Induced fault slip: fast or slow?

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In collaboration with Paul Segall
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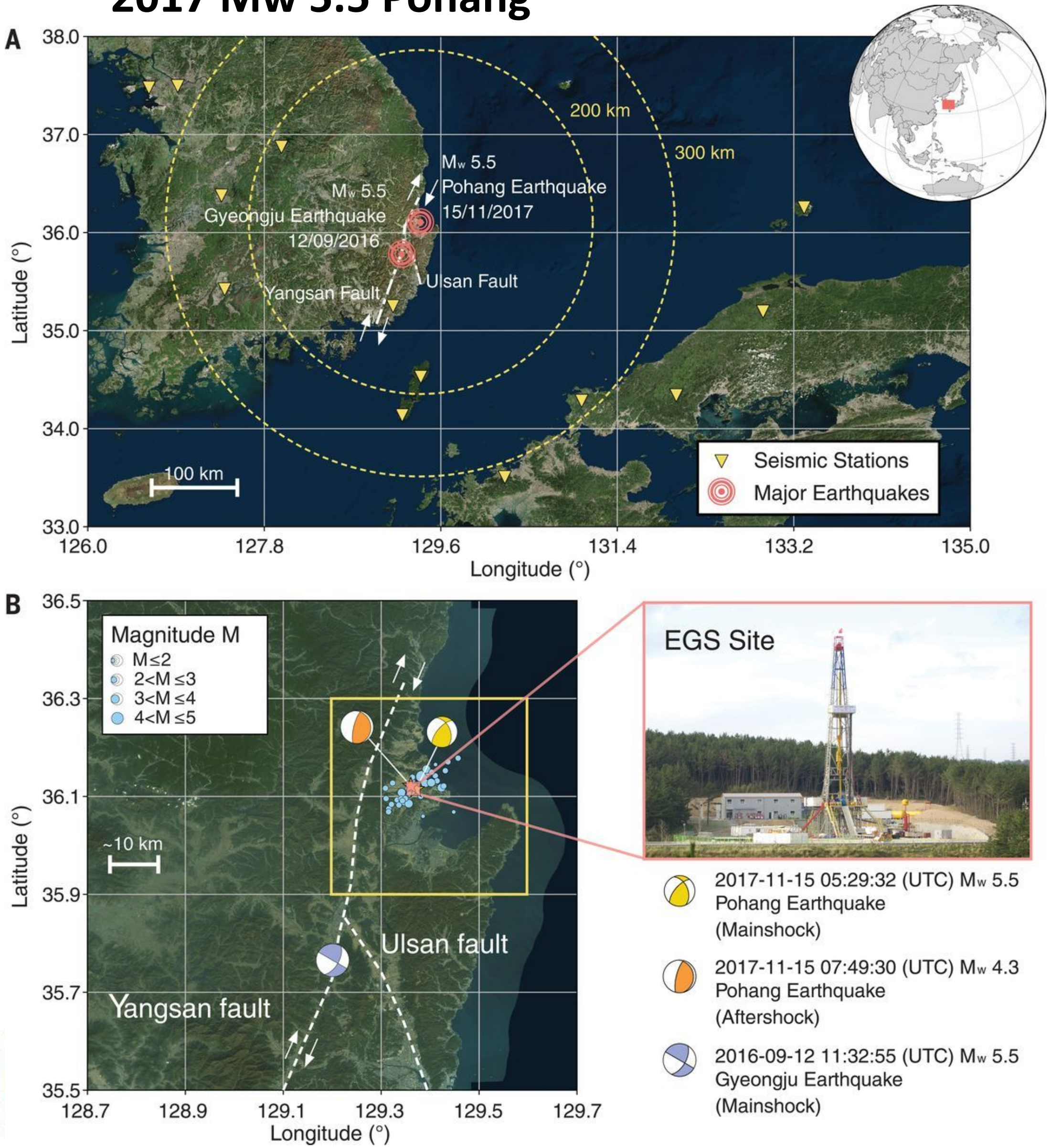
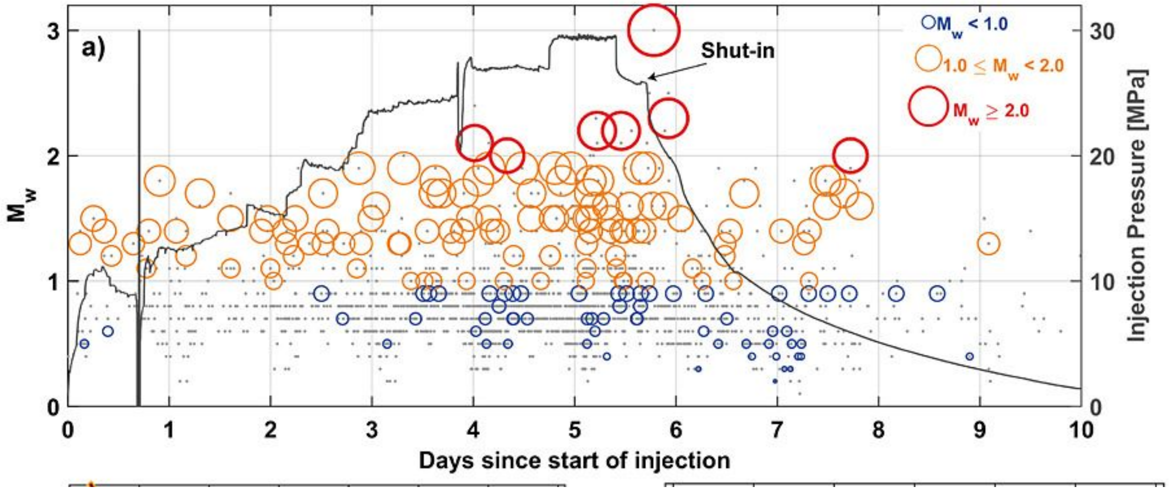
Examples of induced seismicity in geo-energy projects

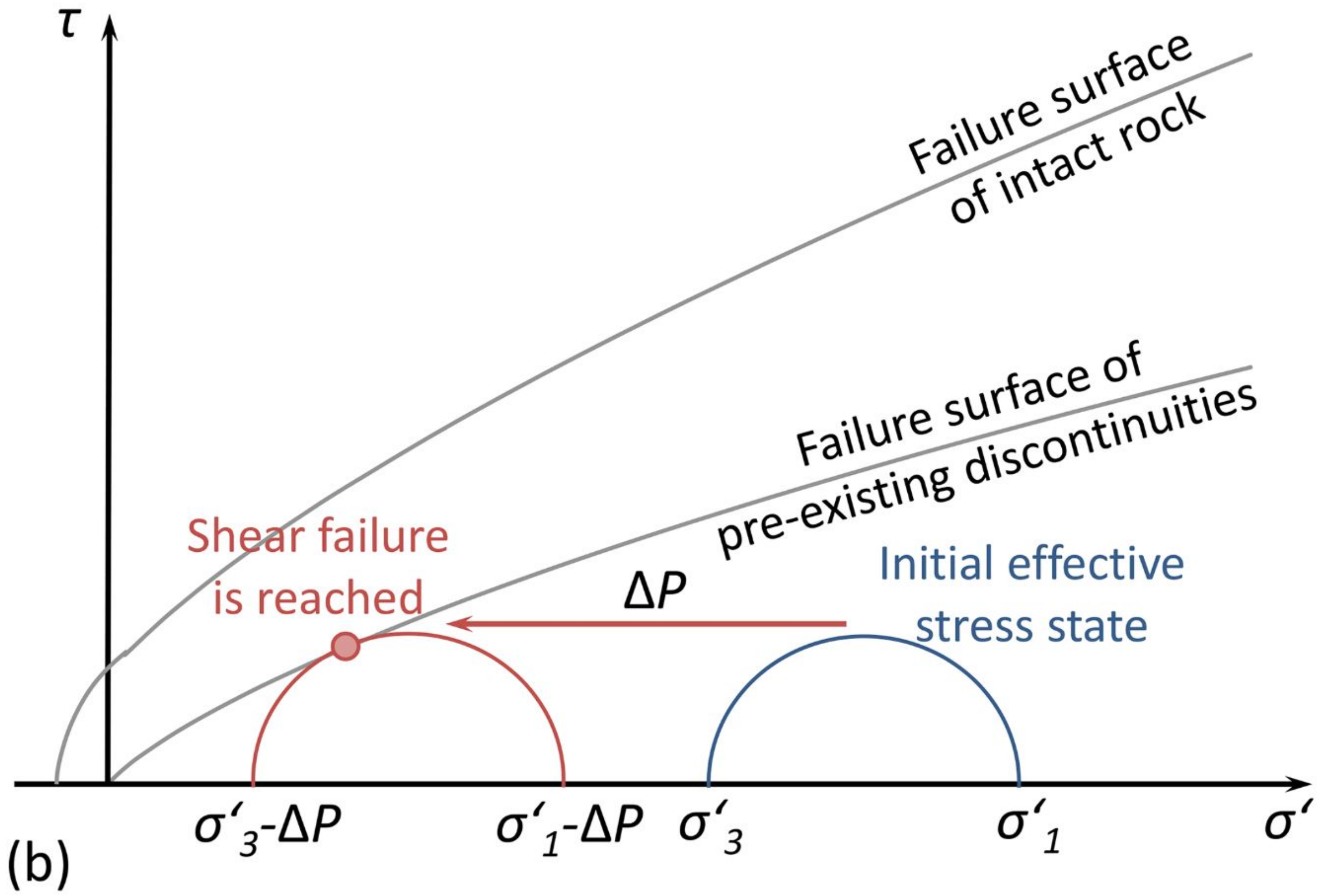
2017 Mw 5.5 Pohang



2006 Mw 3.4 Basel



Fault slip induced by decrease in effective stress



Frictional stability criteria

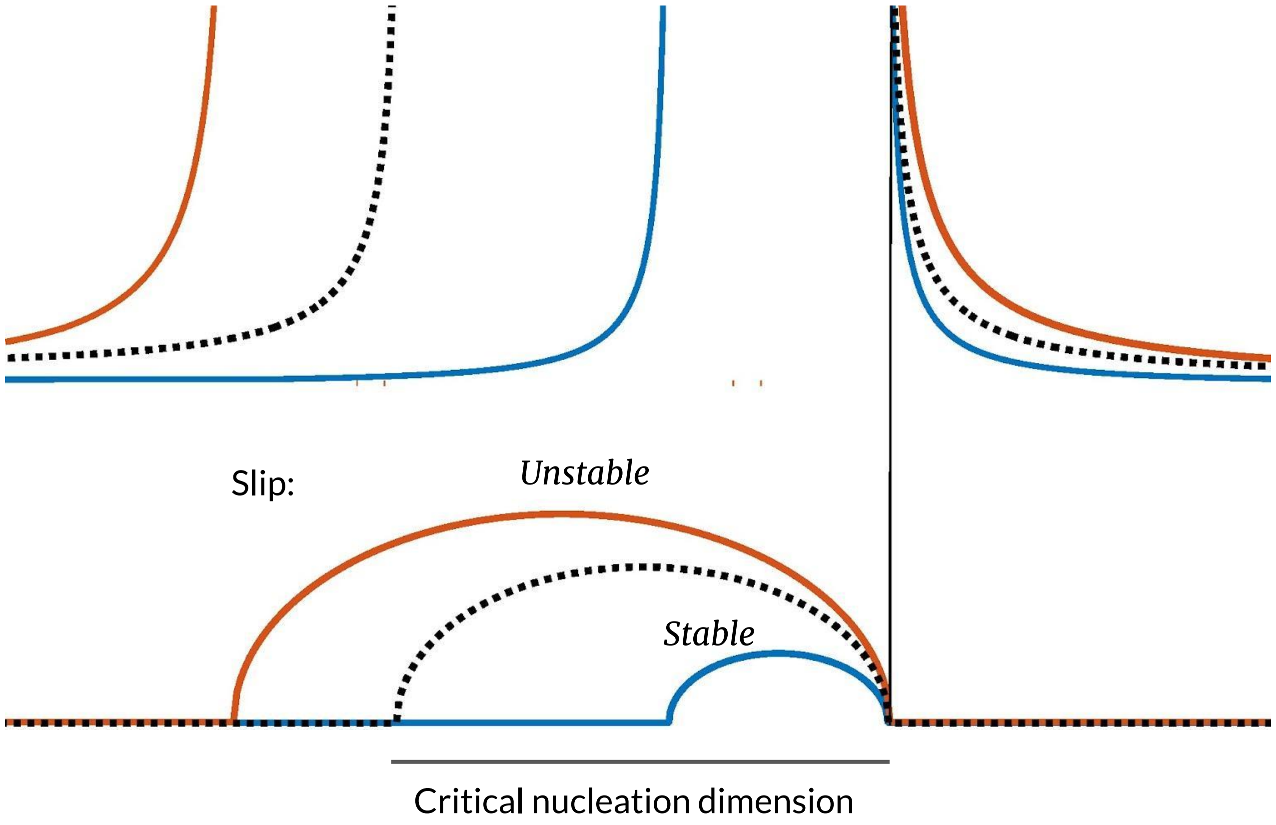
Rate weakening vs. rate strengthening:

$$\frac{\partial f_{ss}}{\partial V} \geq 0 \longrightarrow \text{Stable sliding}$$

$$\frac{\partial f_{ss}}{\partial V} < 0 \longrightarrow \text{Potentially unstable sliding}$$

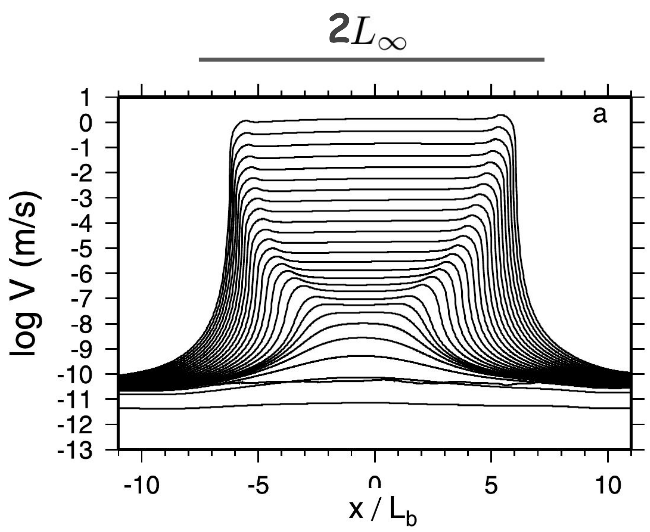
Unstable sliding above critical nucleation length

Stress outside slipping region:



For rate-state, ageing law friction:
(*Rubin & Ampuero, J. Geophys. Res., 2005*)

$$L_\infty = \frac{b}{\pi(b-a)^2}\frac{\mu' d_c}{\sigma}$$

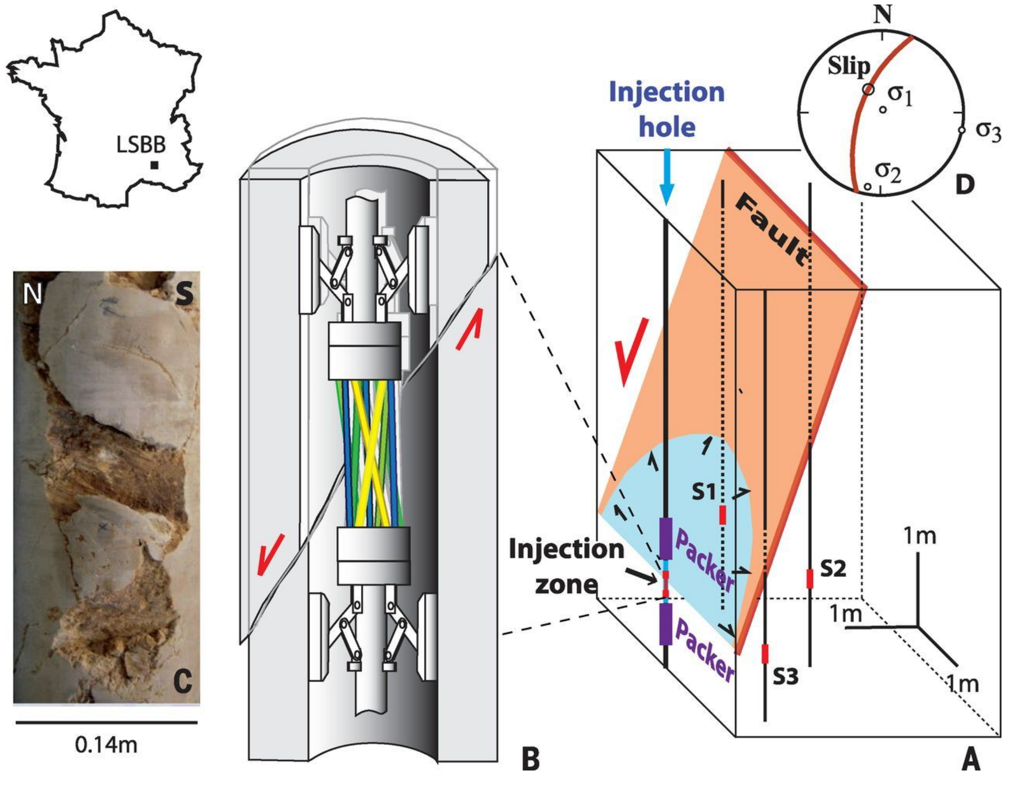


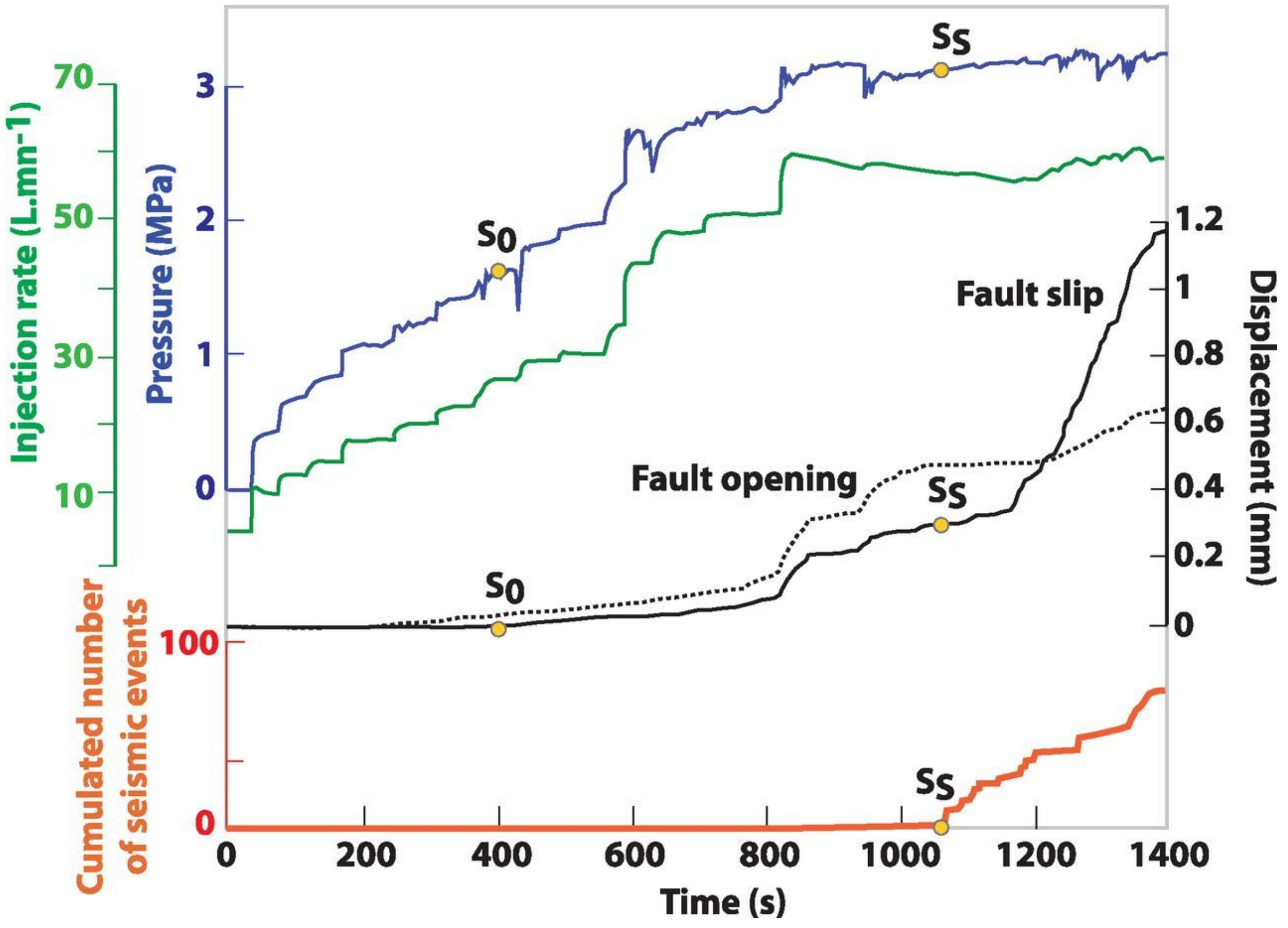
Similar dimensions can be found for:

- other frictional laws (e.g. *Ampuero & Rubin, J. Geo. Res., 2008*)
- rough faults (*Tal, Hager & Ampuero, J. Geo. Res., 2018*)

Evidence for seismicity triggered by aseismic slip

Guglielmi et al, 2016

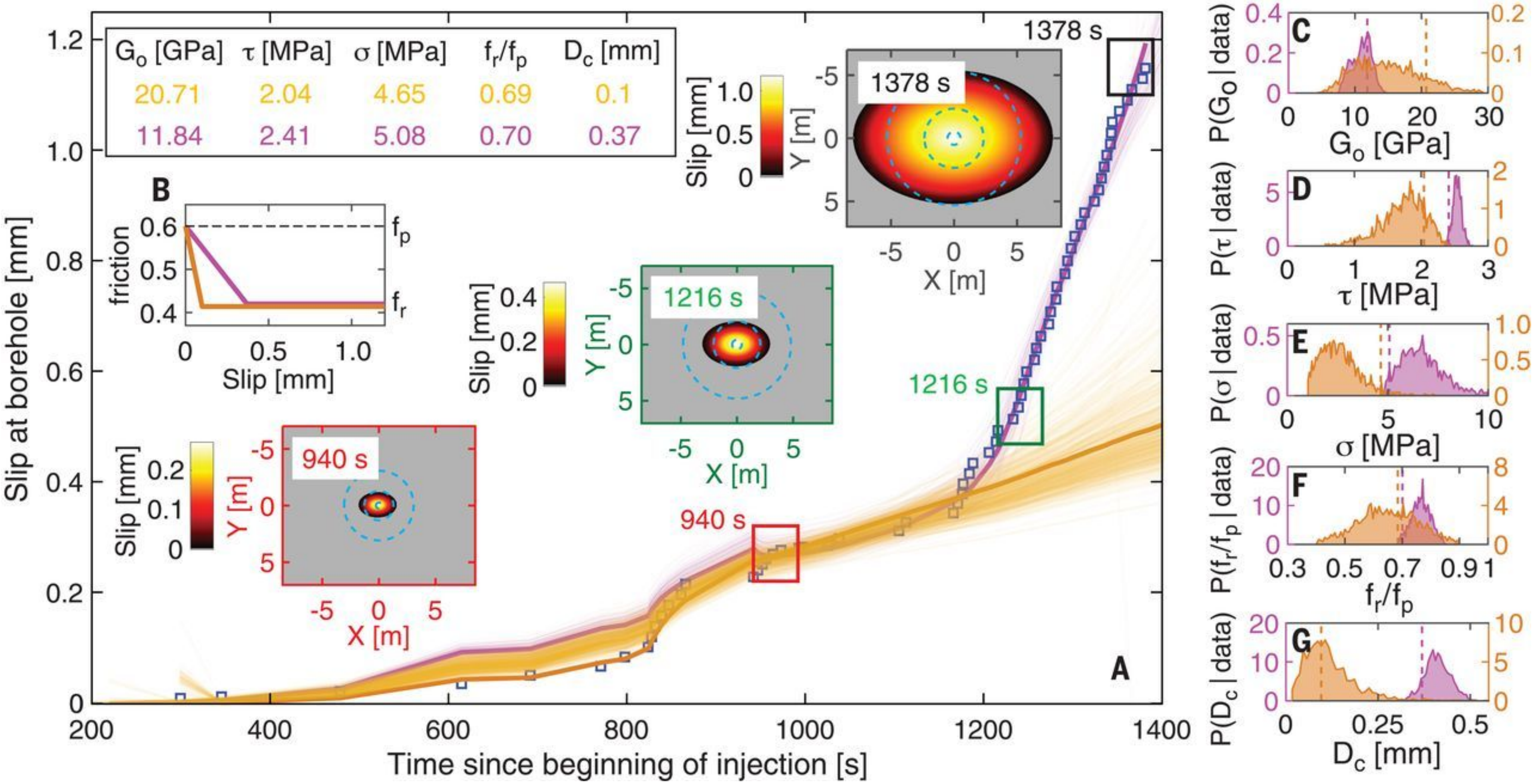




Modeling reproduces aseismic slip event

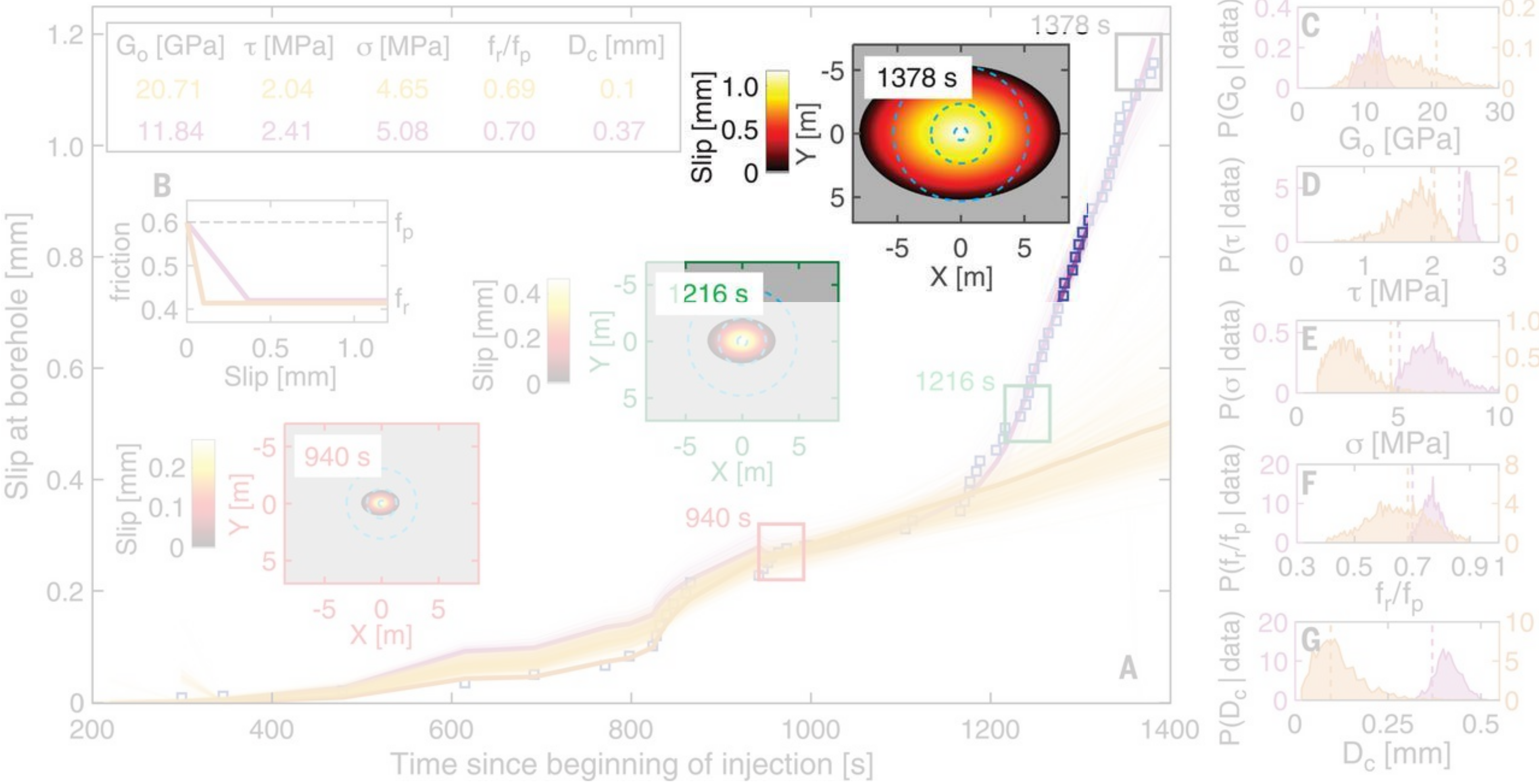
Bhattacharya et al., 2019

Slip weakening friction



Scale of aseismic slip comparable to nucleation length

How much aseismic slip could happen at a km-scale?



Roughness modulates fault stability

e.g. Cattania and Segall, 2021

Nucleation length decreases with normal stress:

$$L_{nucl} = f(a, b)\ \frac{\mu' D_c}{\sigma}$$

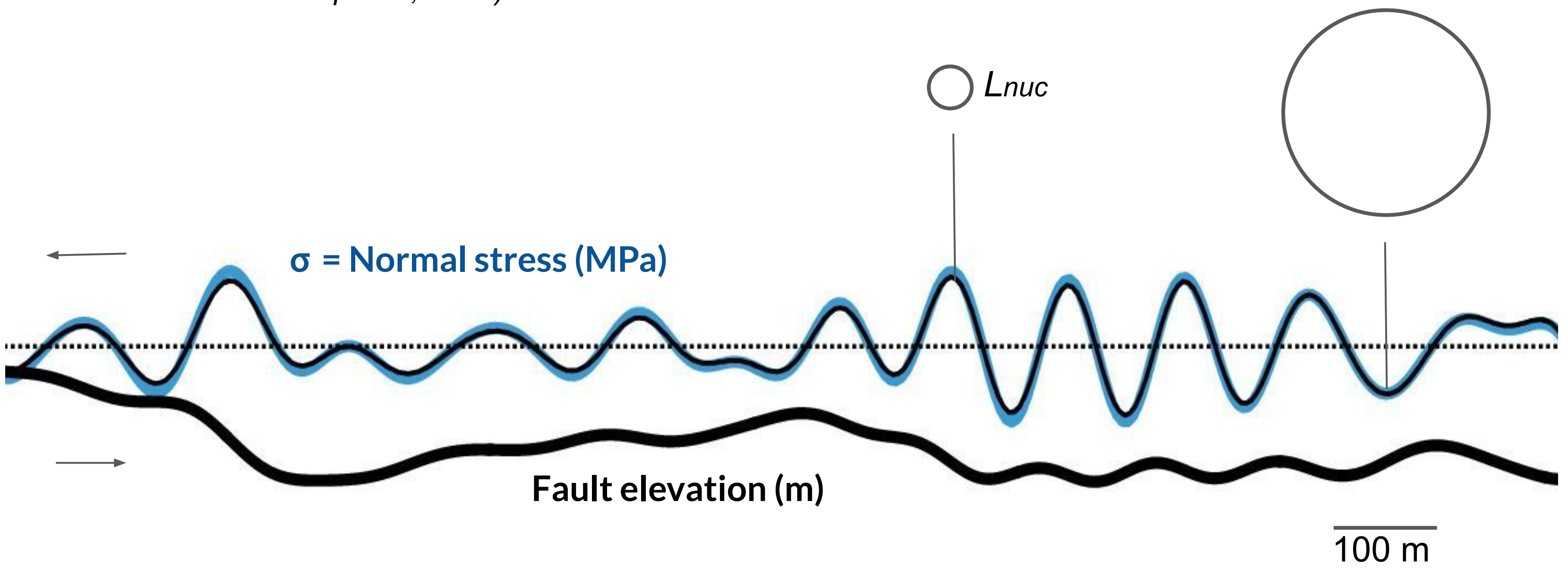
(e.g. Ruina, 1983; Rubin and Ampuero, 2005)

Asperity
High σ
Small nucleation length

Unstable
Interseismically locked, breaks seismically (stick-slip)

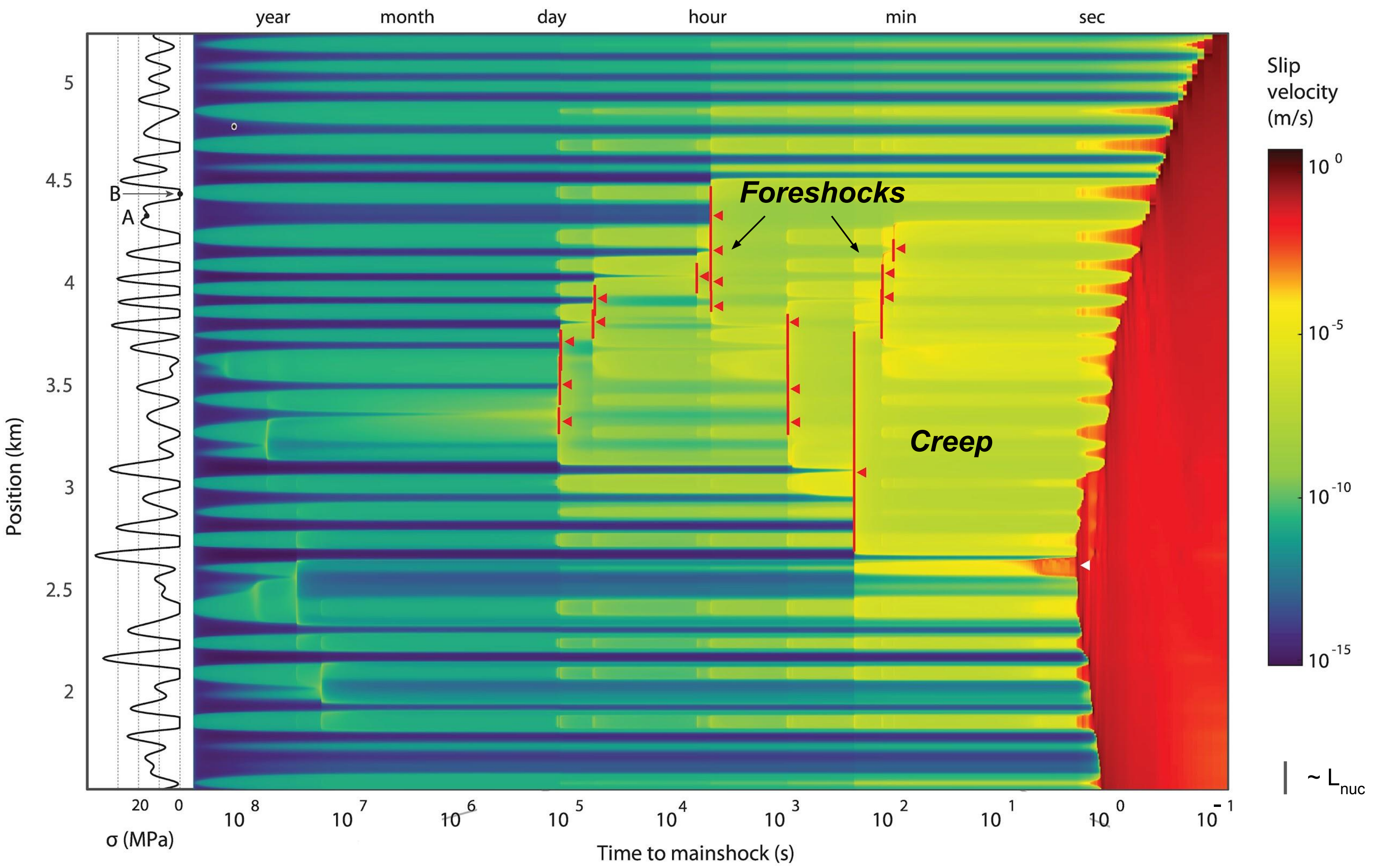
Creeping patch
Low σ
Large nucleation length

Conditionally stable
Does not accelerate towards instability



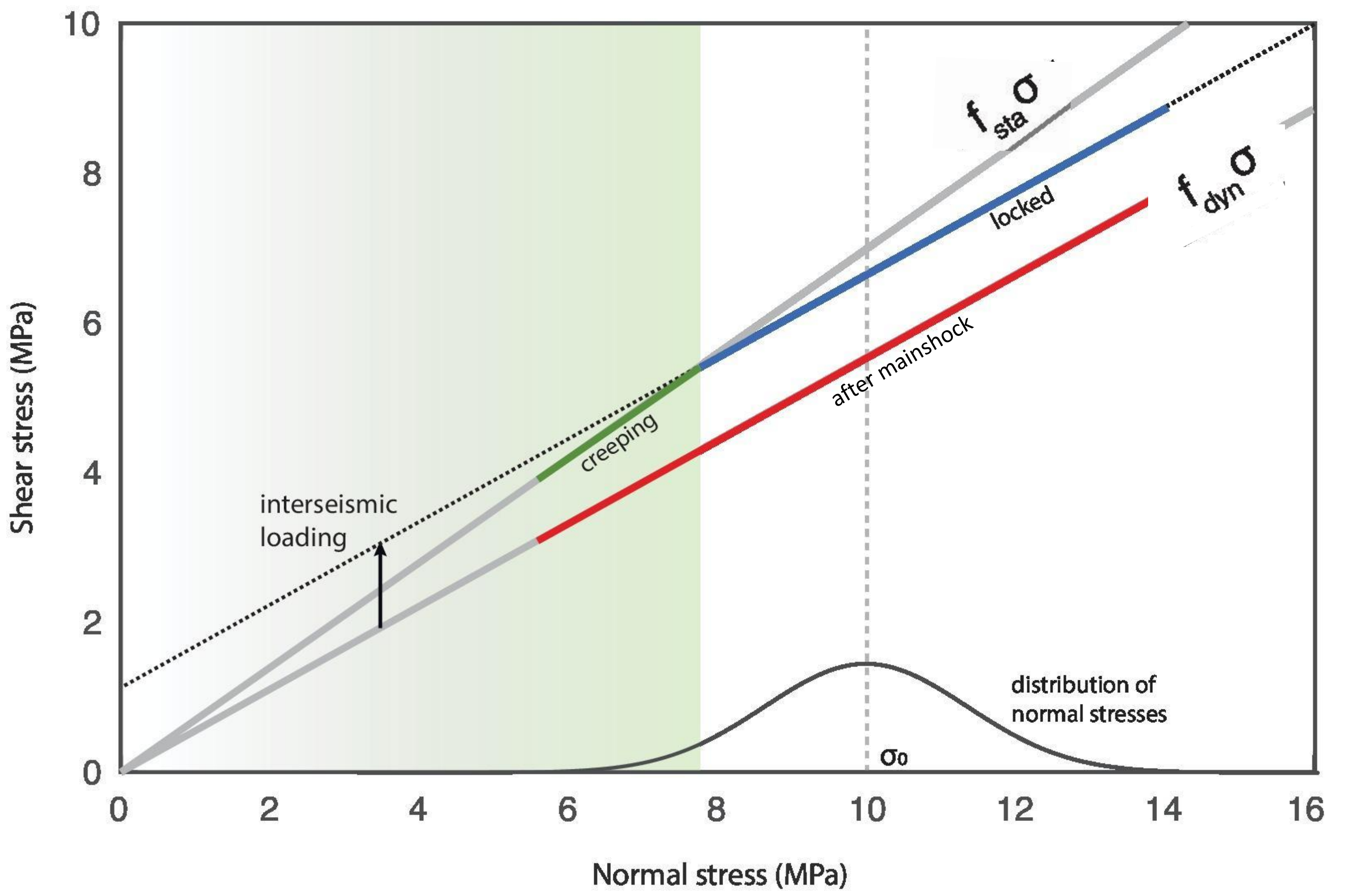
Fault roughness enables extended creep

Creeping area >> L_{nuc}



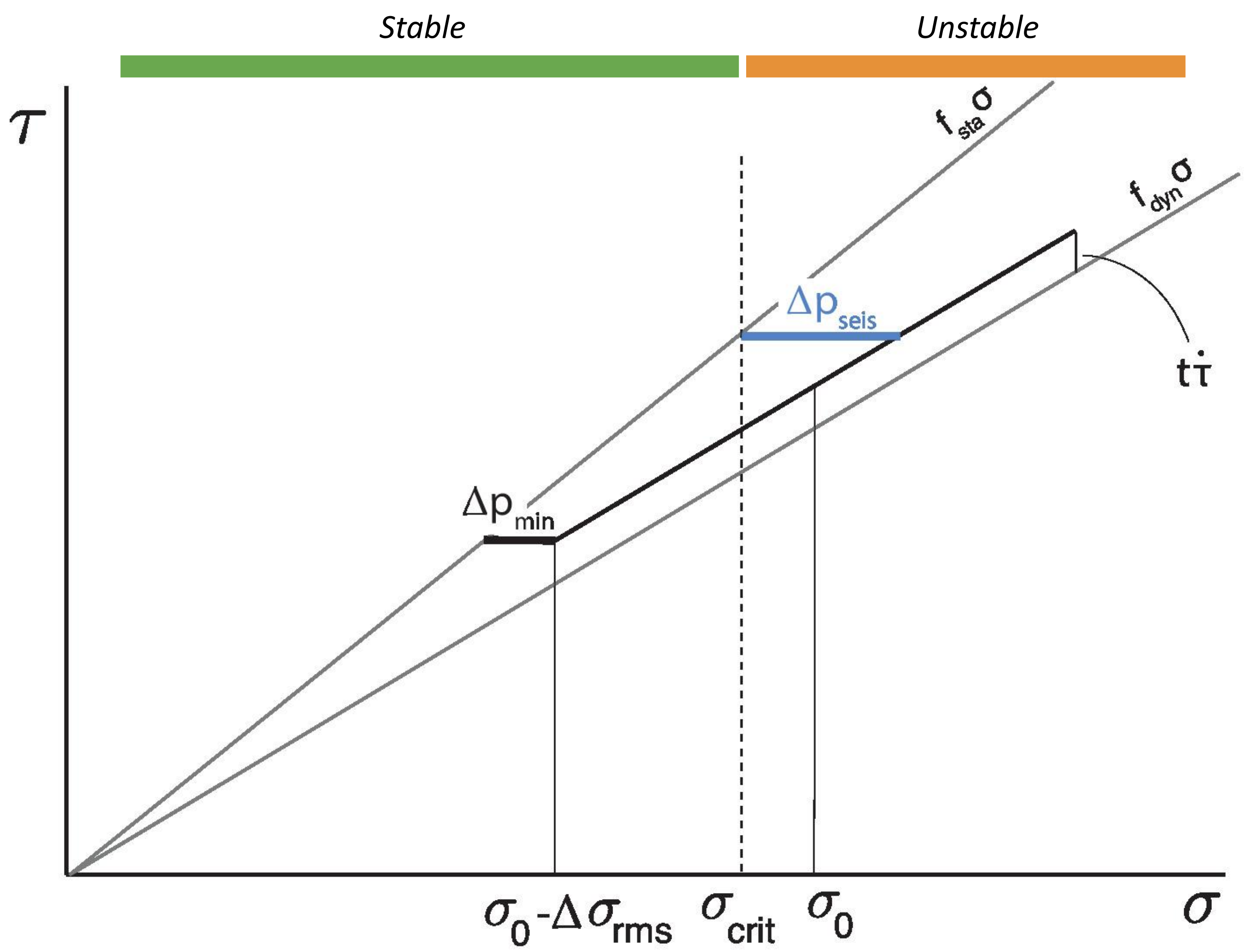
Cattania and Segall, 2021

State of stress on a rough fault



State of stress on a rough fault with injection

Localized aseismic slip expected to occur before any seismic activity

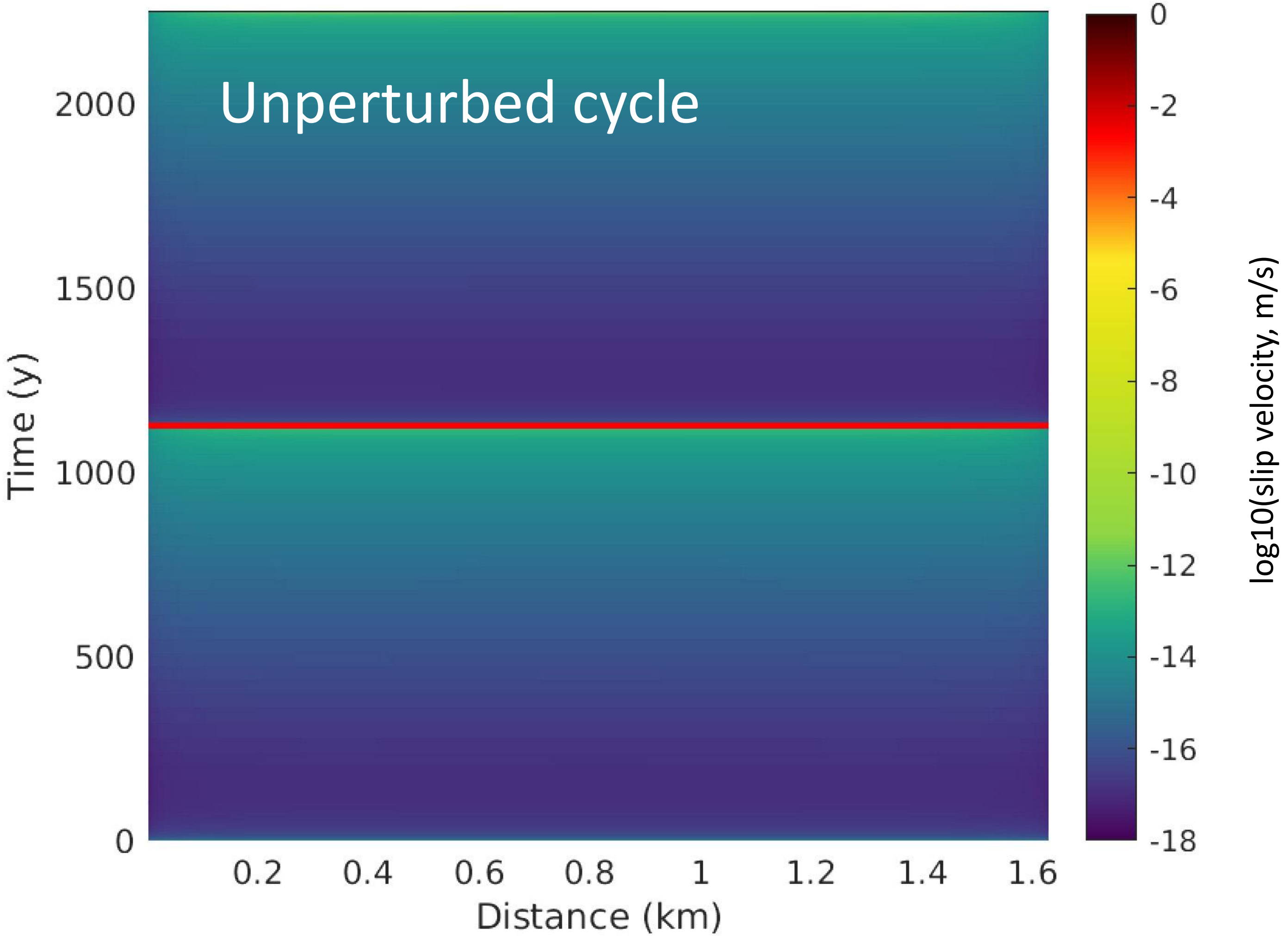


Implications:

- Reduced seismic release
- Slow slip can trigger delayed seismicity

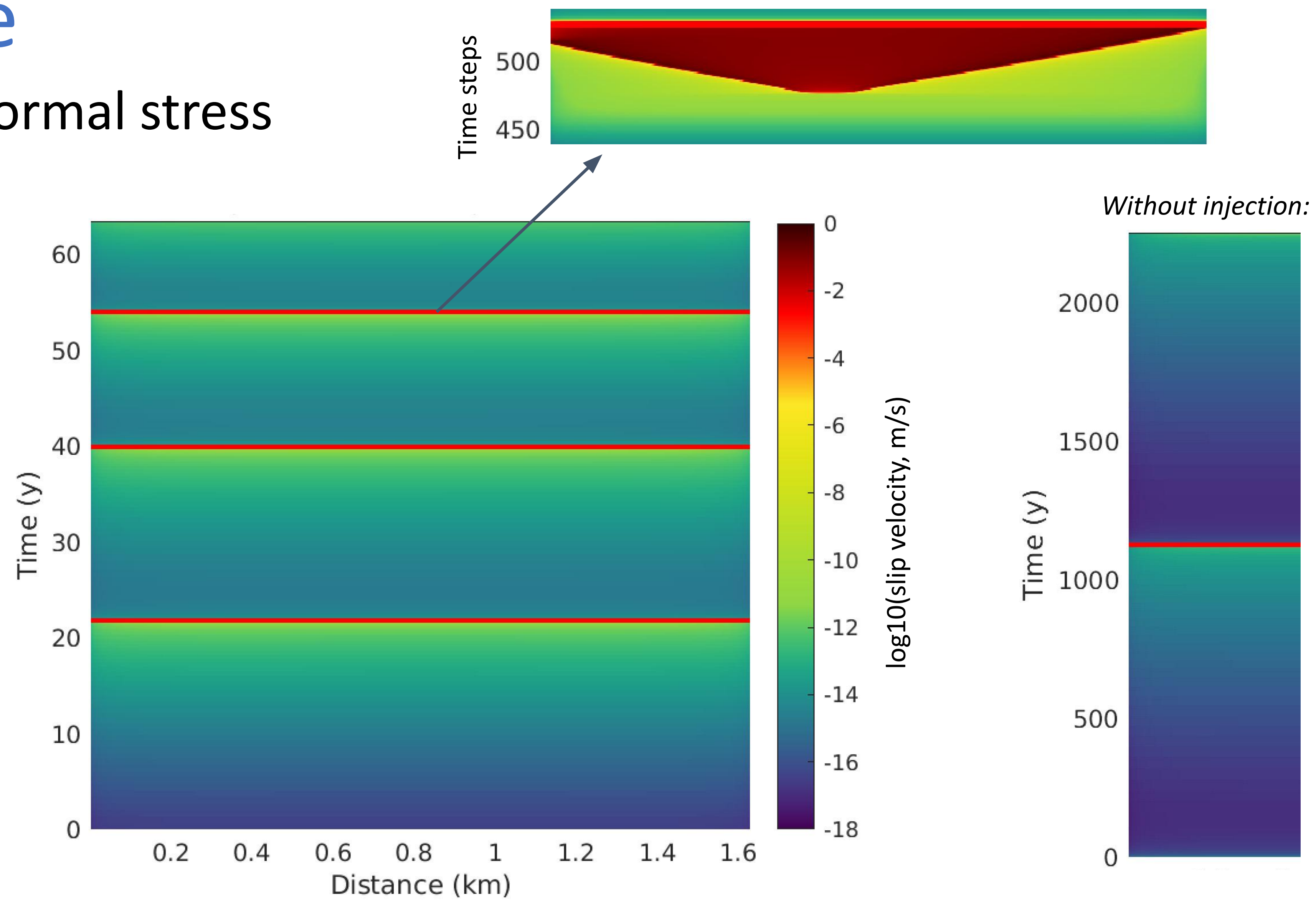
Simulation of a simple seismic cycle

- Quasi-dynamic earthquake cycle simulator (FDRA)
- 2D plane-strain
- Elastic bulk
- Fault loaded by uniform shear stressing rate
- 20 MPa normal stress



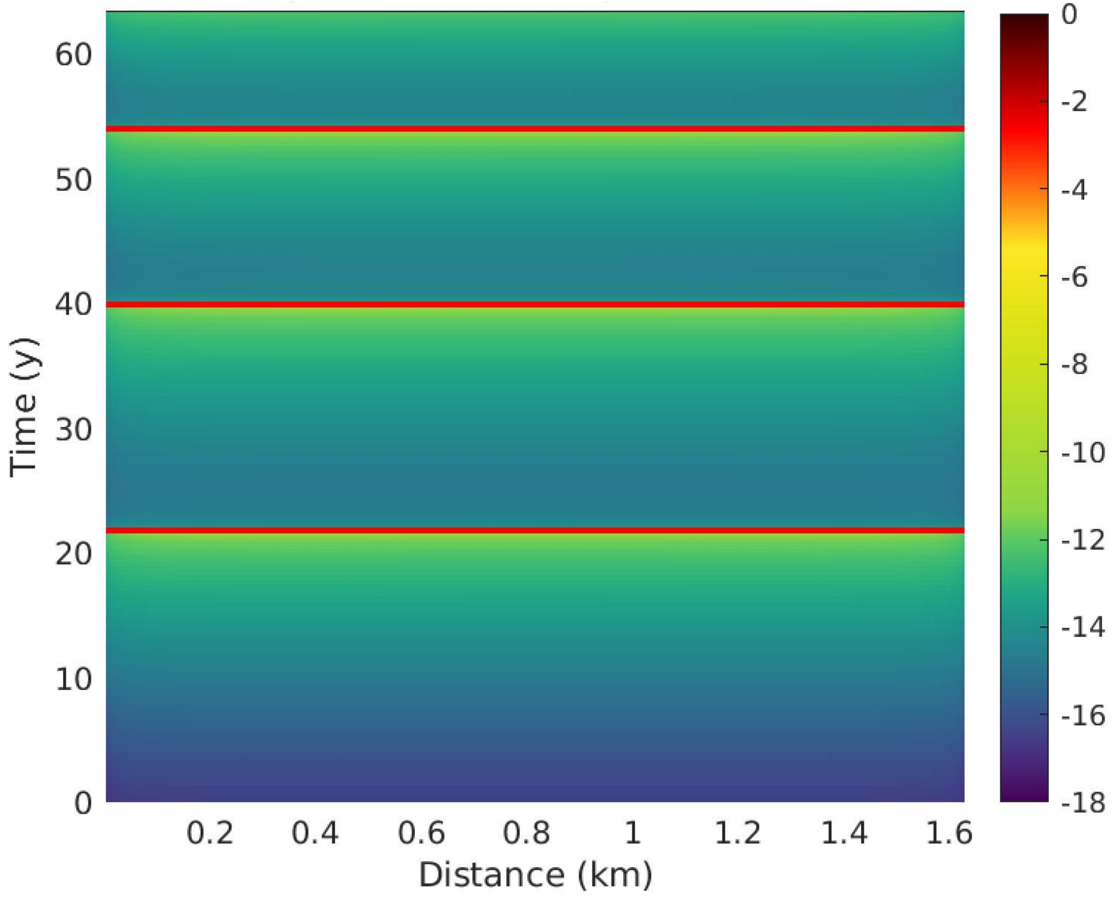
Perturbed cycle

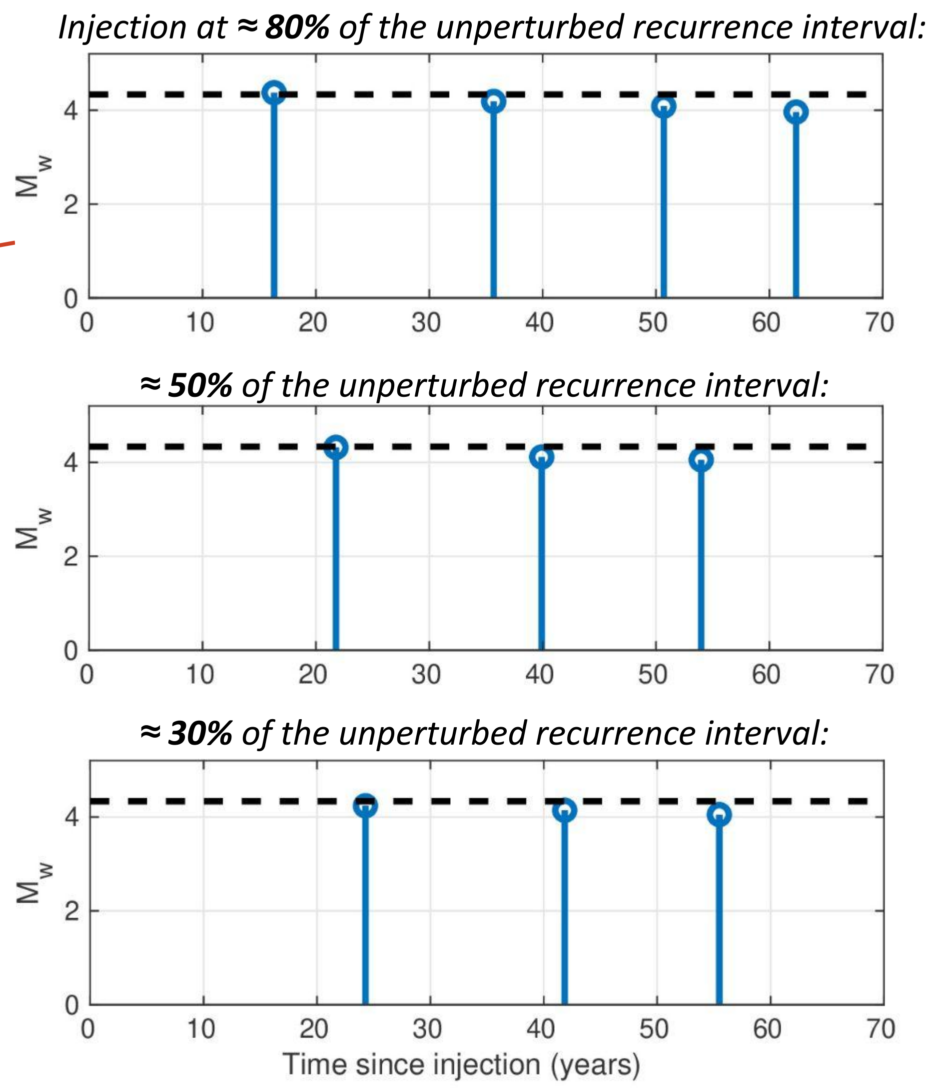
Uniform decrease in normal stress at 0.1MPa/yr



Decrease in recurrence interval, moment

Due to decrease in σ_{eff}

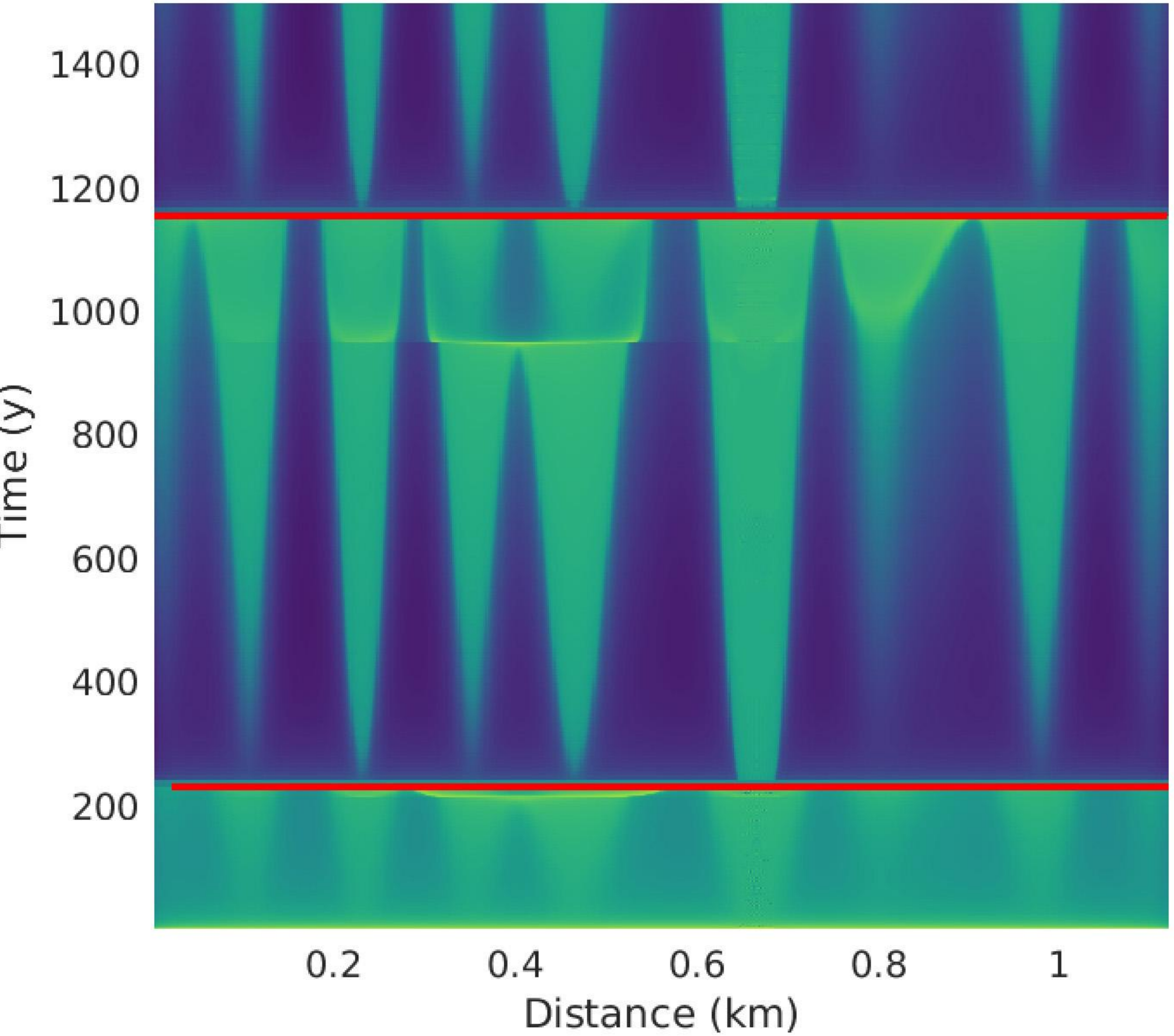




Injection on a rough fault: slow slip, smaller earthquakes

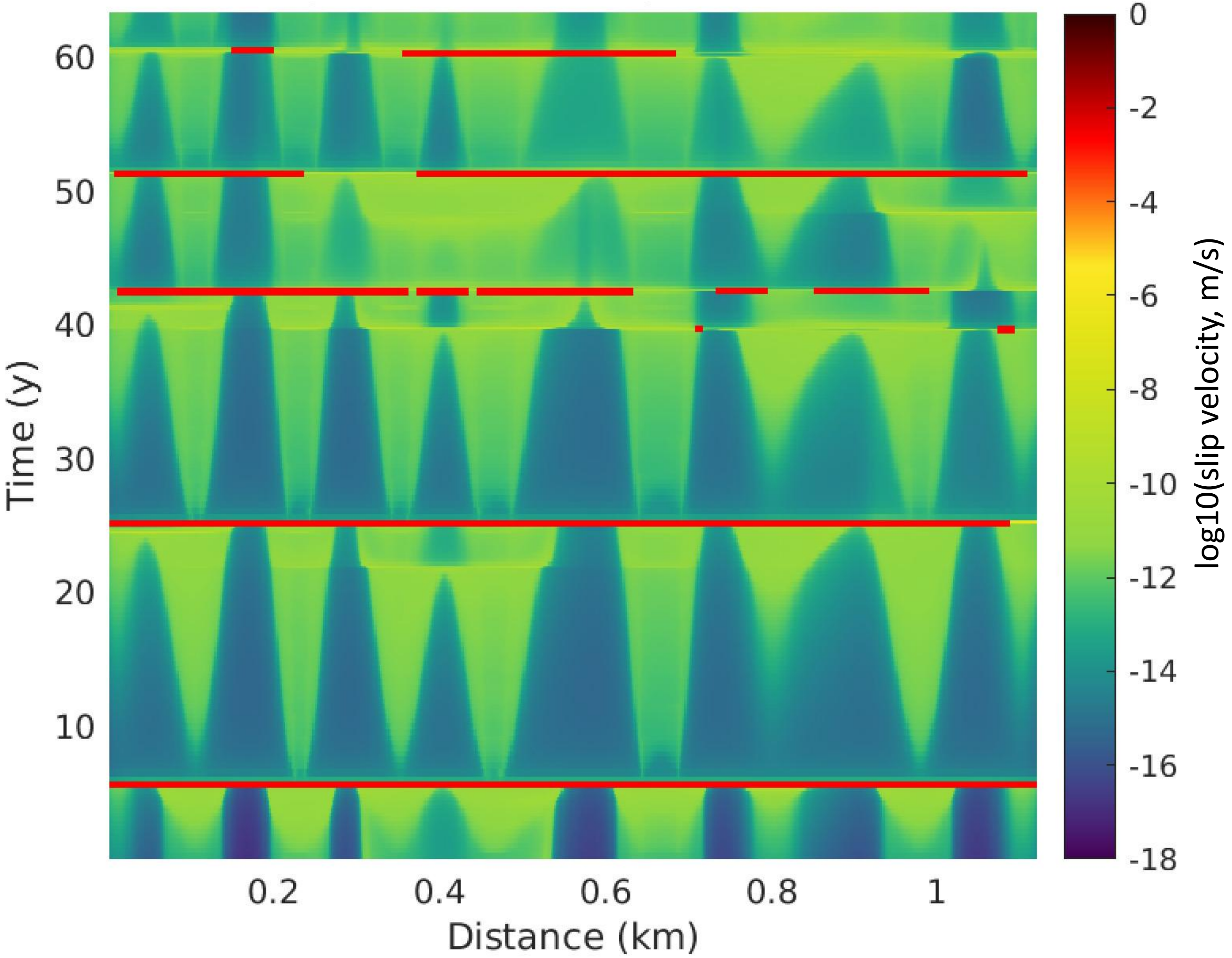
Unperturbed cycle:

Aseismic slip = 15%



Perturbed cycle:

Aseismic slip = 60%



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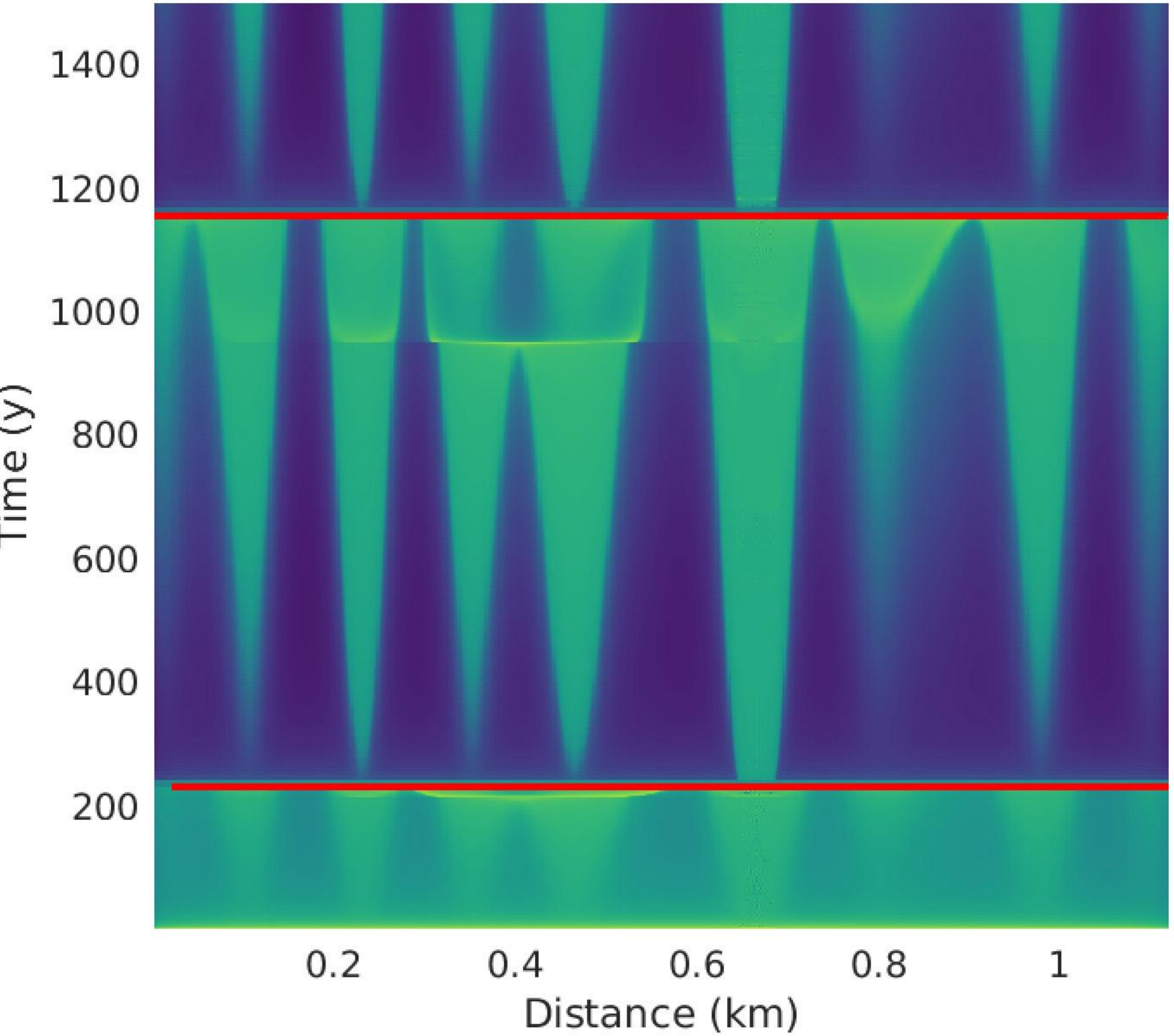

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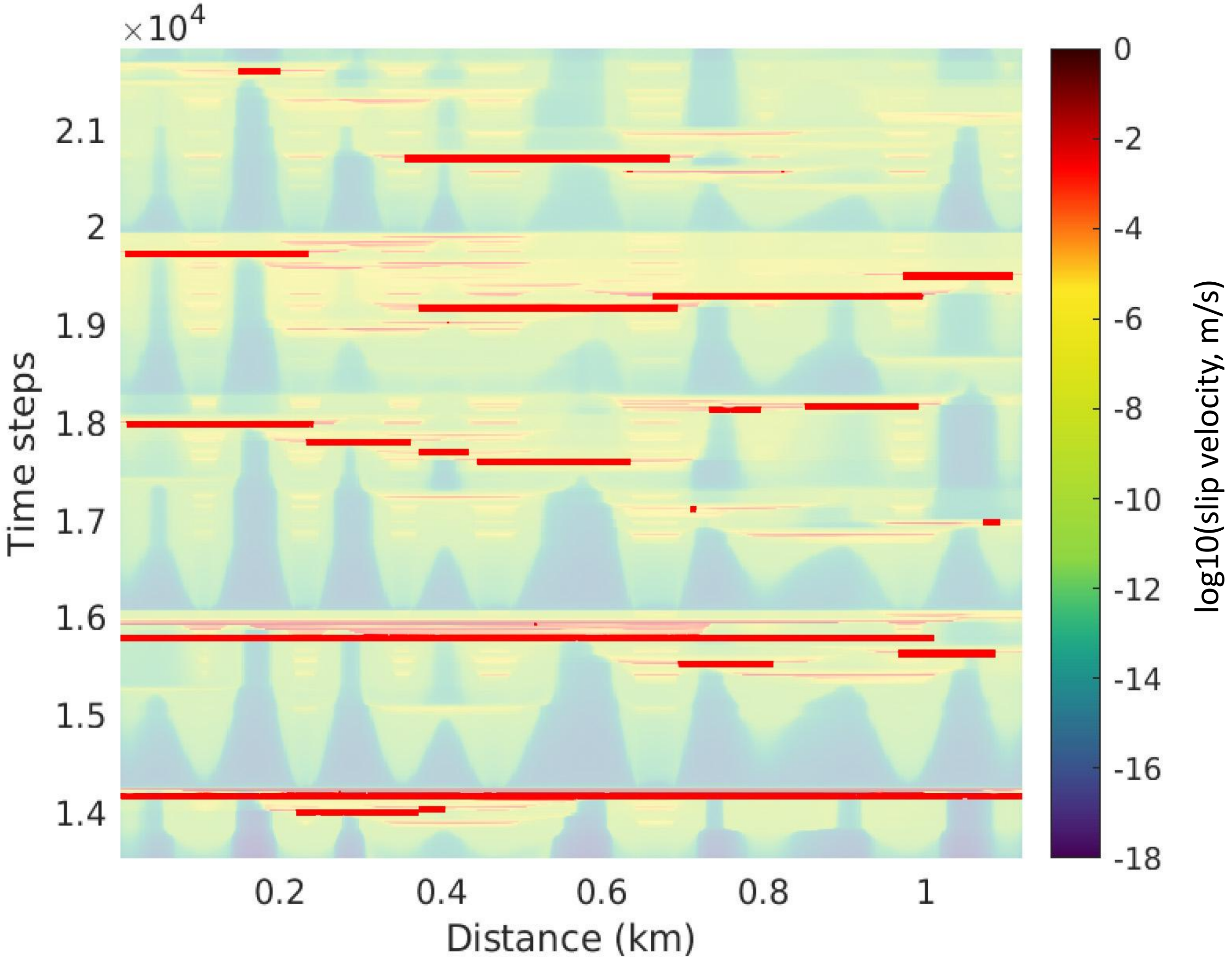
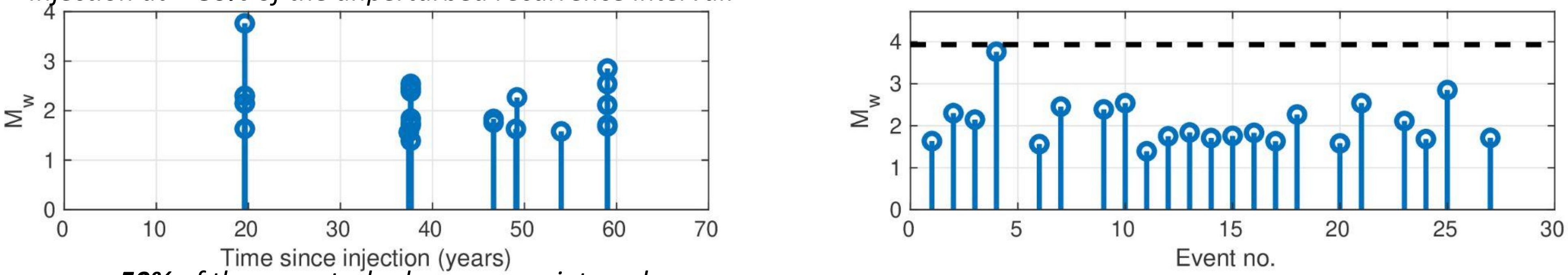
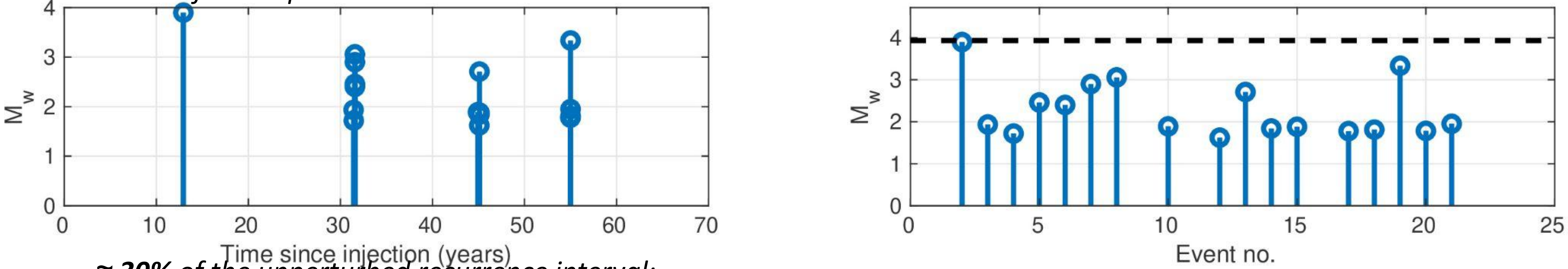


Significant reduction in magnitudes

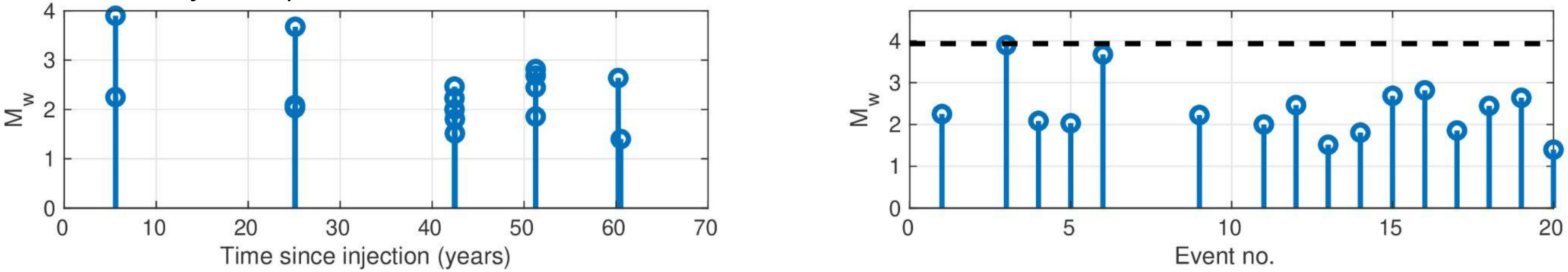
*Injection at ≈ **80%** of the unperturbed recurrence interval:*



*≈ **50%** of the unperturbed recurrence interval:*

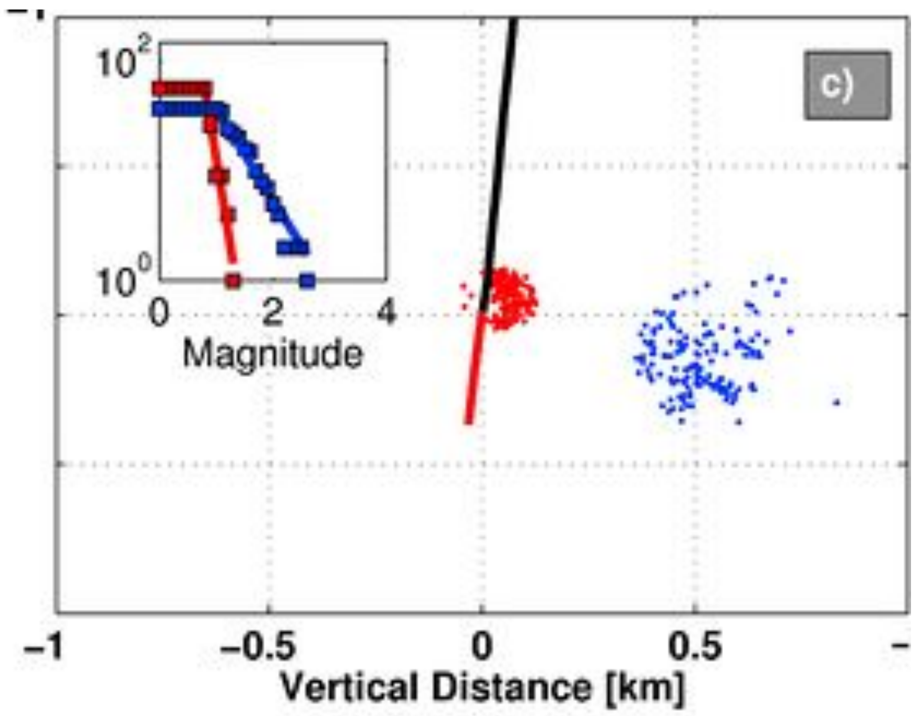


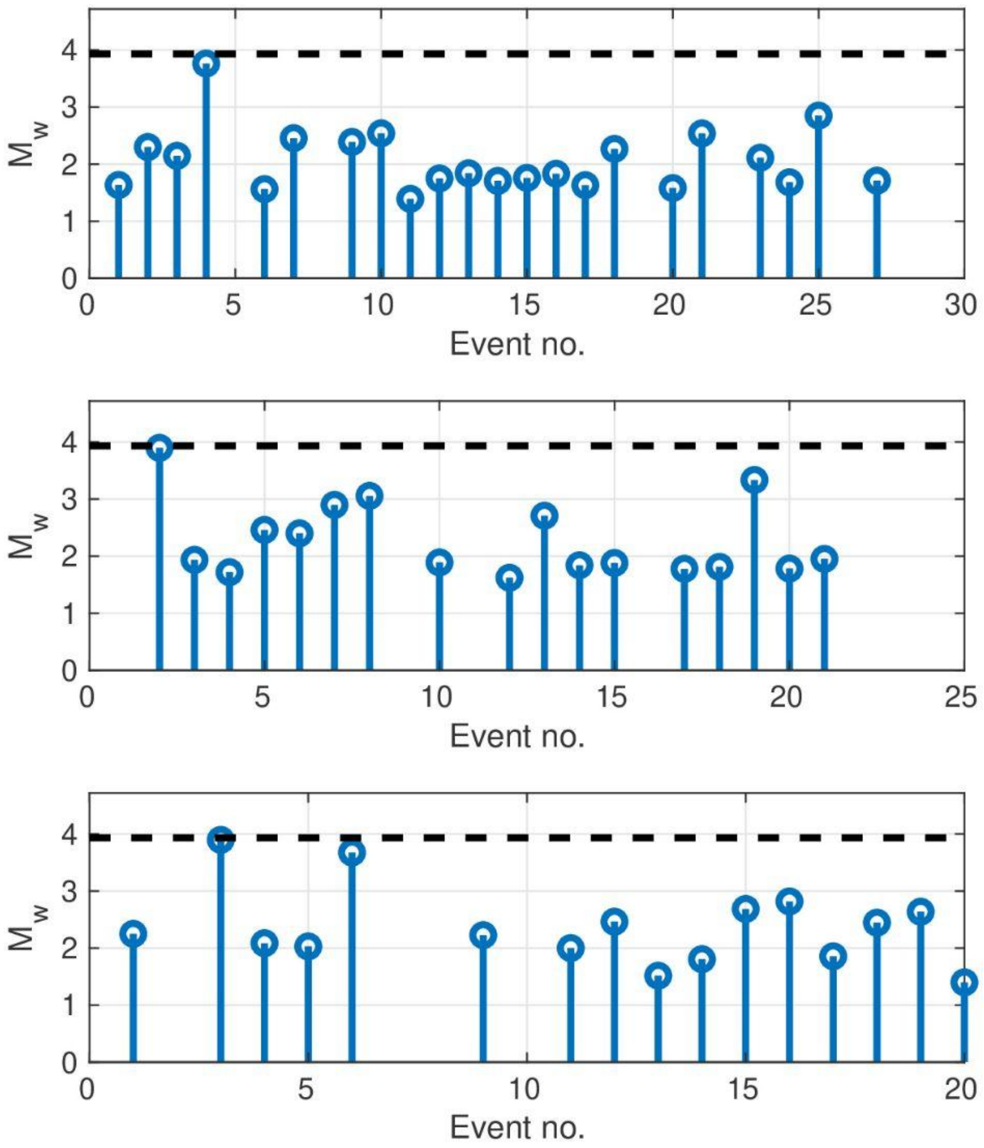
*≈ **30%** of the unperturbed recurrence interval:*



High b-value correlated with high pore pressure

Bachman et al. 2012
high b-value near injection

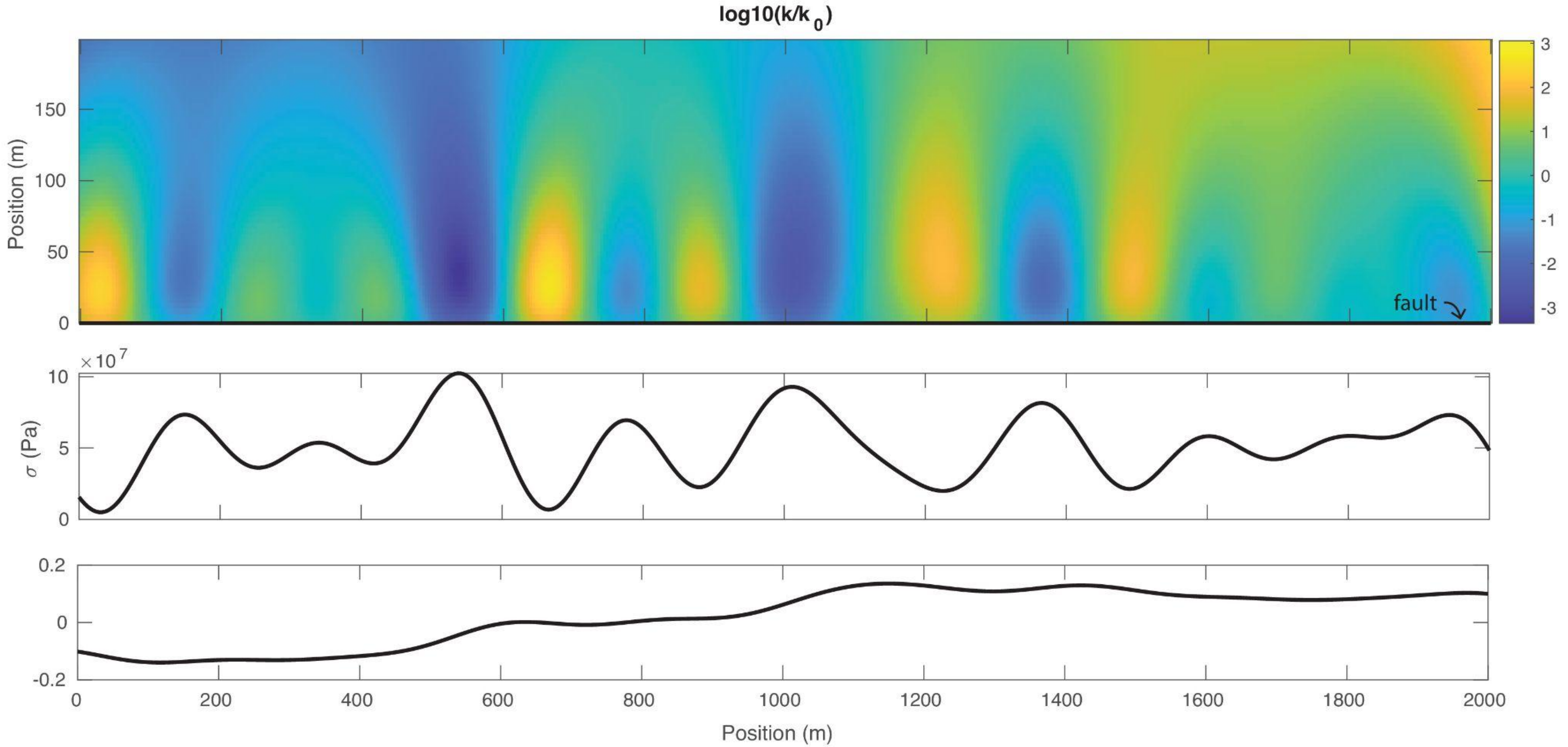




Normal stress heterogeneity → k heterogeneity

Rice (1992):

$$k = k_0 \exp\left(\frac{-\sigma}{\sigma^*}\right)$$



Weak fault patches experience earlier stress changes

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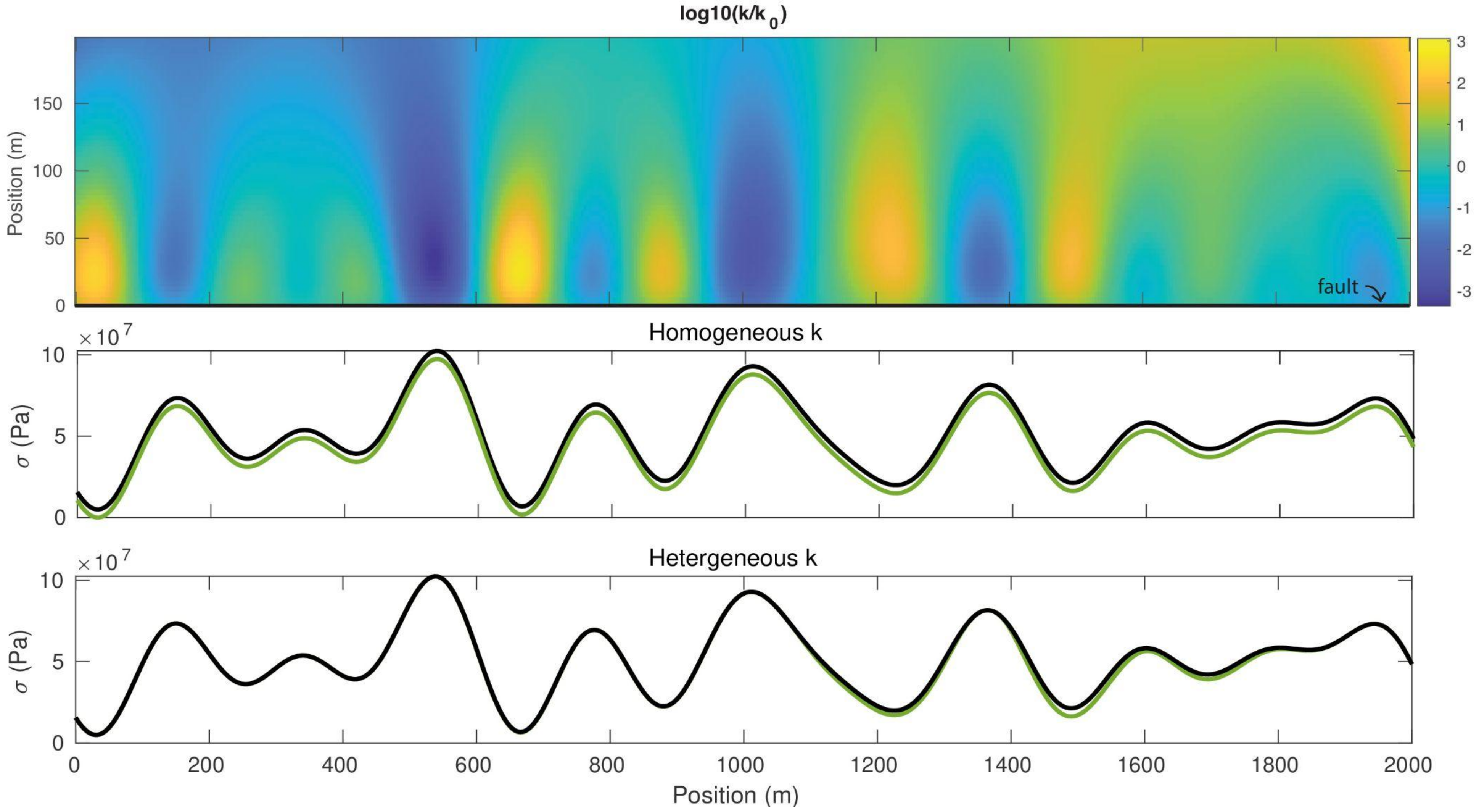
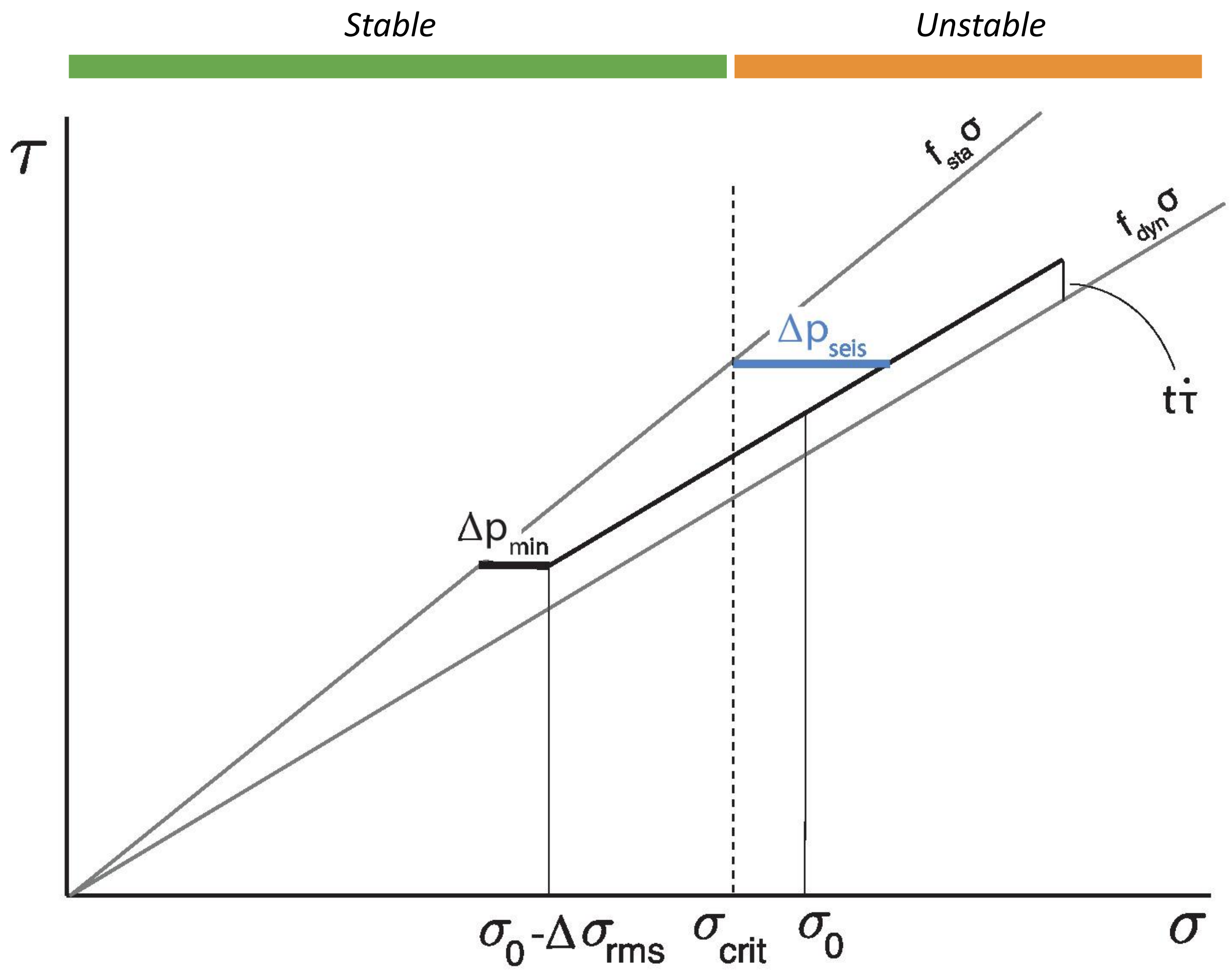


Conclusions

- Pore pressure changes affect fault frictional stability

  (opposite effect to Coulomb stress analysis)



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  (1) a large fraction of aseismic slip
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We need to develop models of induced seismicity that account for these effects

Couple them with more sophisticated geomechanical models

Test against observation of induced microseismicity