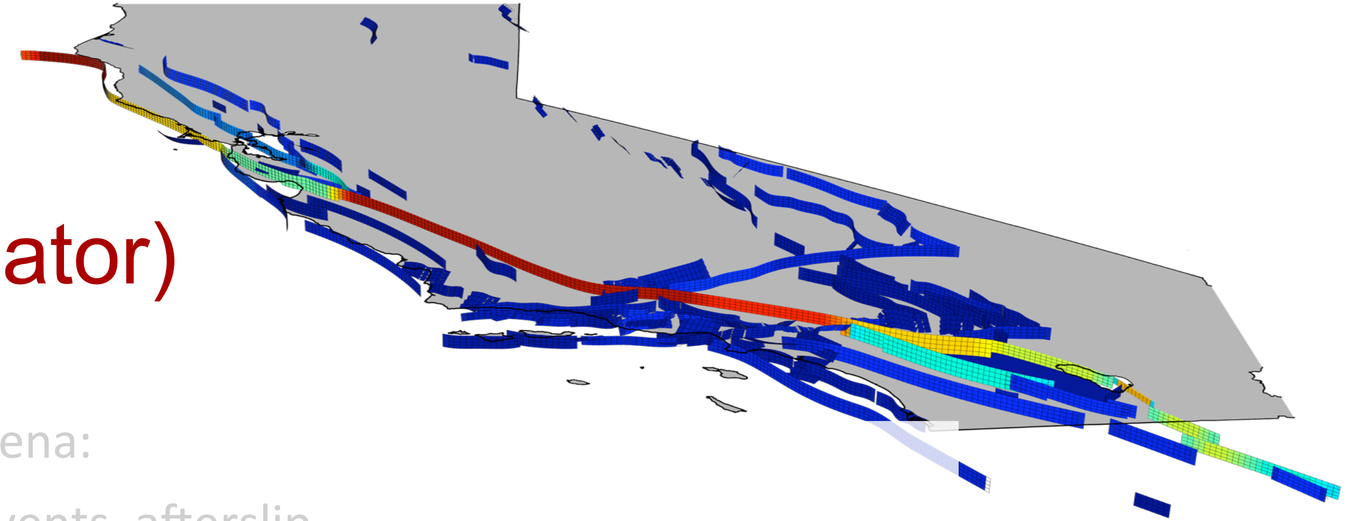

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- High resolution models of geometrically complex fault systems
  - → Up to 10^6 fault elements
  - → Range of earthquake magnitudes M=3.5 to M=8 (for 1 km^2 triangular elements)

RSQSim
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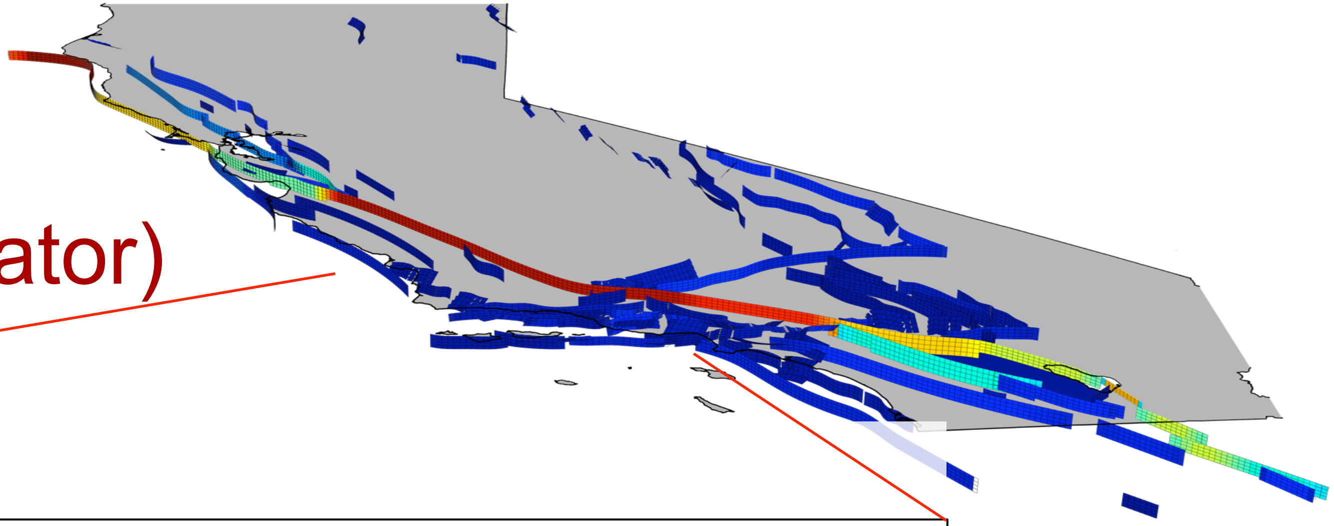

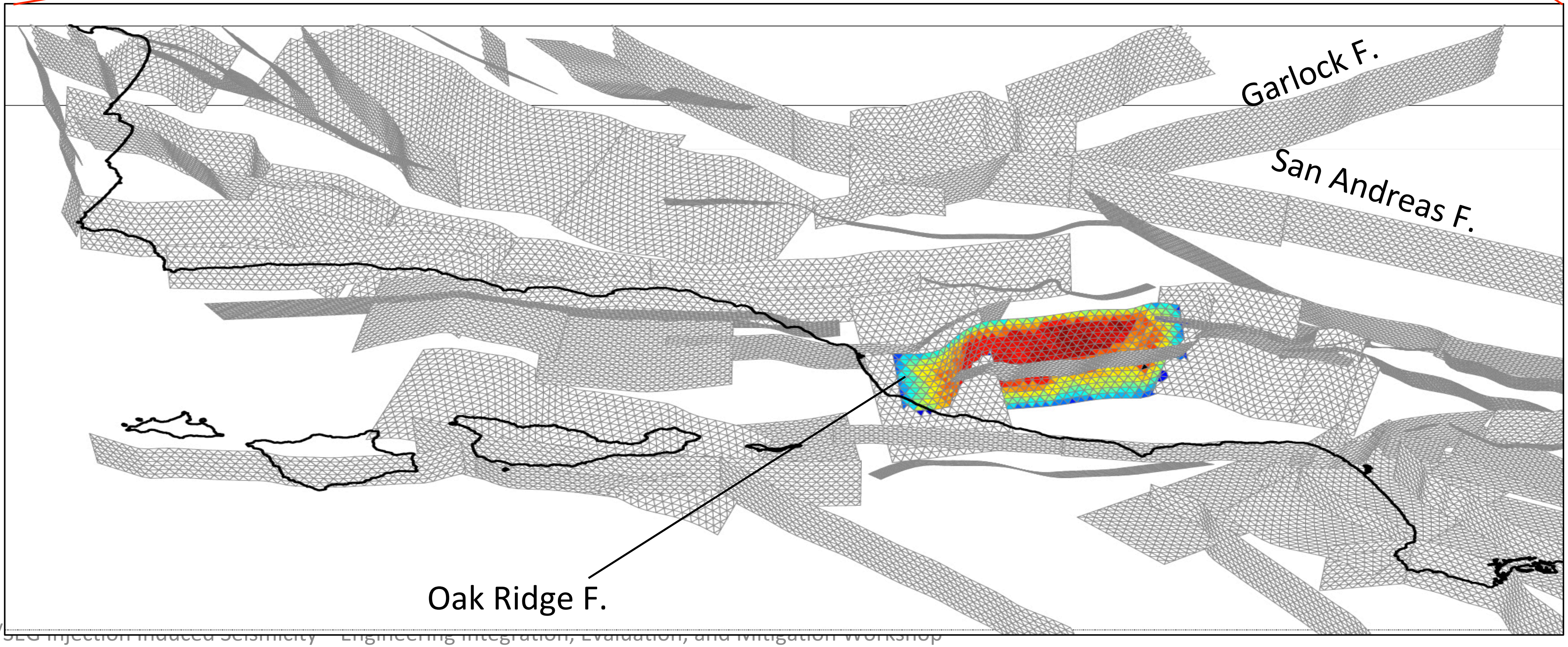

RSQSim
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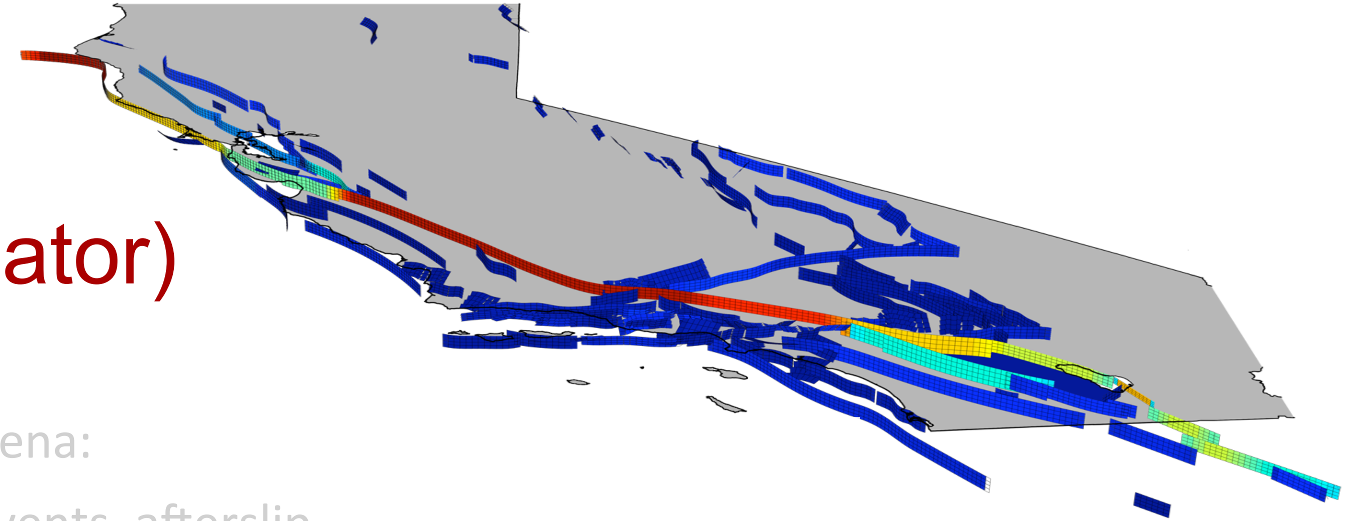

- Comprehensive simulation of fault slip phenomena:
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- High resolution models of geometrically complex fault systems
  - → Up to 10^6 fault elements
  - → Range of earthquake magnitudes M=3.5 to M=8 (for 1 km^2 triangular elements)
- Highly efficient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

What do we need to begin a simulation?

- External stressing history (from a reservoir model)
- Fault geometry
- Constitutive parameters
- Tectonic driving stress (perhaps neglect these in relatively aseismic regions)
- Initial 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)
    - Final stress from a large event is a previous simulation (from RSQSim)
    - Evolved stress from a tectonically driven simulation (from RSQSim)

Modeling Injection-Induced Seismicity with the Physics-Based Earthquake Simulator RSQSim

by James H. Dieterich, Keith B. Richards-Dinger, and Kayla A. Kroll

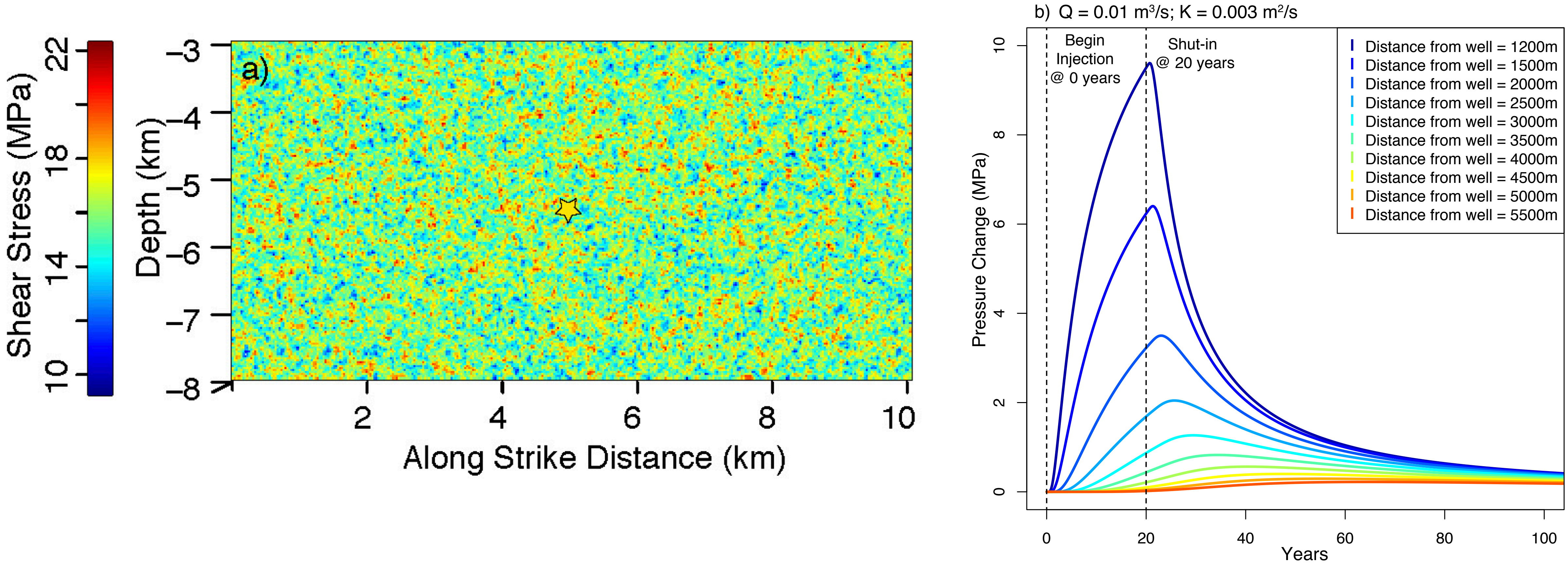
Seismological Research Letters Volume 86, Number 4 July/August 2015 1

Space-time characteristics are highly dependent on the pattern and magnitude the of initial stresses

How do we include effects of fluid injection in RSQSim?

- RSQSim itself knows nothing of pore-fluid pressure diffusion, poroelastic effects, etc.
- Must supply external stressing history
- Geomechanical reservoir model
  - Changes in effective normal stress
  - Poroelastic effects
- Not fully coupled – no feedback
  - seismic slip does not affect the permeability structure, etc.
- Preliminary experiments use a simple analytic expression for pore-fluid diffusion (Wang, 2000).

Fault and "Reservoir" Model



- Linear diffusion model based on analytical solutions for a point-source in an semi-infinite, isotropic half-space (Wang, 2000).
- Variable injection parameters:
  - Well location(s)
  - Injection Rate
  - Diffusivity $\left(\kappa = \frac{k}{\eta \phi c}\right)$; permeability, porosity, compressibility, viscosity

Dependency on Rate-State Parameters

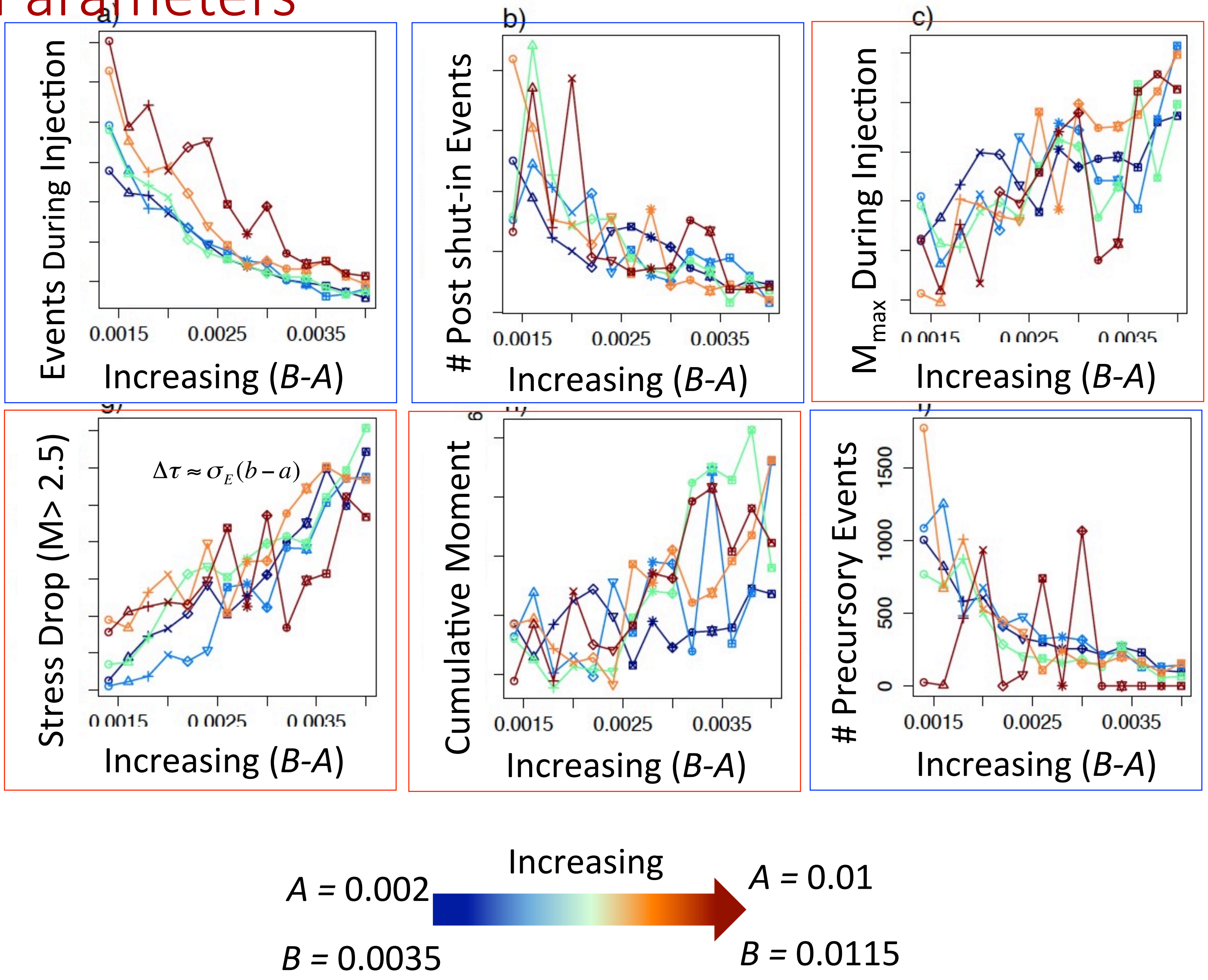
$$\tau = (\sigma - p)\left[\mu_0 \boxed{(b - a)} \ln\left(\frac{\theta V^*}{D_c}\right)\right]$$

Earthquake Stress Drops:

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

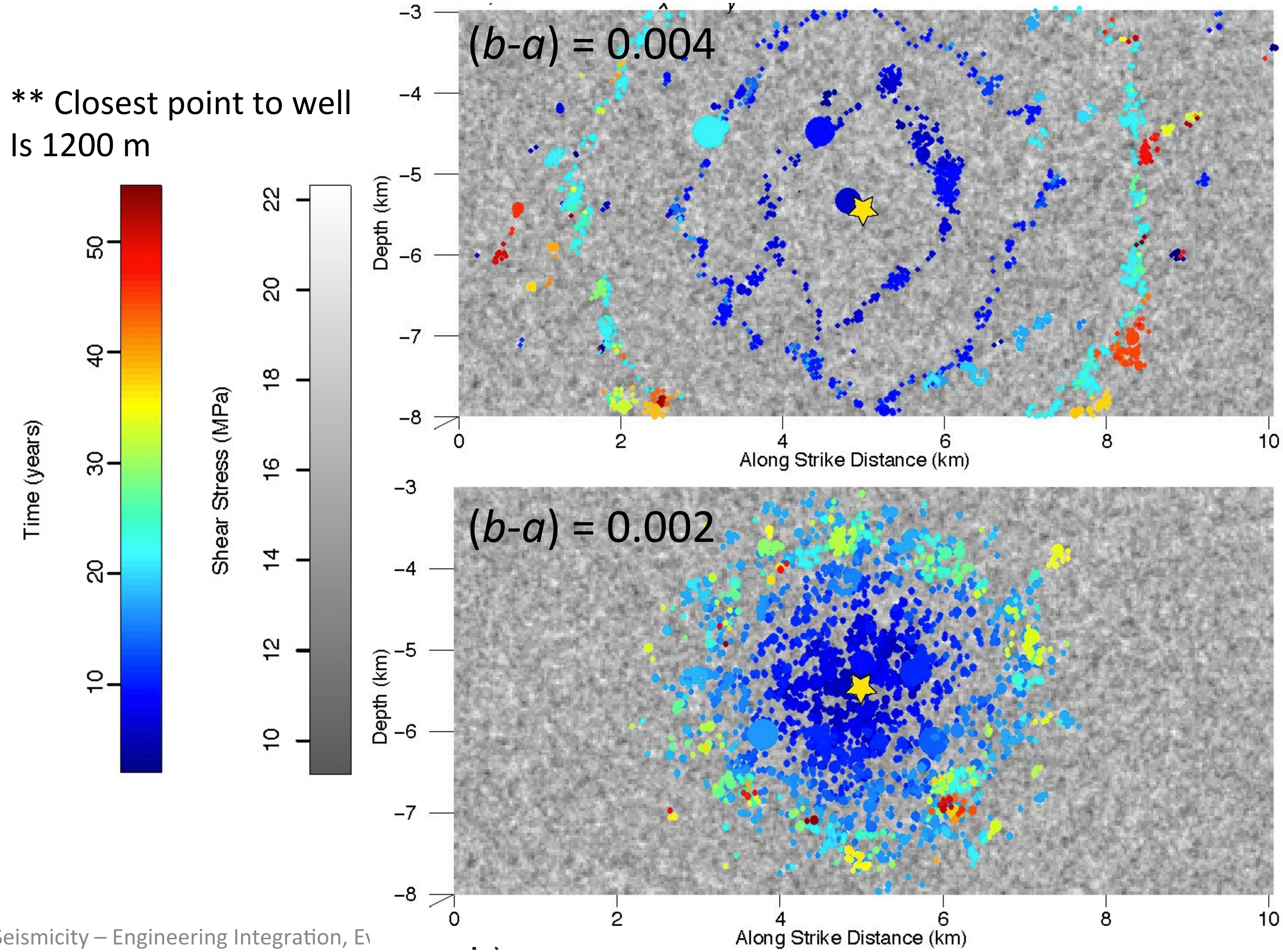
$$\Delta\tau \approx \sigma_E (b-a)$$

$$\Delta\tau = \sigma(\mu_d - \mu_s)$$



Spatial Variation due to (*b-a*)

** Closest point to well
Is 1200 m



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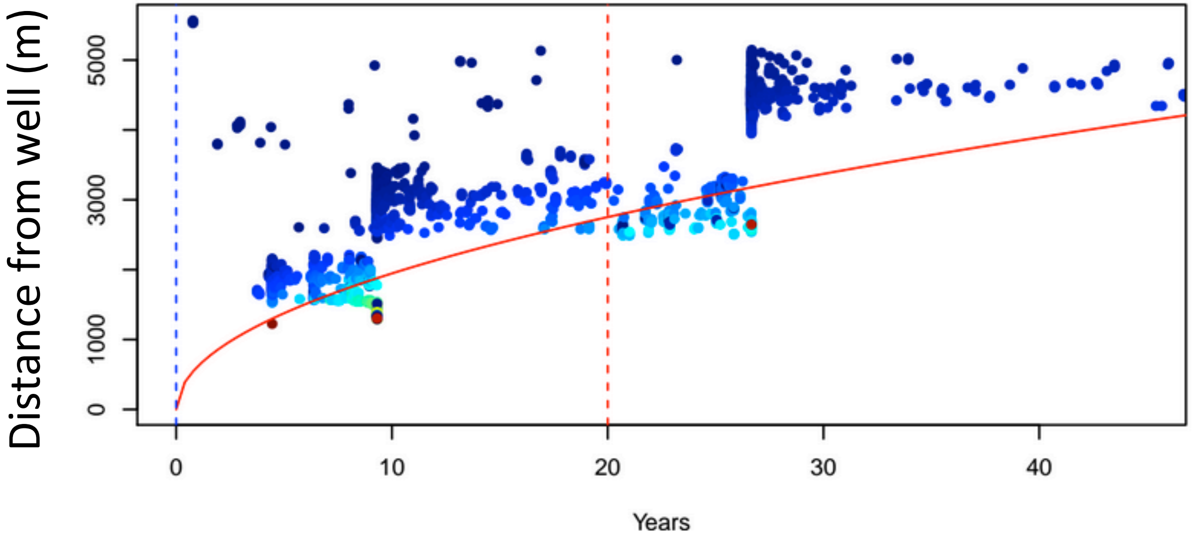
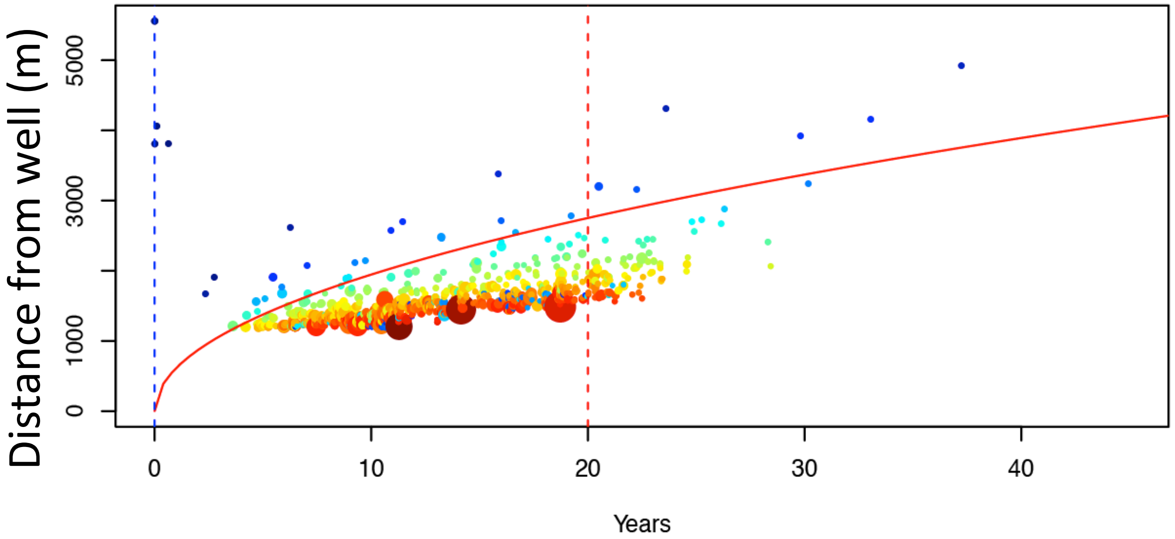
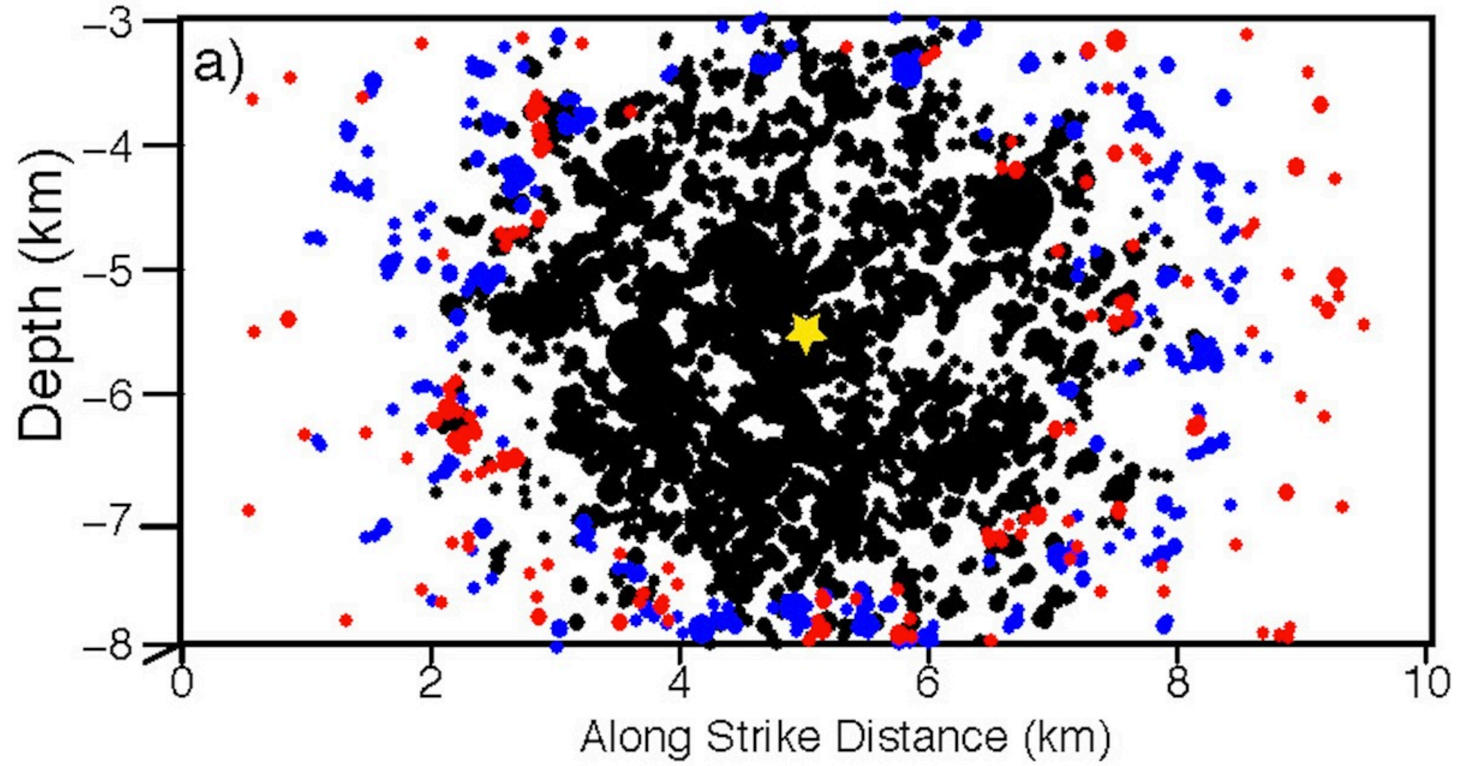
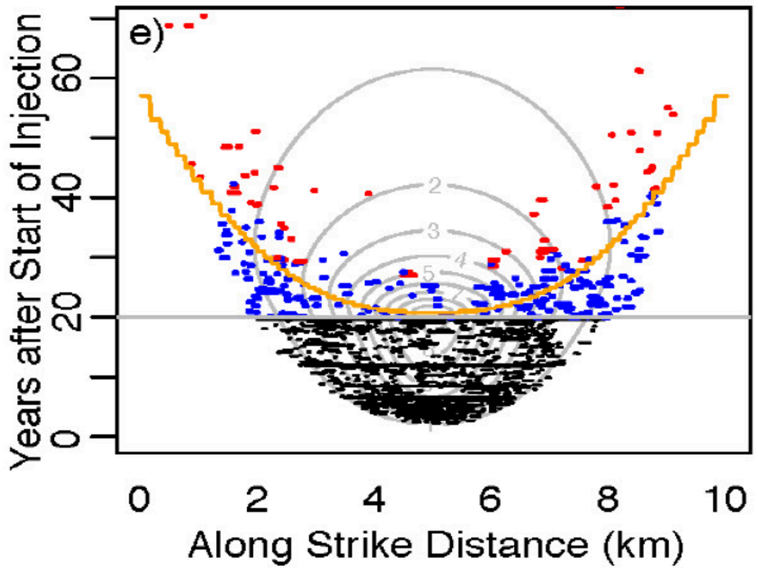
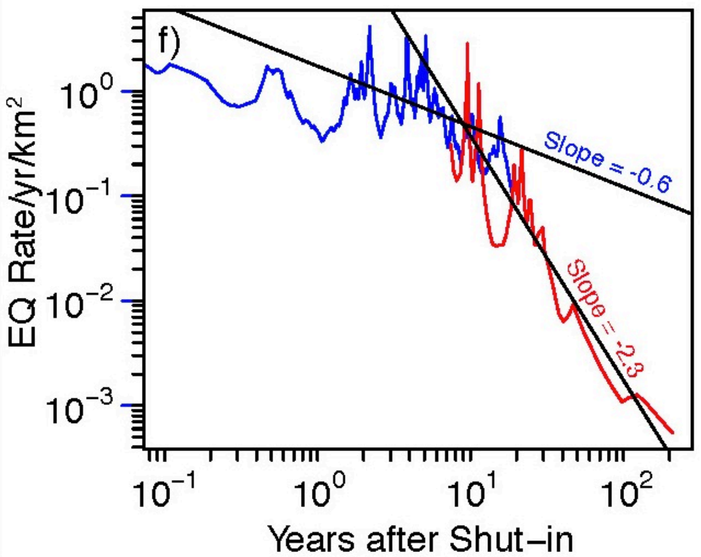




Post Shut-in Seismicity Rates

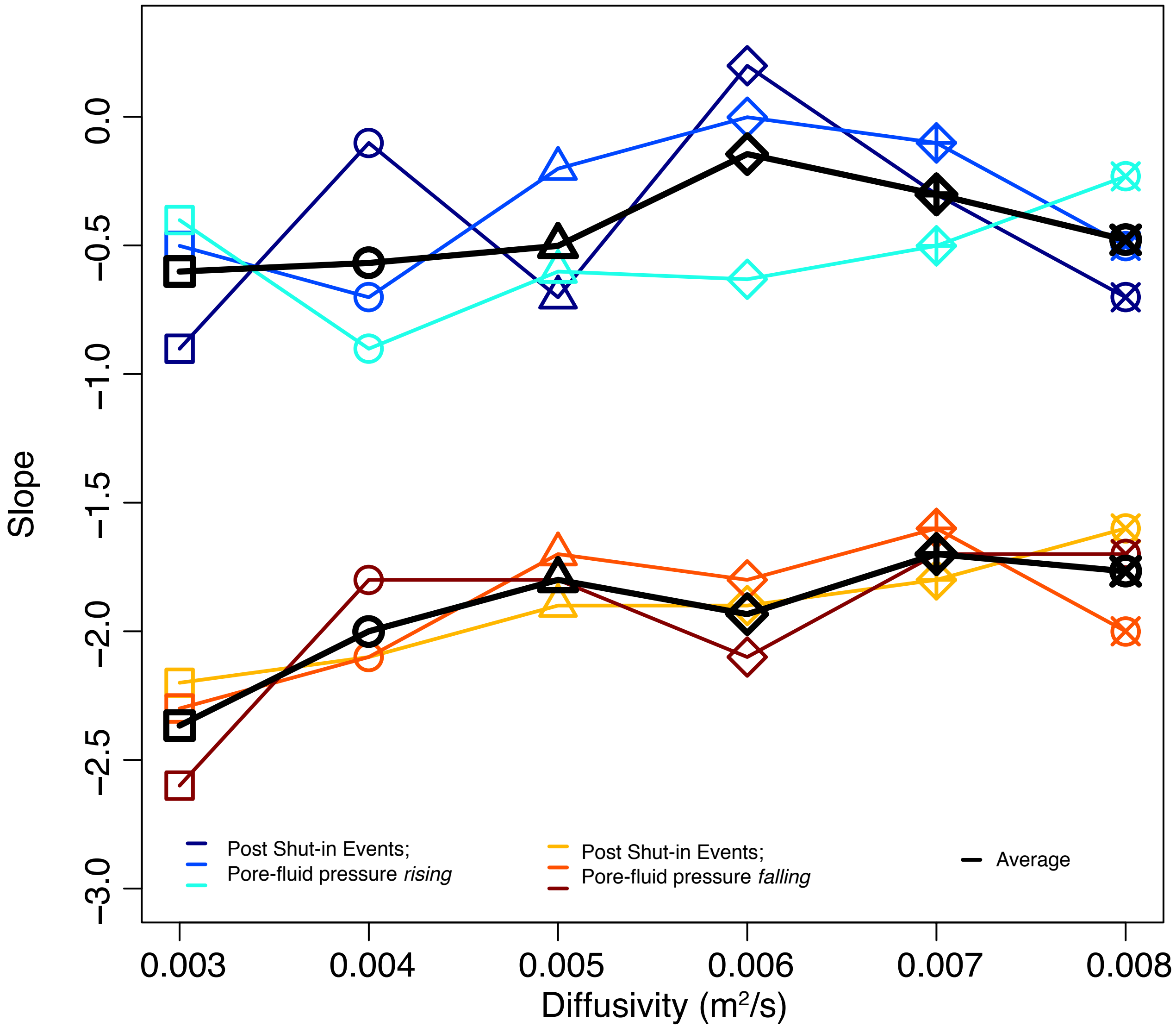






- Events that occur during the injection period
- Events that occur after shut-in, as the pore-fluid pressure is rising
- Events that occur after shut-in, as the pore-fluid pressure is dropping
- Time at which the pore-fluid pressure starts to decrease (projection from the row of elements at -5500 m depth, even wiht the well)

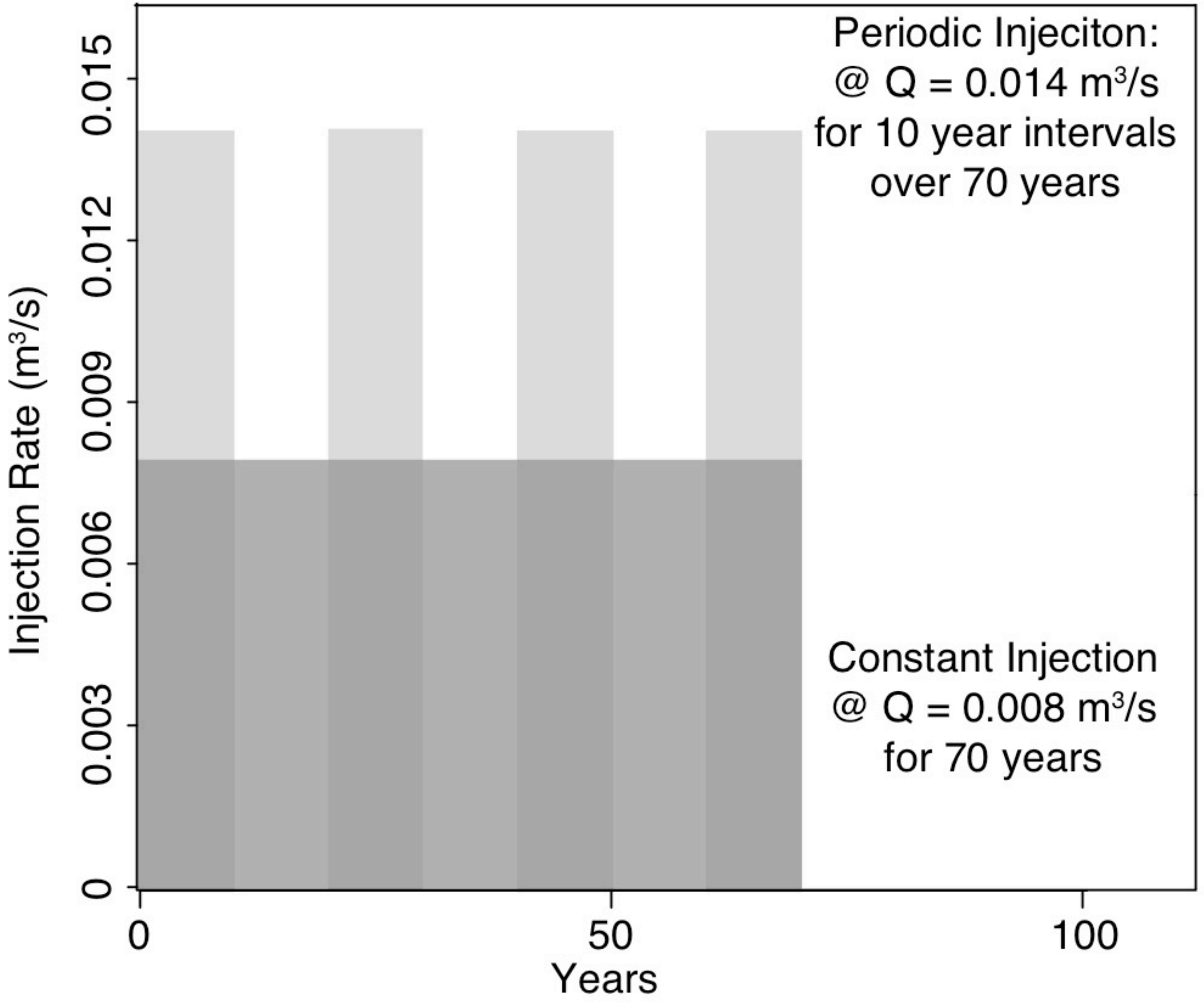
Decay Rate with Diffusivity



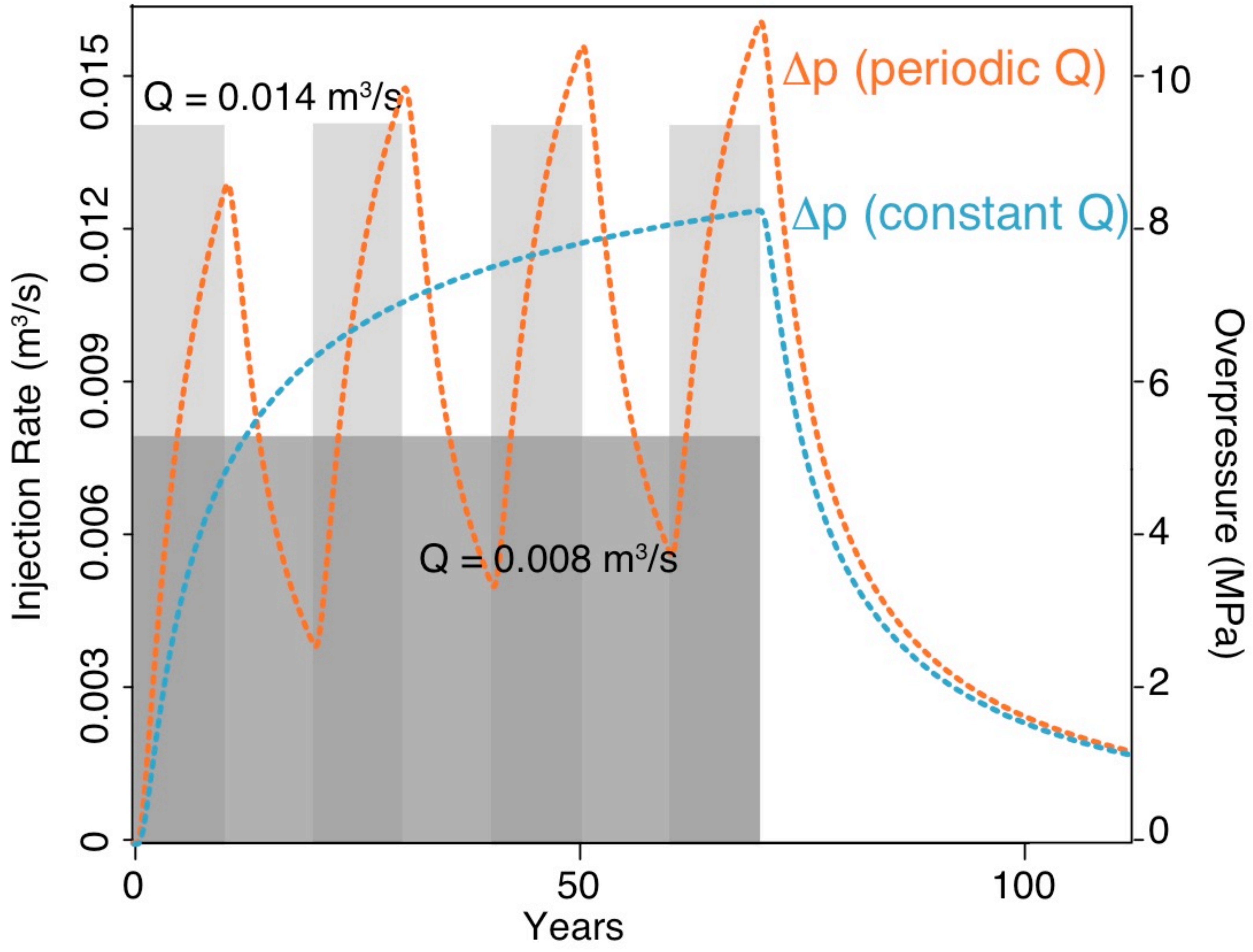
Comparing Injection Histories

Is seismicity controlled by changes in peak overpressure or constant injection rate?

- Constant injection duration (70 years)
- Constant injected volume ($1.8 \cdot 10^7$ m^3)
- Variable injection rate
  - Constant (0.008 m^3/s)
  - Periodic (0.014 m^3/s)



Pressure Change in Response to Constant and Periodic Injection Rate

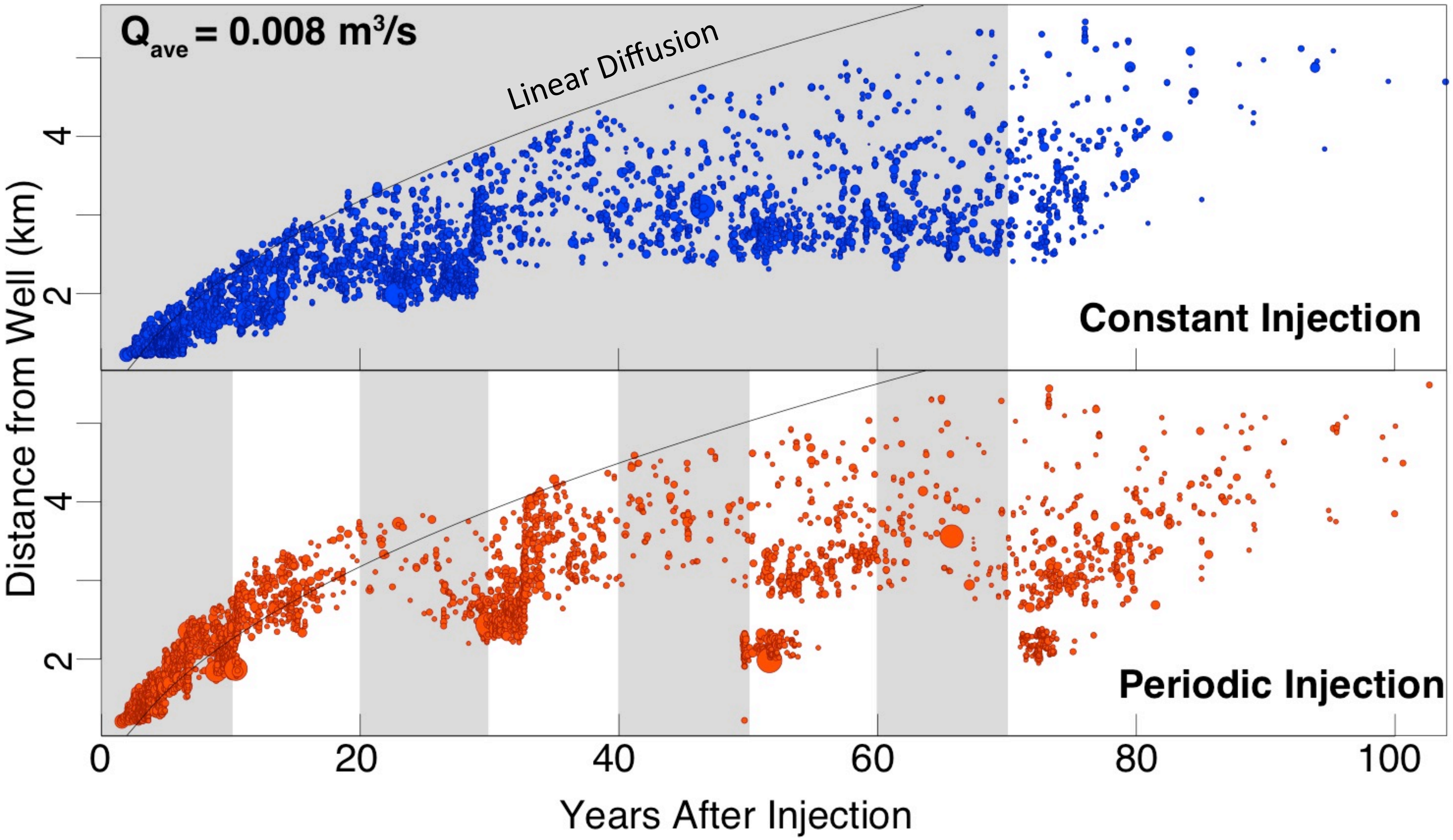


Overpressure on Element closest to well

Results: Spatial Distribution with Time

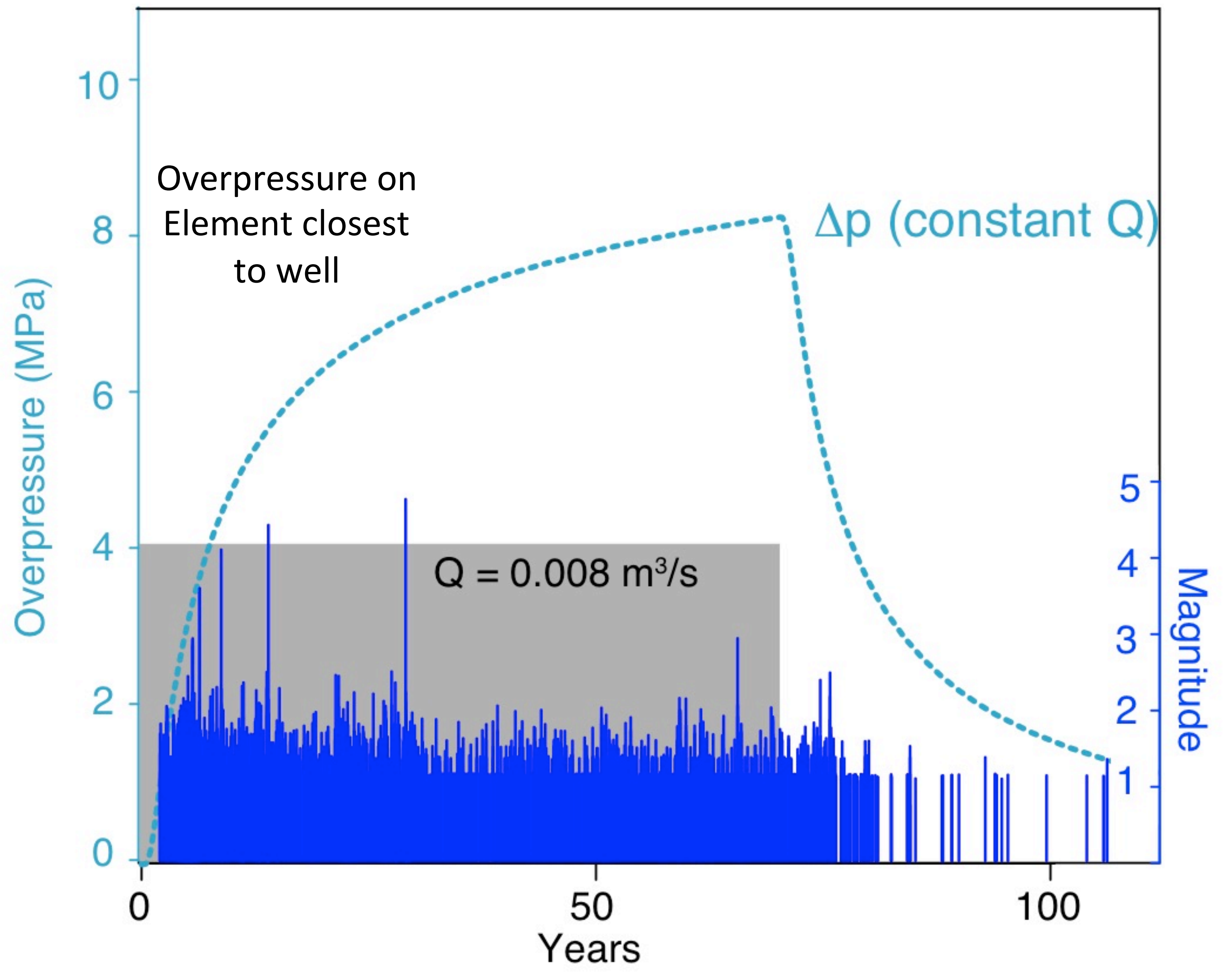
Closest fault element to well = 1.2 km

Scale by earthquake magnitude



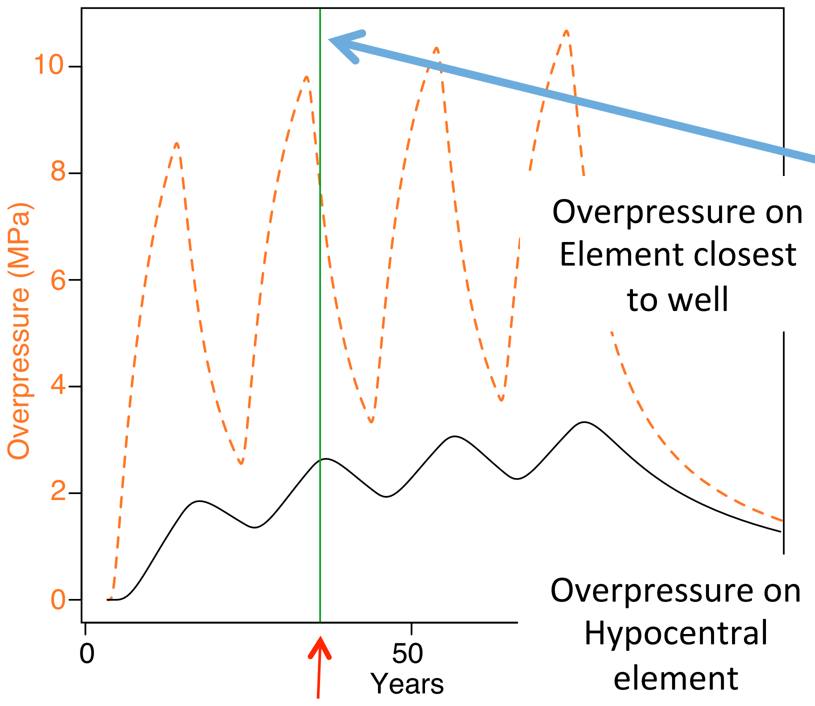
Results: Earthquake Magnitude with Time (Constant Injection Rate)

- Max magnitudes increase with time
- No large, post shut-in events
- 4 M> 3.5 events within ~ 20 years
- Relatively constant rate

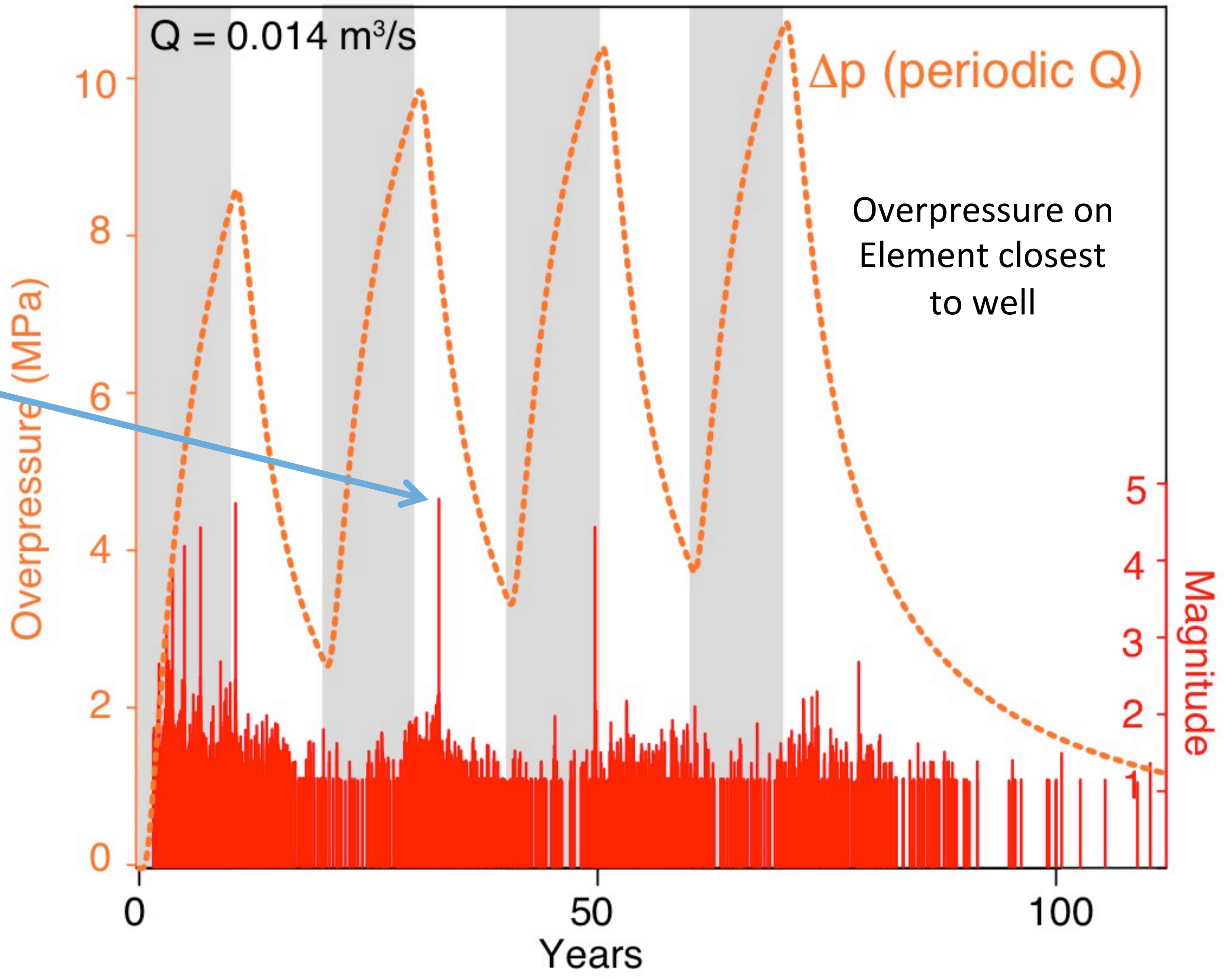


Results: Earthquake Magnitude with Time (Periodic Injection Rate)

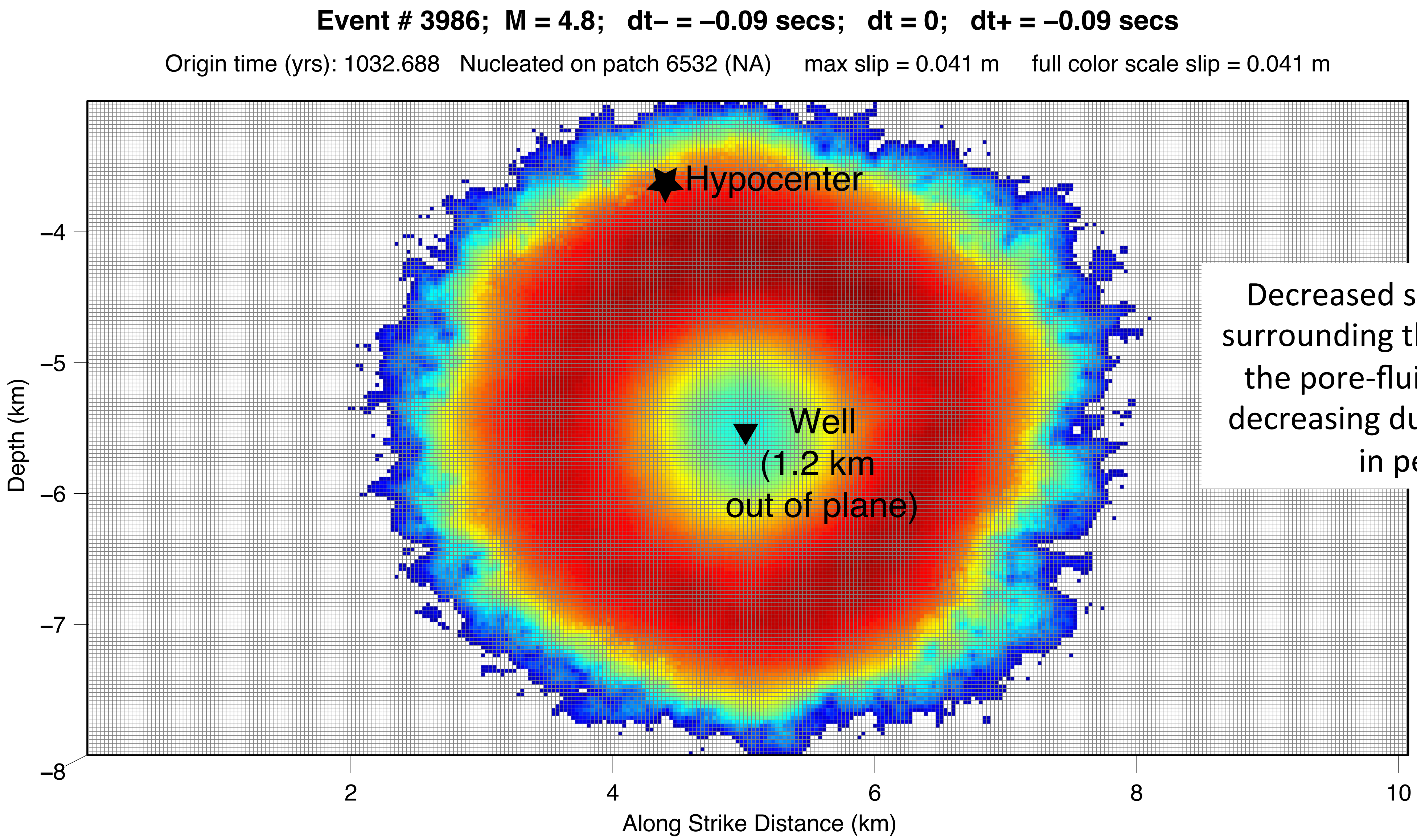
- Max magnitudes increase with time
- Most large events occur after shut-in
- Large events occur over ~50 years
- Earthquake rate fluctuates



Overpressure on hypocenteral element is rising at the time of the M4.5



Results: Earthquake Magnitude with Time (Periodic Injection Rate)



Decreased slip in regions surrounding the well, where the pore-fluid pressure is decreasing during the shut-in period

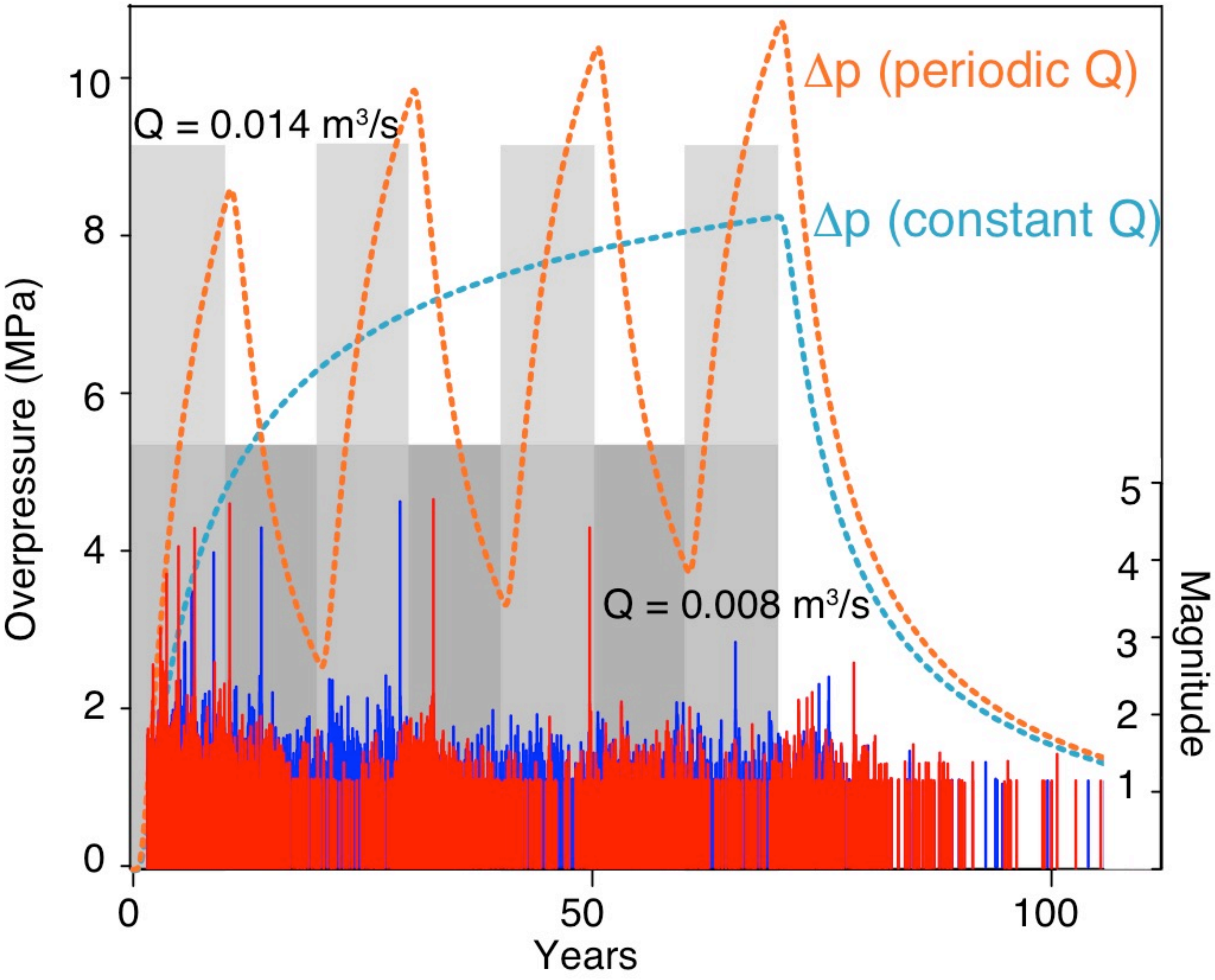
Results: Compare Earthquake Magnitudes with Time

Constant Q:

- Fewer large events (4 M>3.5)
- Earliest large events are smaller and have longer inter-event times

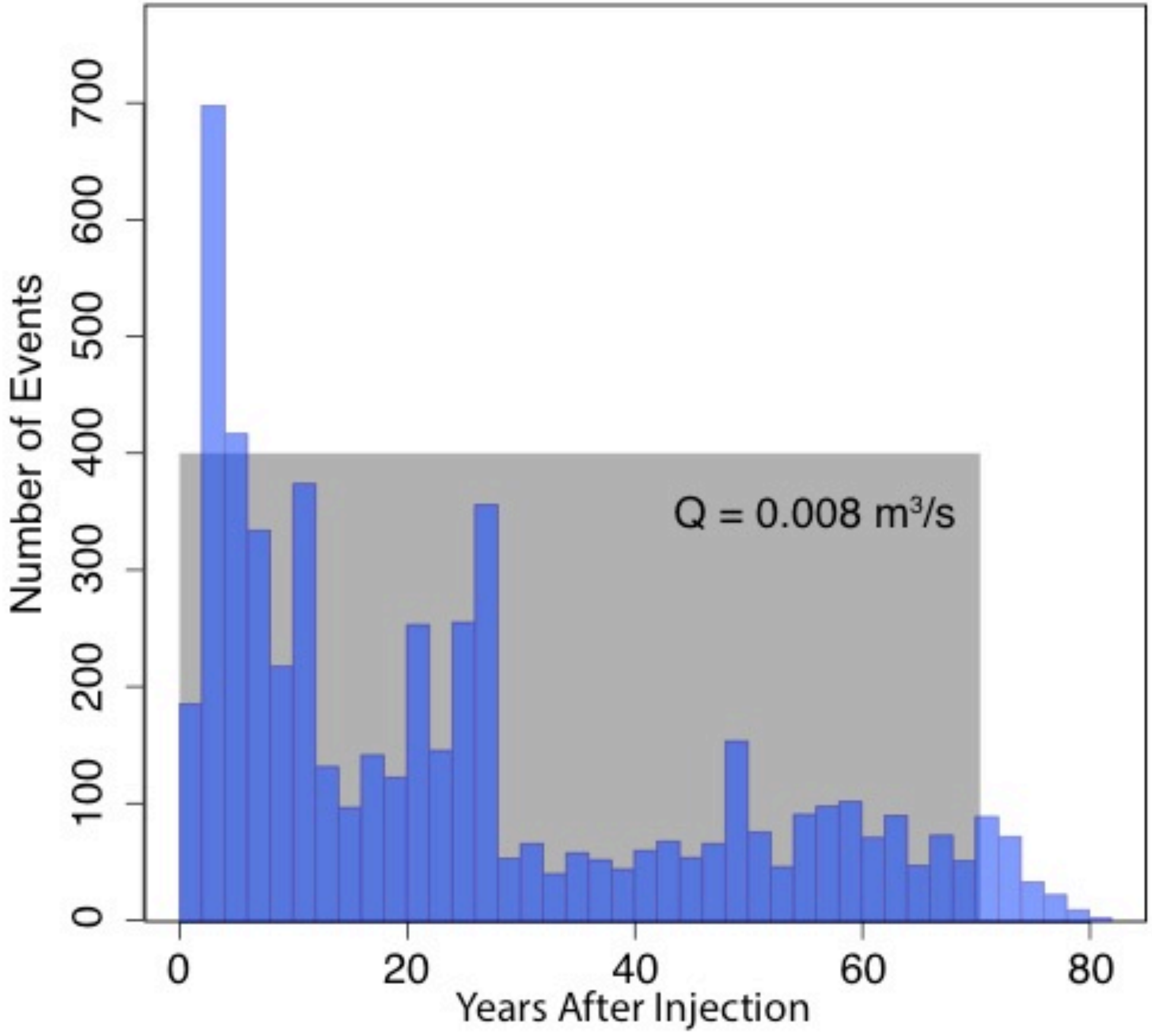
Periodic Q:

- More large events (7 M>3.5), especially early in the sequence
- Earliest large events are bigger and have shorter inter-event times
- Longer inter-event time after first injection period



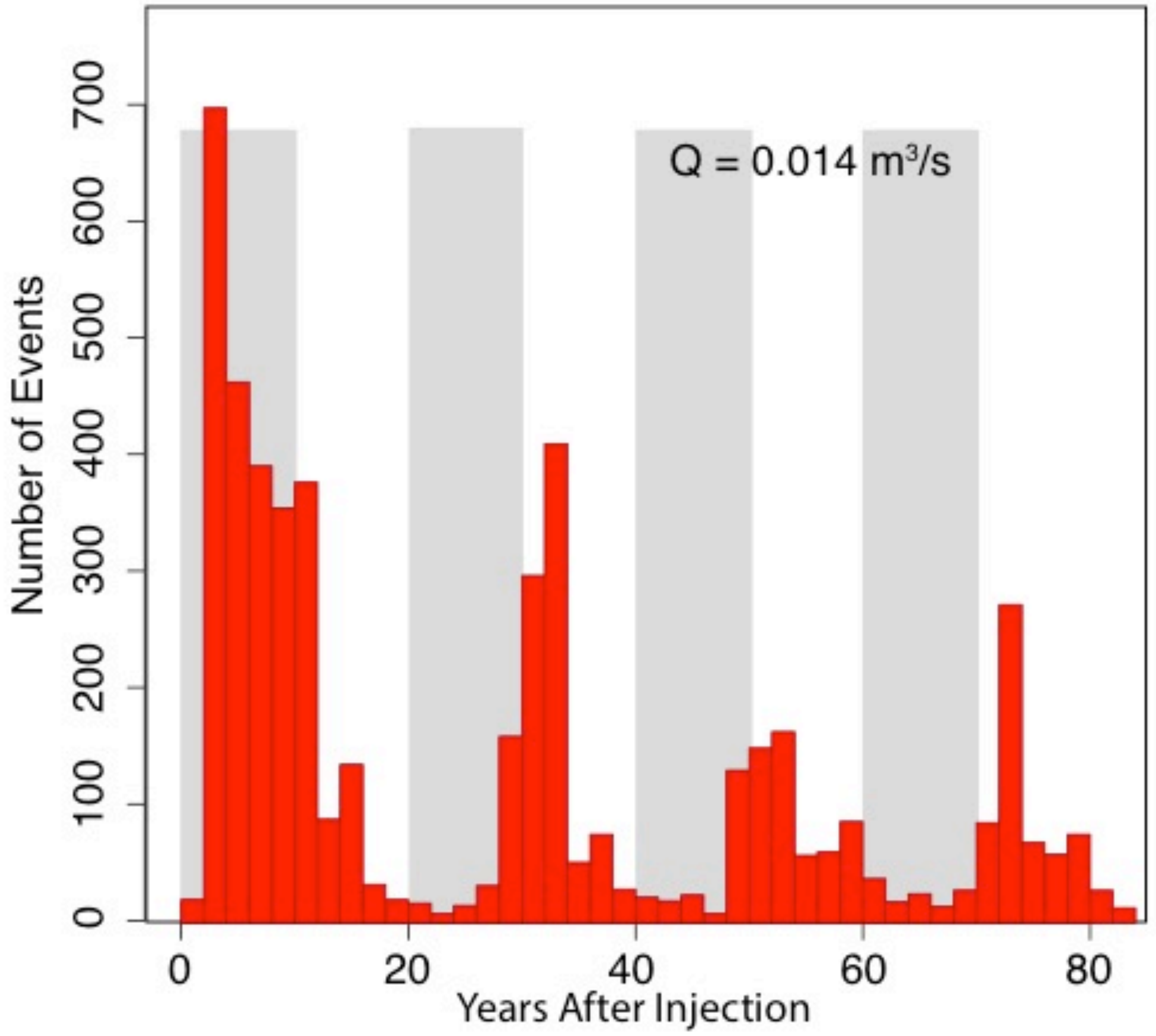
Results: Number of Events with Time (Constant Q)

- Most events occur shortly following injection
- Event rate decays with time



Results: Number of Events with Time (Periodic Q)

- Early events occur mostly during first injection period
- Later events primarily occur during the time shut-in cycle
    - Aftershocks following post shut-in large events
- Event rate fluctuates with time, but decreases overall



Results: Compare Number of Events with Time

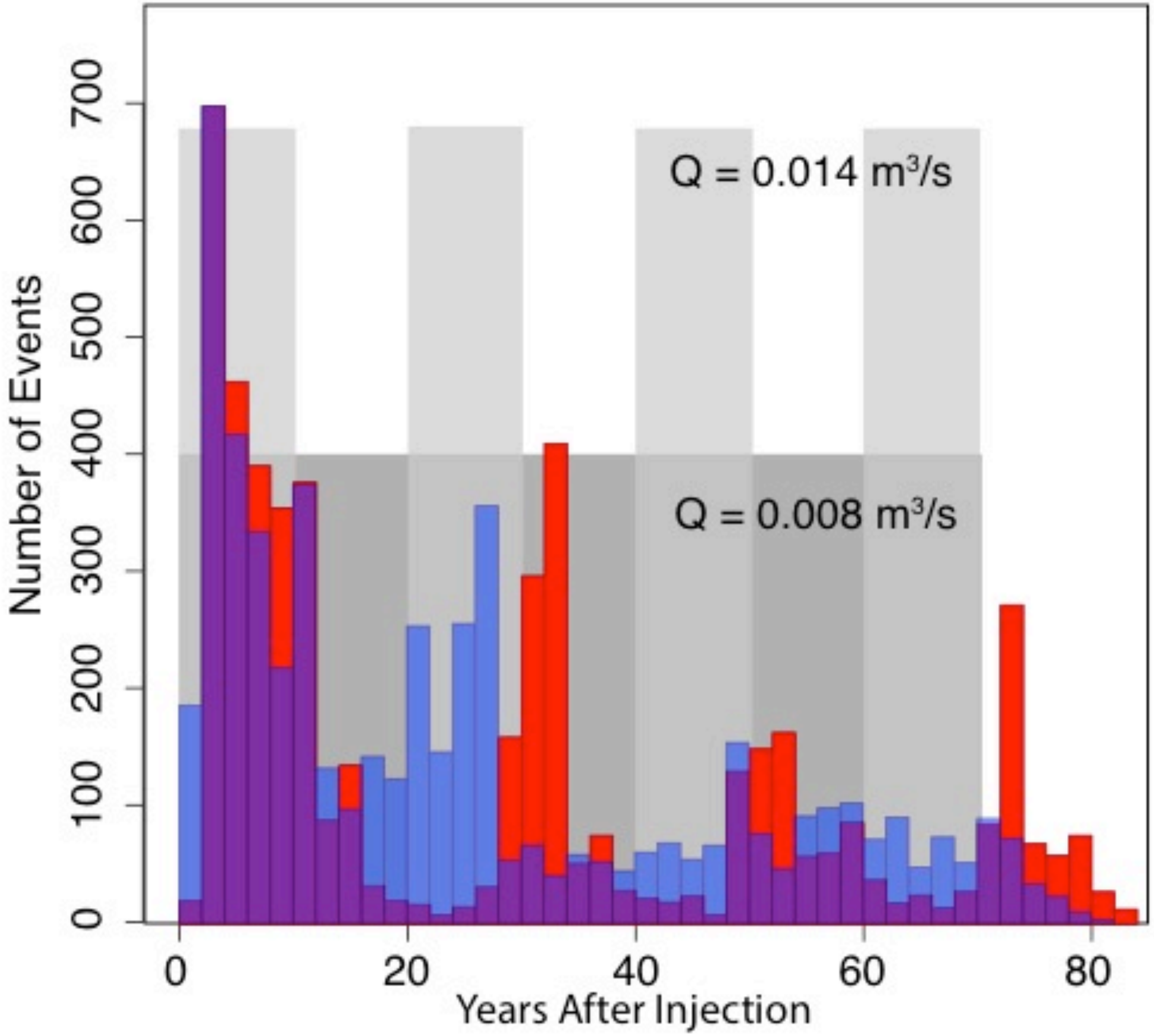
- Relatively similar history during the first 15 years

Constant Q:

- Event rates decay with time
- Highest rates within the first 25 years

Periodic Q:

- Highly variable earthquake rate
- Several periods of increased rate



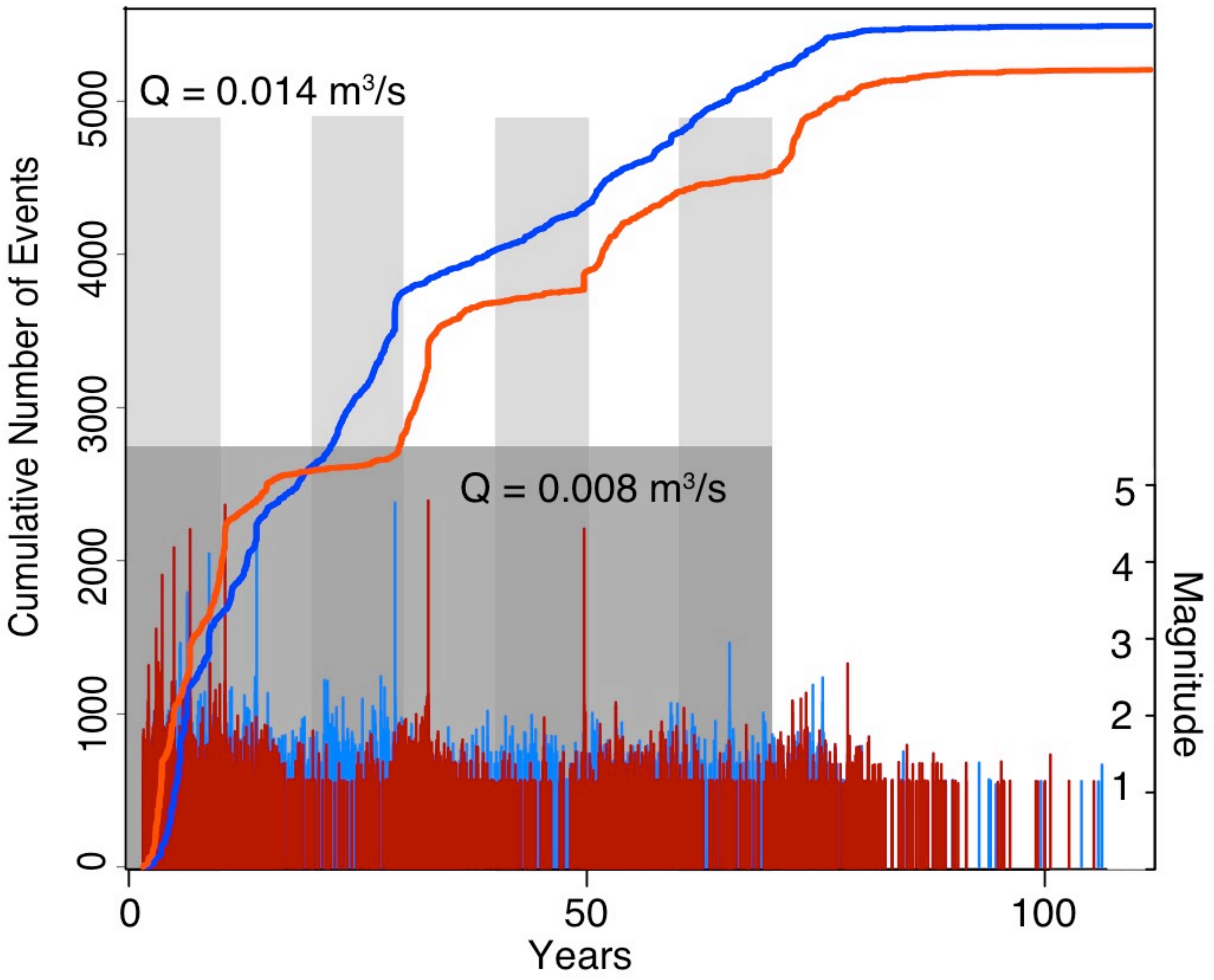
Results: Compare Cumulative Number of Events with Time

Constant Q:

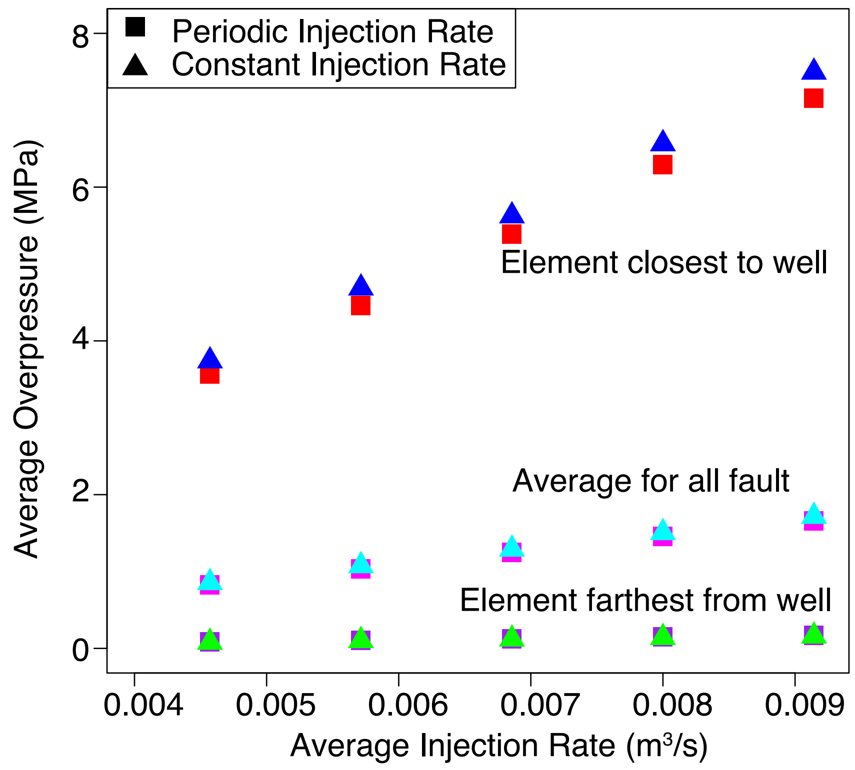
- Three distinct periods of events:
  - 1000 – 1025: highest rate
  - 1025 – 1075: moderate rate
  - 1075+: quiescence
- More events total

Periodic Q:

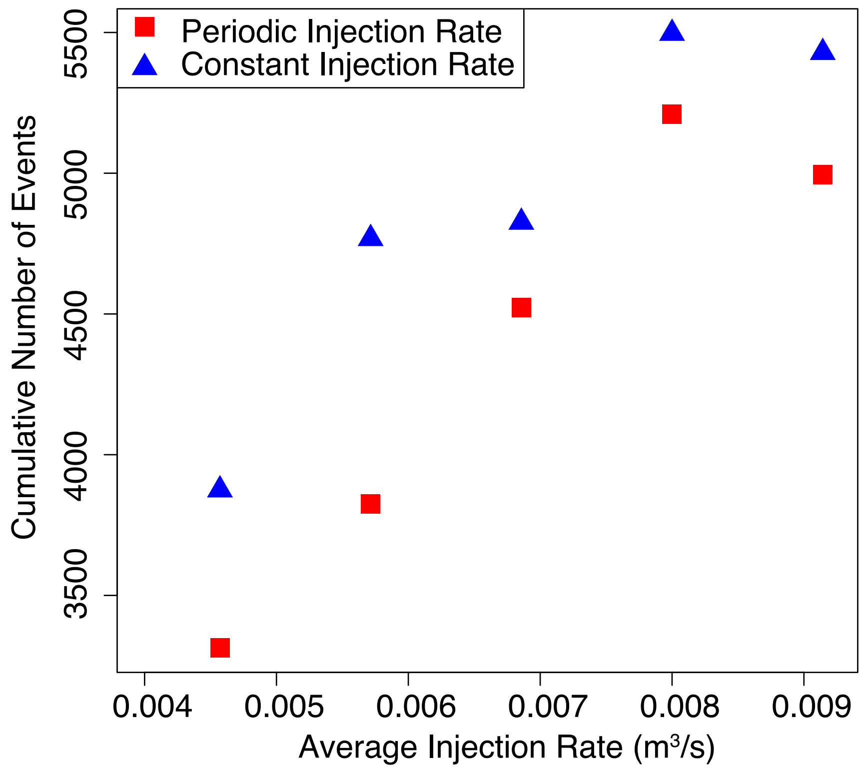
- Highly variable earthquake rate
- Apparent increased rate leading up to large events
- Fewer events total



Summary: Constant vs. Periodic Injection Rates

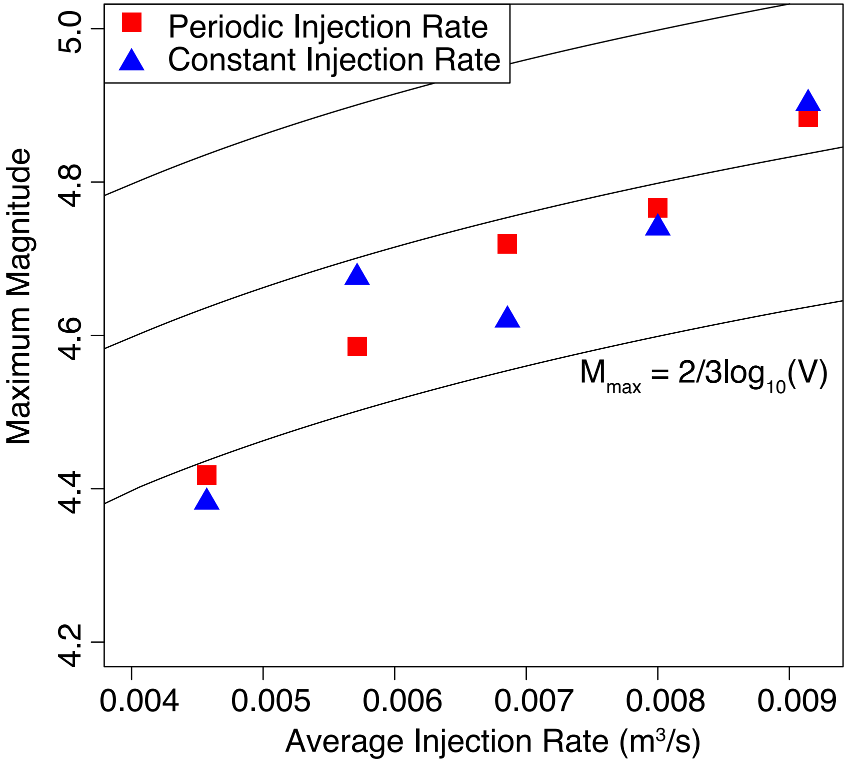


- Overpressure is greater for period injection
- Average overpressure increases with increasing injection rate

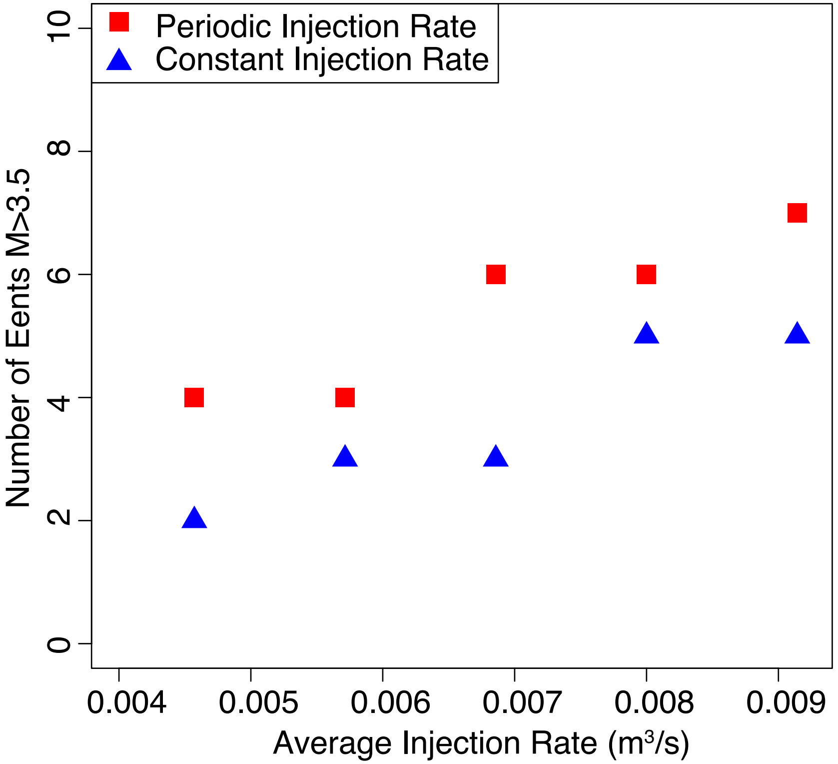


- Constant injection rates lead to large total number of events

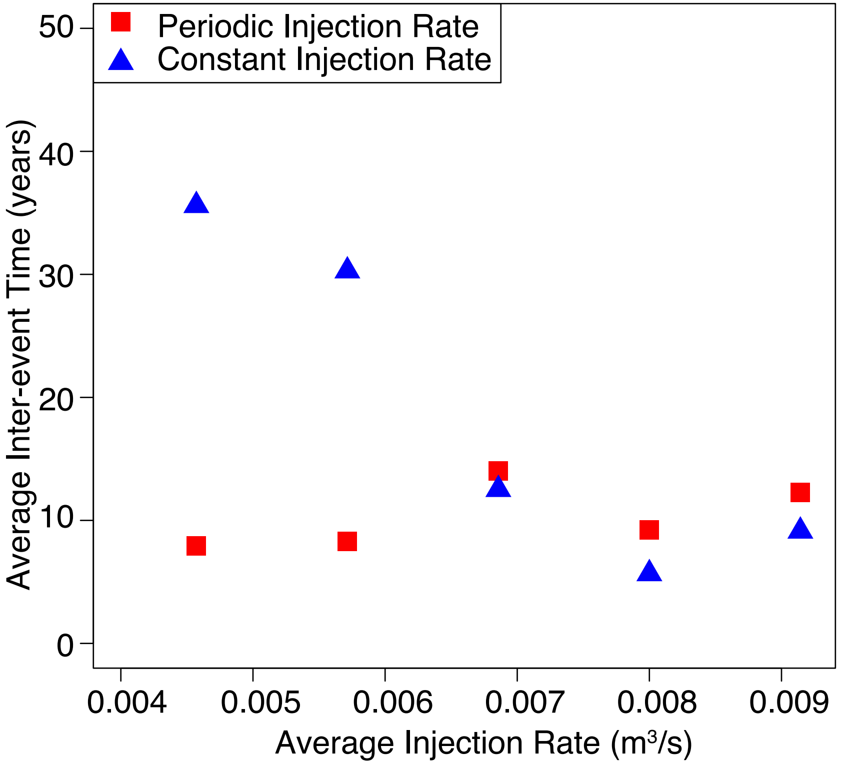
Summary: Constant vs. Periodic Injection Rates



- M_{max} increases with increased injection rate
- M_{max} is not systematically larger by injection rate.
- Slope is larger than M_{max} scaling by injected volume.



- More events M>3.5 with periodic injection history



- Inter-event times are inversely related in constant average injection rates
- Relatively unaffected by periodic injection rates

Conclusions

- Rate-state constitutive parameters highly influence induced sequences

Injection Methods (with roughly equivalent average overpressures over time):

1. Low constant injection rates
   - More events overall
   - Fewer large events
   - Larger events have longer inter-event times
2. Periodically injecting at high rates
   - Fewer events
   - More large events
   - Shorter inter-event times

Acknowledgements

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- NSF
- SCEC

Questions?

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