Physics of Injection-induced Earthquakes Unveiled by Seismic Wave Analysis and Numerical Models

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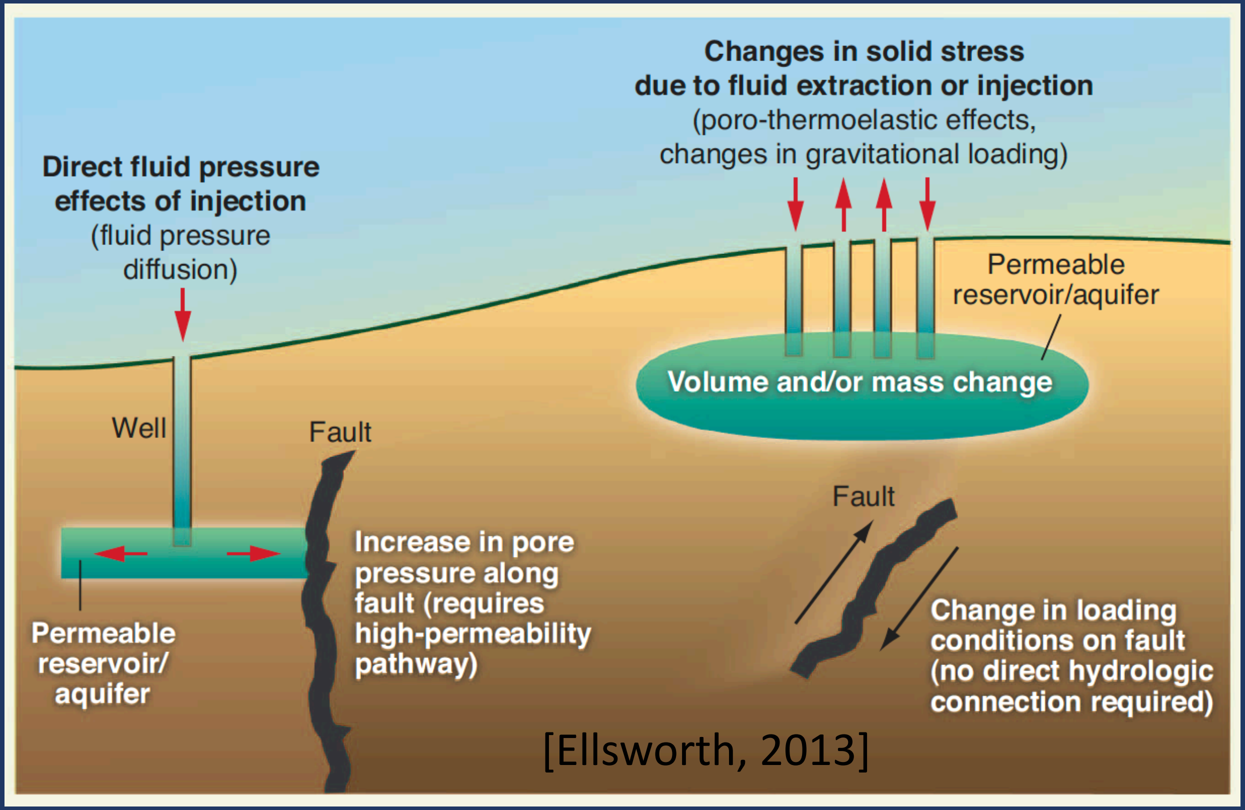

- How large is the change of fluid pressure or poroelastic stress? Will it cause a significant change of earthquake stress release?
- Can fluid migration leave a signature in ground motions?
- Are earthquakes always a direct response of fluid injection?

Overview

- Stress drop analysis of induced and tectonic earthquakes
- Rupture directivity analysis of induced earthquakes
- Simulations of earthquakes cycles on faults with normal and shear stress perturbations

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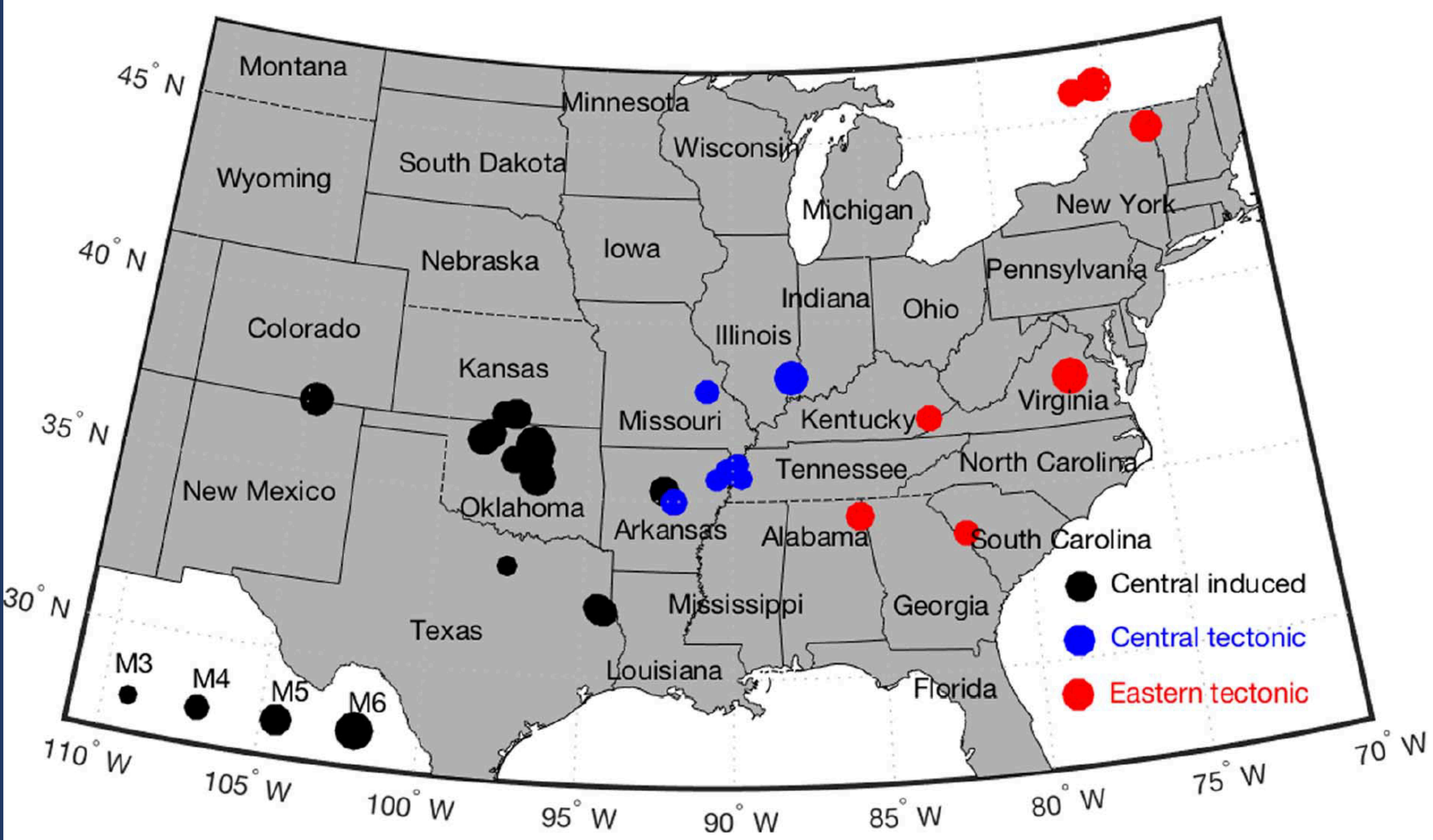
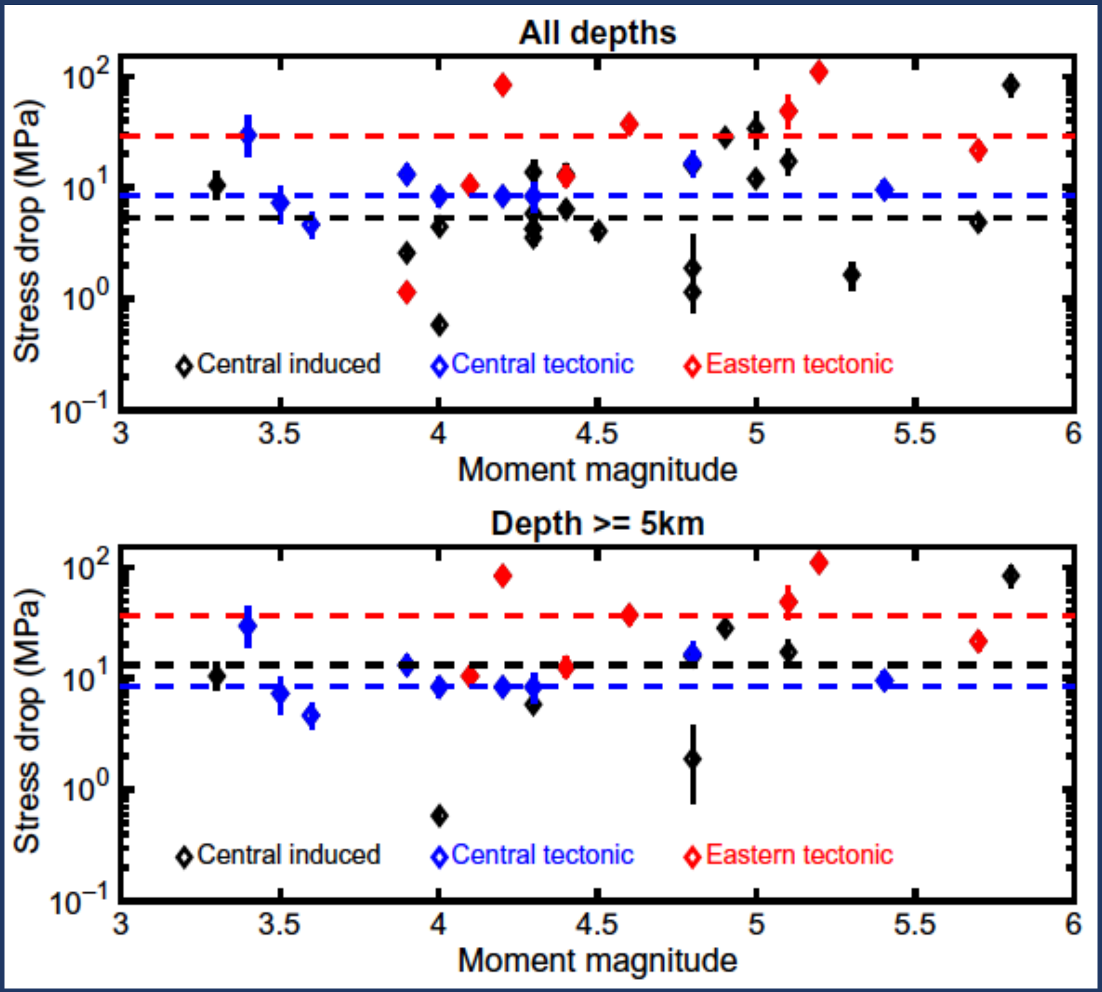
- Are induced earthquakes always a direct response of fluid injection?

I: Mw 3.3-5.8 Induced and tectonic earthquakes in the central and eastern US



[Huang, Ellsworth and Beroza, 2017]

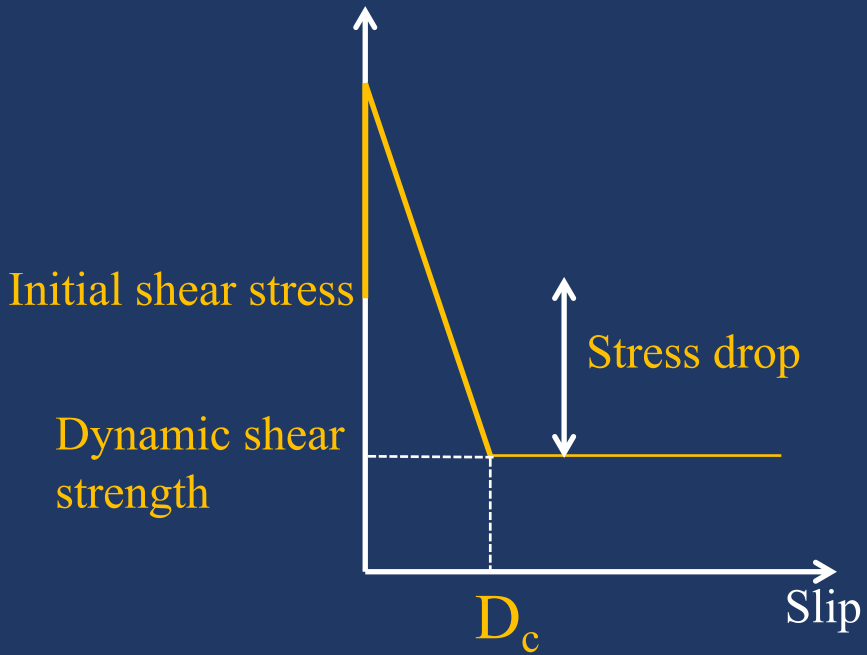
I: Stress drop results

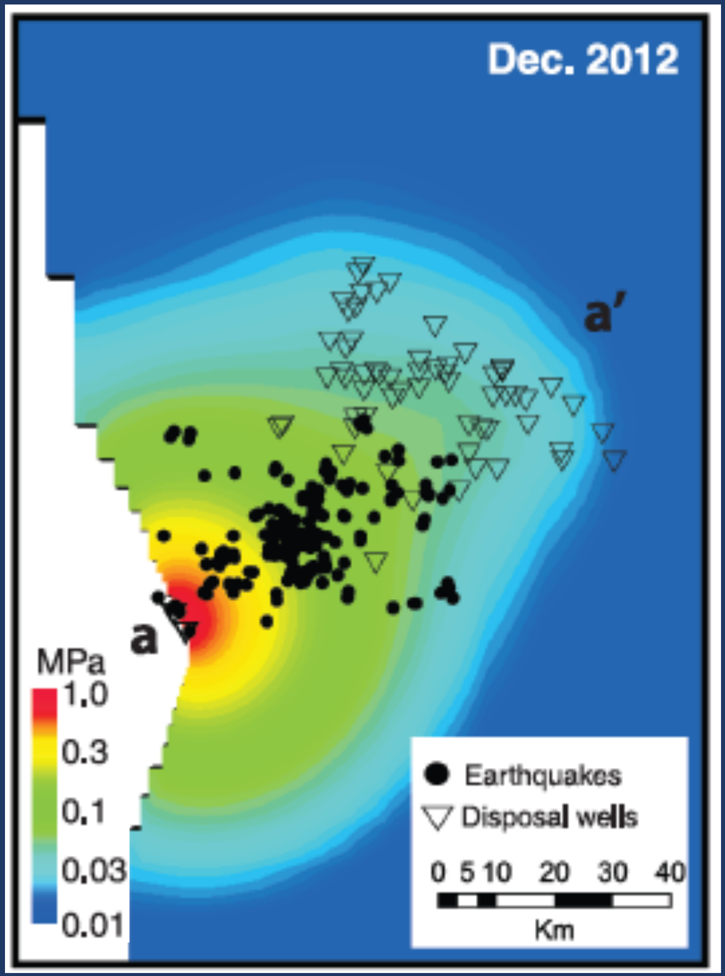


- For tectonic earthquakes, eastern US stress drops are larger than central US stress drops by a factor of ~3 (reverse vs. strike-slip)
- Stress drops of induced earthquakes are similar to those of tectonic ones when depth difference is considered.

[Huang, Ellsworth and Beroza, 2017]

I: Small pore pressure or stress change is sufficient to induce earthquakes on critical faults.

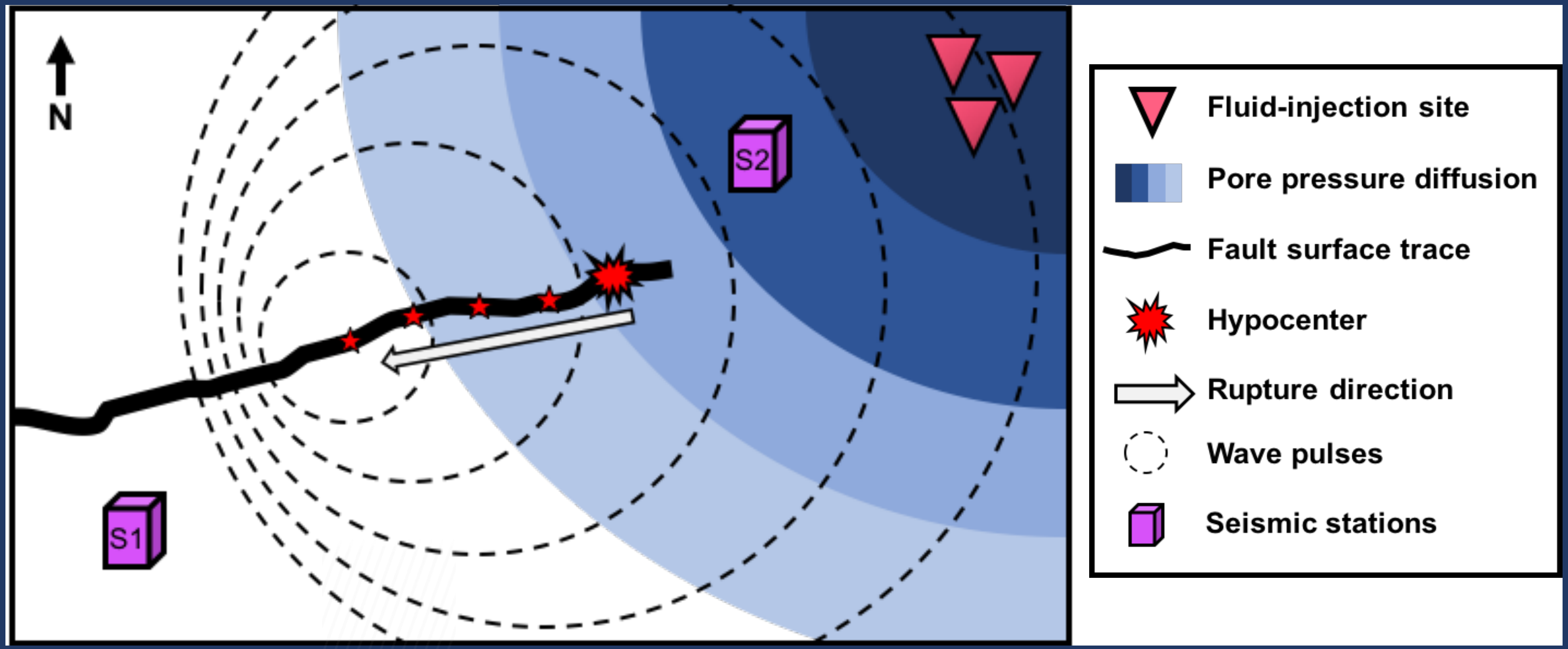




[Keranen, et al., 2014]

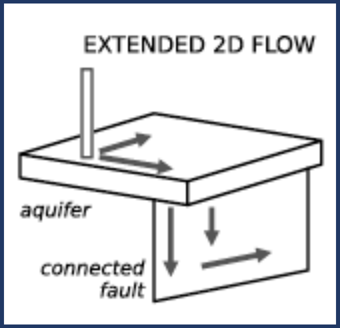
- The difference between stress drops of induced and tectonic earthquakes is pore pressure x dynamic friction coefficient.
- Stress drop is mainly controlled by tectonic stress.

II: Can fluid migration leave a signature in ground motions of induced earthquakes?

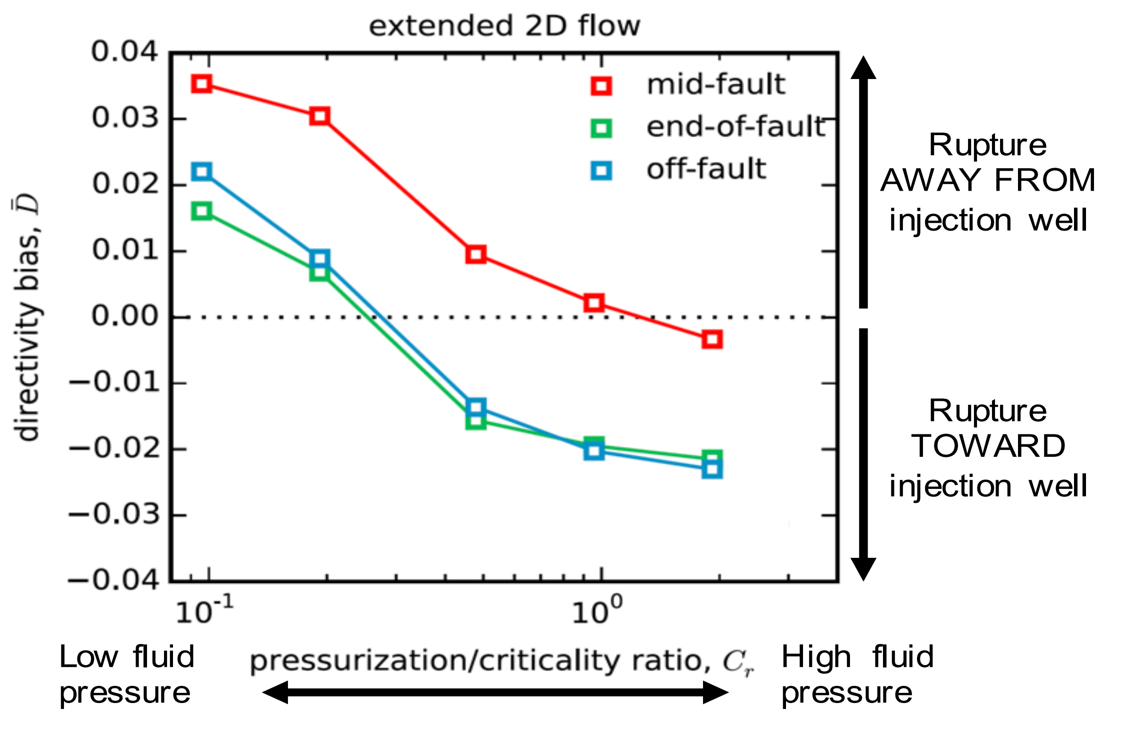


Rupture tends to propagate away from injection sites for uniform fault stress conditions.

II: Earthquake models with heterogeneous stress

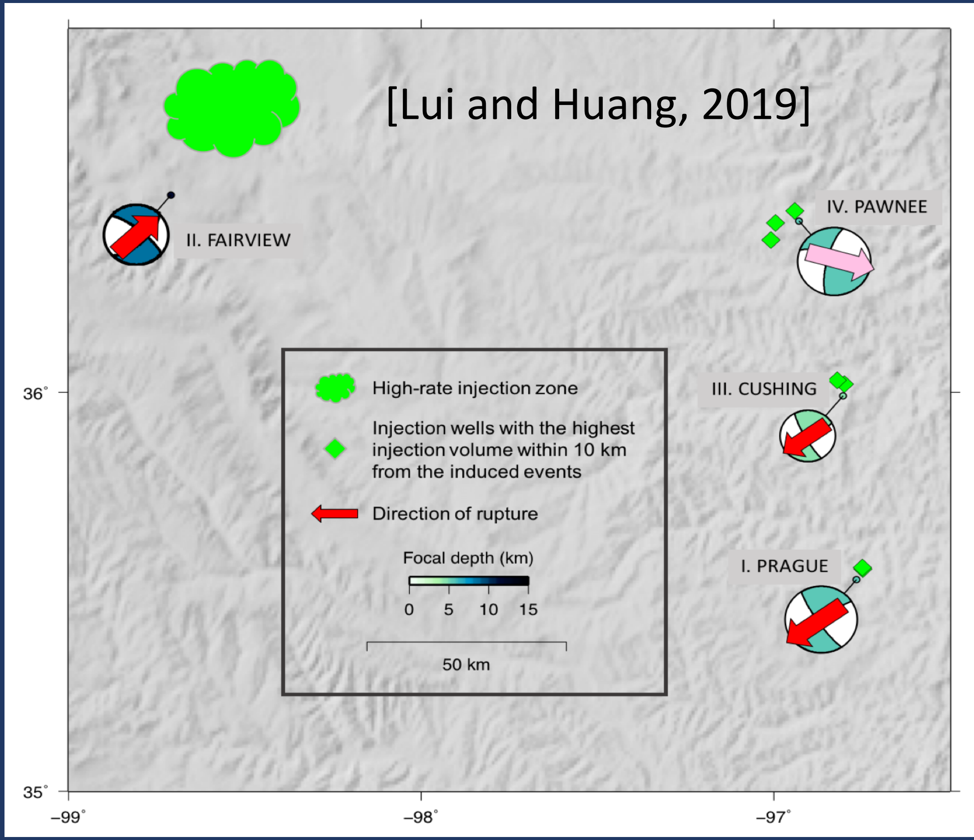


Off-fault injection favors rupture towards injection wells when pressure is high, but rupture away from wells when pressure is low.



[Dempsey and Suckale, 2016]

II: Rupture directivity of major Oklahoma earthquakes



Prague: 1800 m^3/month

Cushing: 8.9×10^4 m^3/month

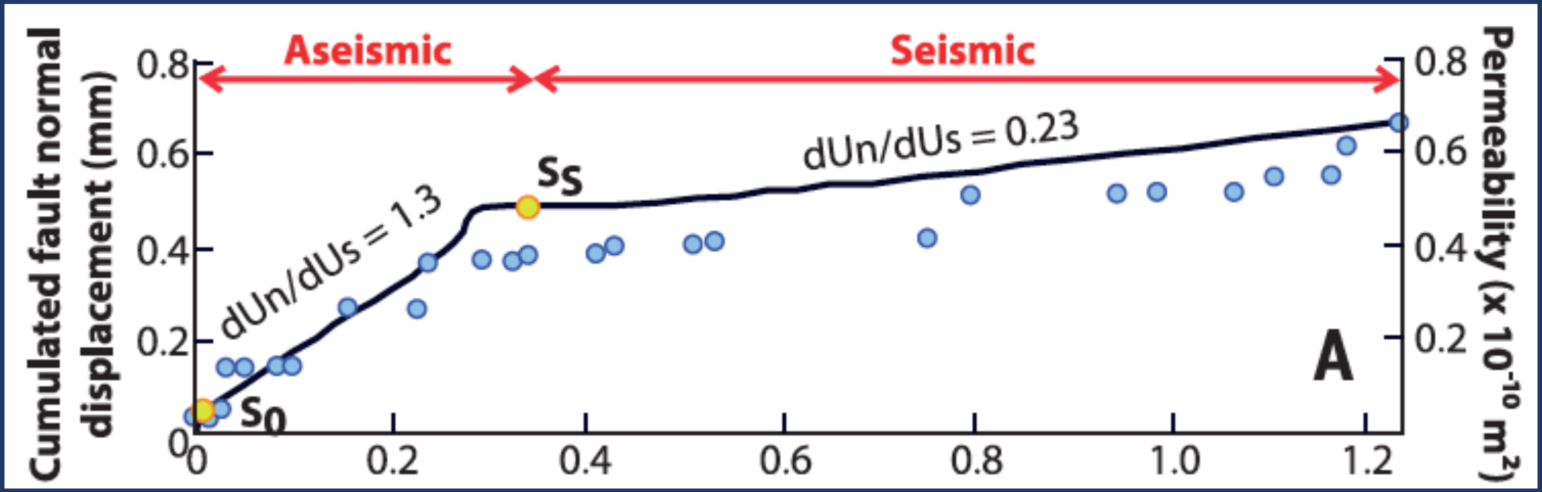
Pawnee: 5.1×10^4 m^3/month

Fairview: 2.2×10^6 m^3/month

with the nearest one exceeding 1×10^5 m^3/month

Larger high-frequency ground motions are expected towards the injection well when injection pressure is high.

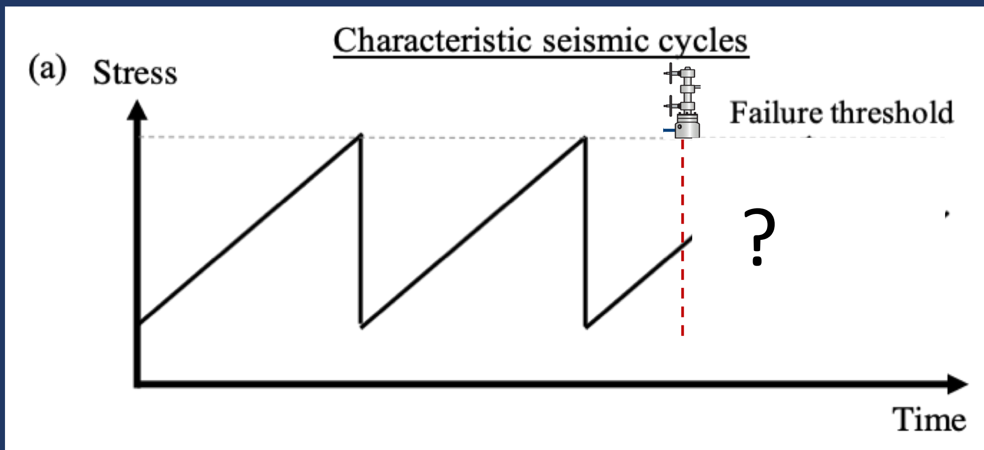
III: Are induced earthquakes always a direct response to fluid migration?

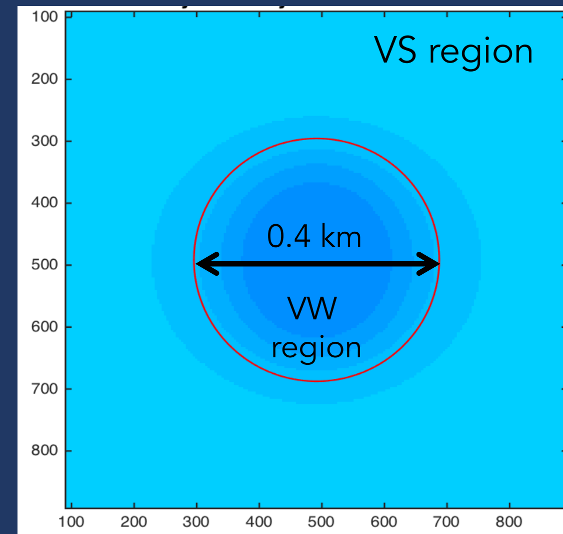


[Guglielmi et al., 2015]

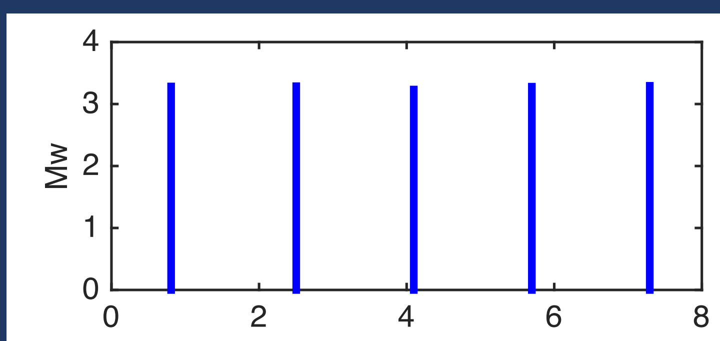
"In average, the energy budget shows that less than 0.1 % of the injection energy induces deformation, whose aseismic component is more than 99.9 %."

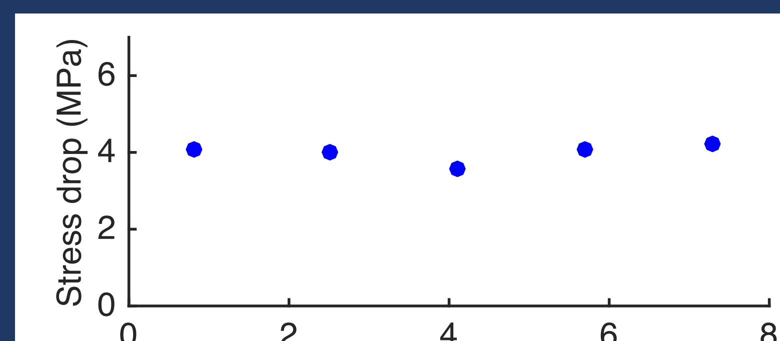
III: Earthquake cycle models with stress perturbation



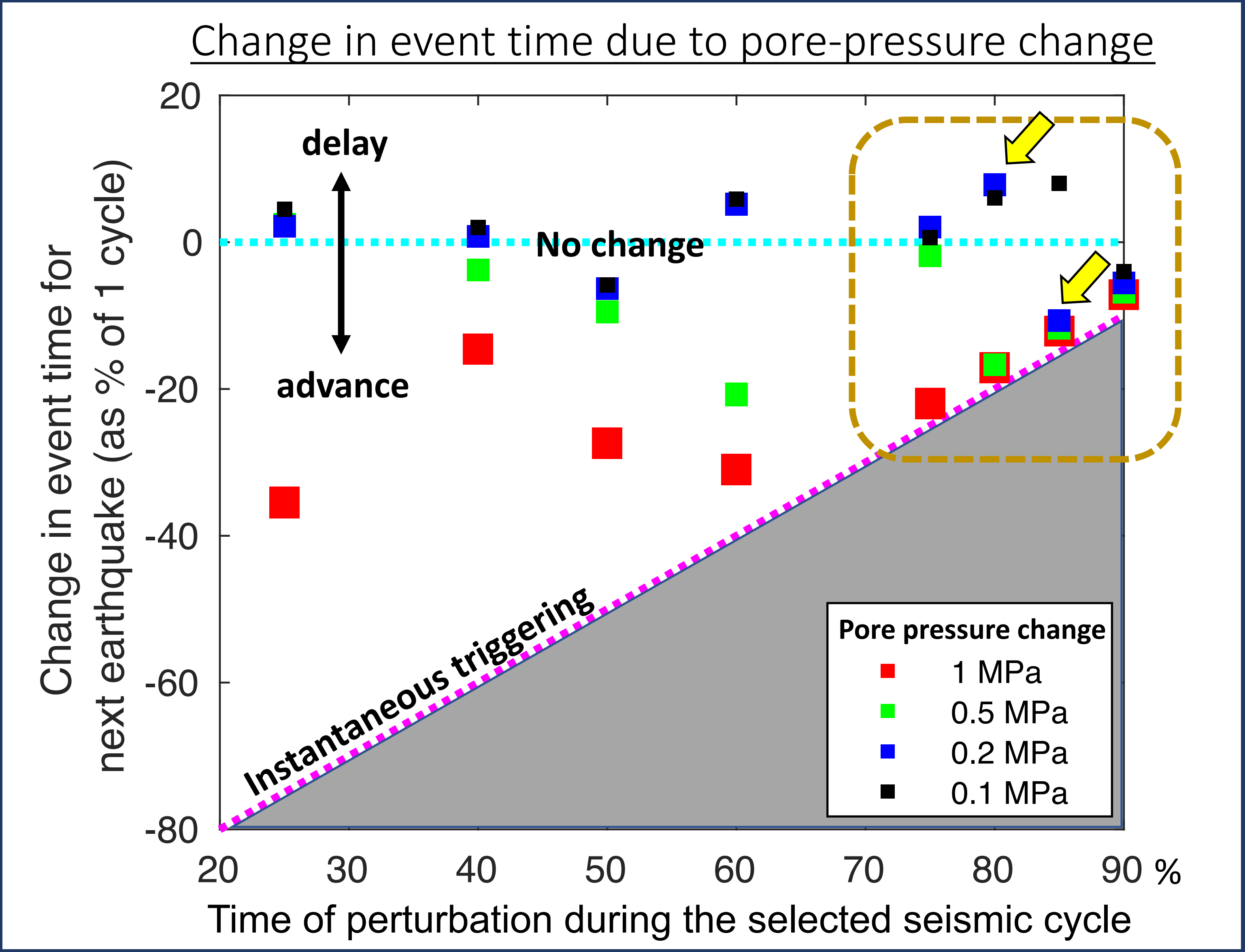


Unperturbed/Tectonic case:

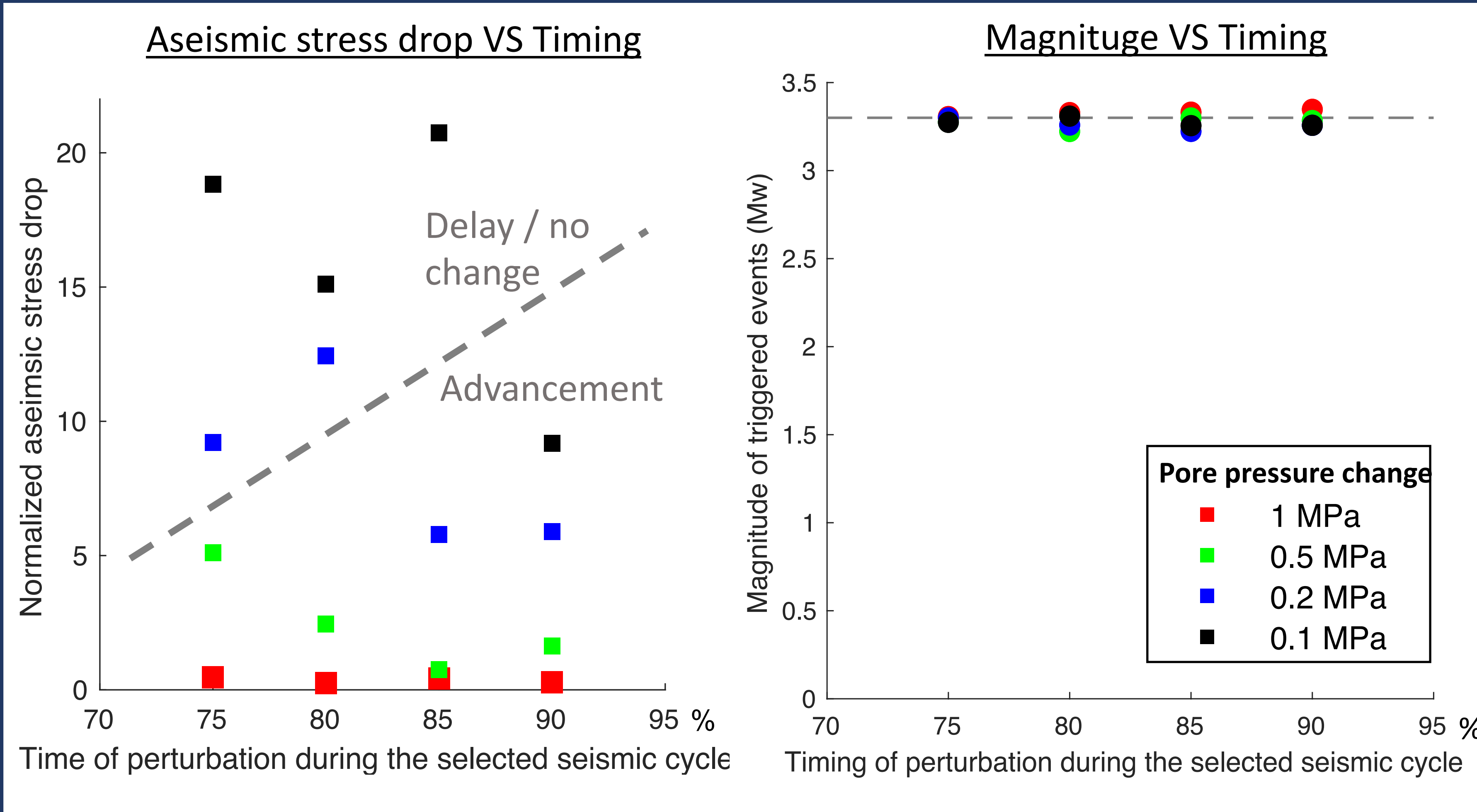


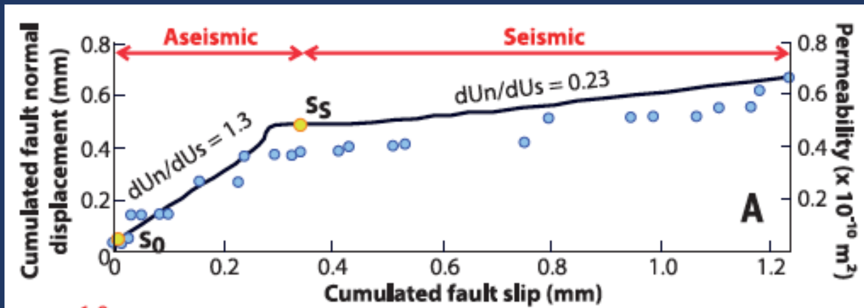


III: Earthquake cycle models with stress perturbation

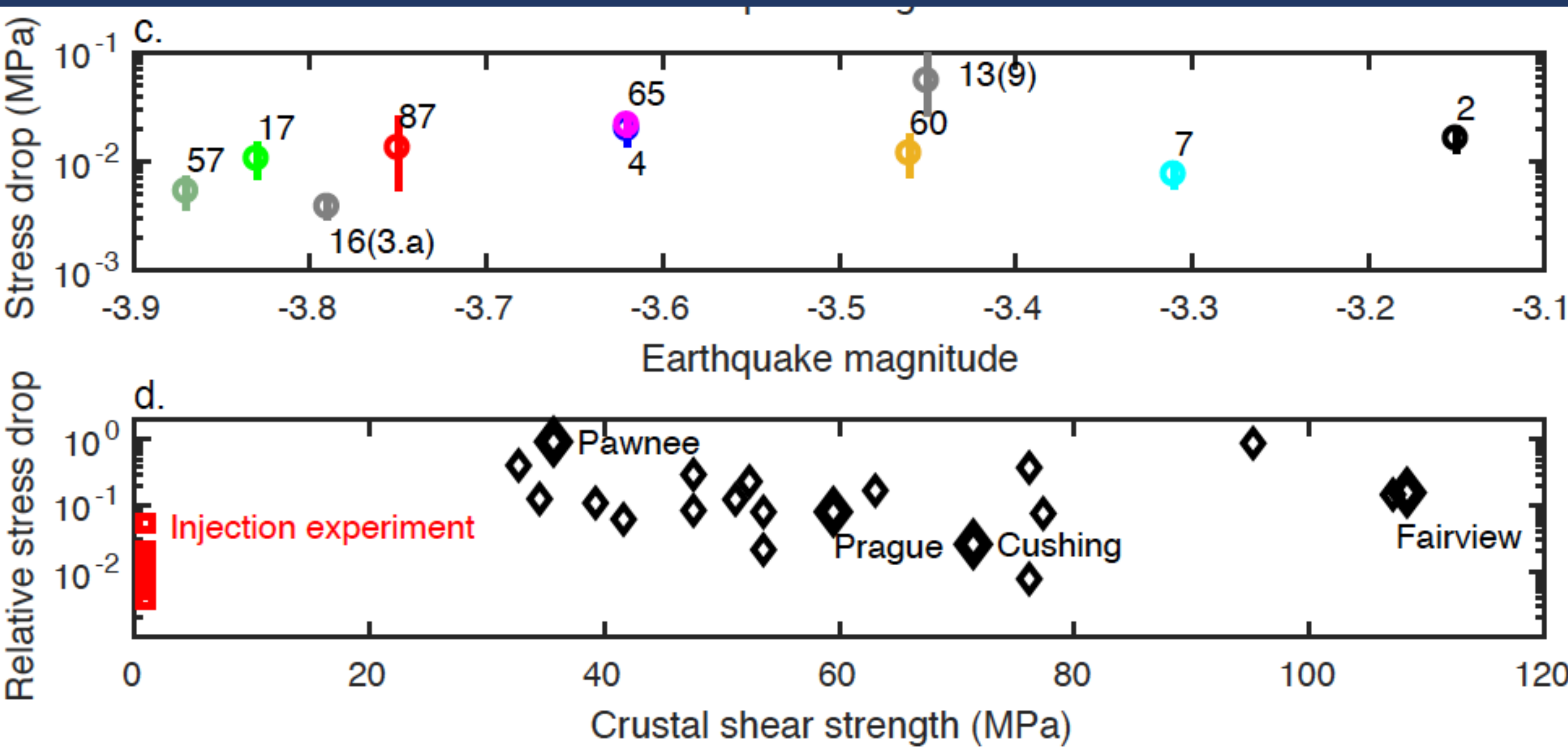


III: Aseismic stress release vs. time of perturbation





Could we tell large aseismic slip from earthquake source parameters?

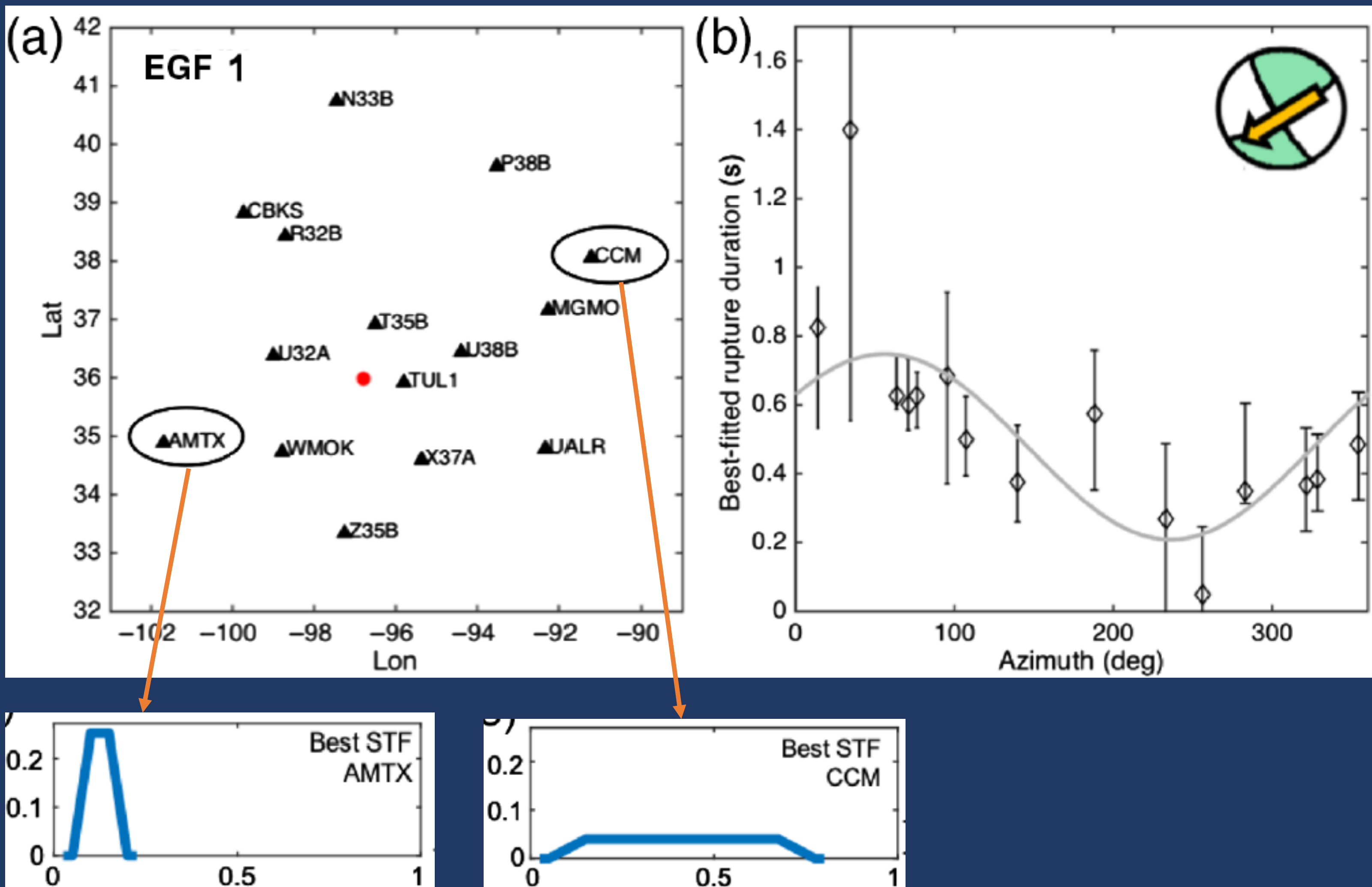


[Huang, DeBarros, and Cappa, *in review*]

Overview

- We find moderate induced and tectonic earthquakes in the central US have similar stress drops, indicating a small pore pressure change on faults.
- The rupture directivity patterns of four major Oklahoma earthquakes are related to the injection pressure of nearby injection wells. Rupture directivity can cause more high-frequency ground motions towards injection wells when the injection pressure is high.
- Small stress perturbation related to fluid injection can cause aseismic slip that can either advance or delay the next induced earthquakes.

II: The 2016 M_w 5.0 Cushing earthquake

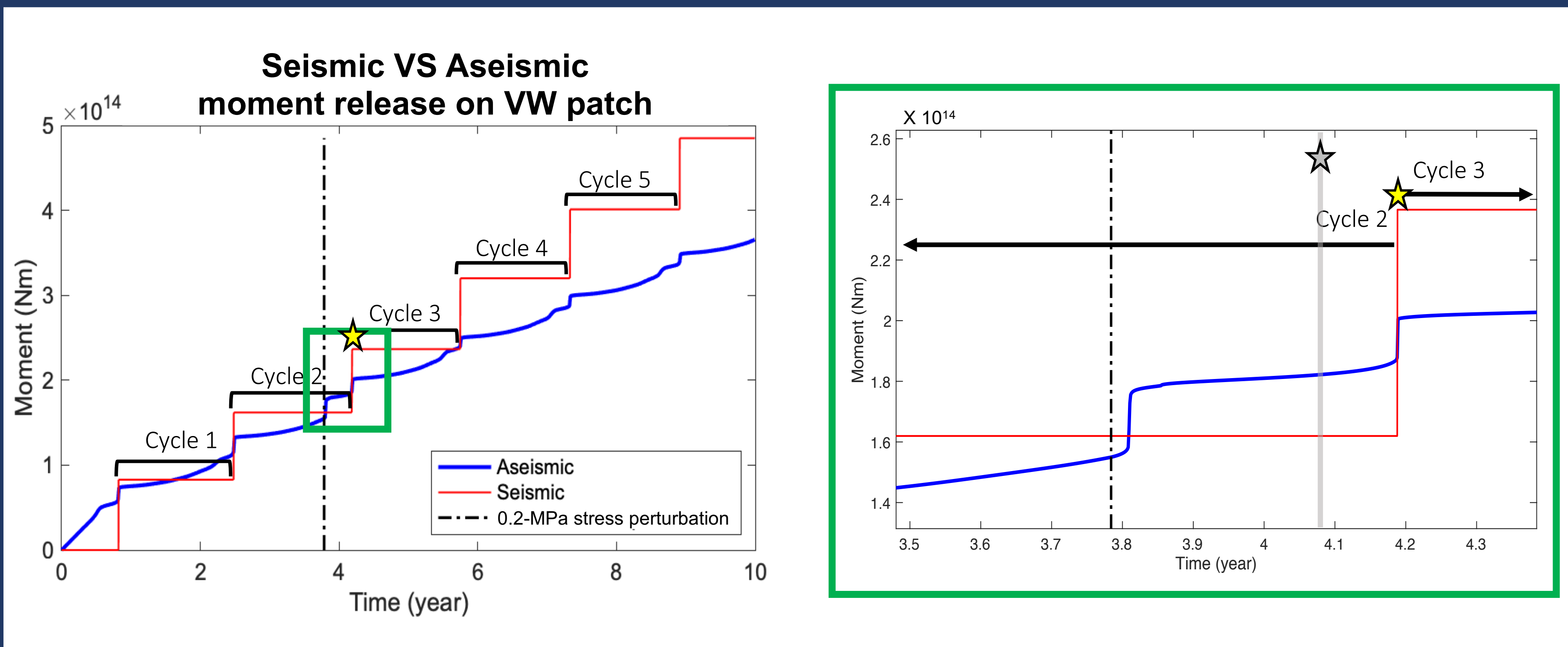


[Lui and Huang, 2019]

III: What happened when earthquakes are delayed?

0.2 MPa pore-pressure change at **80%** of the cycle:

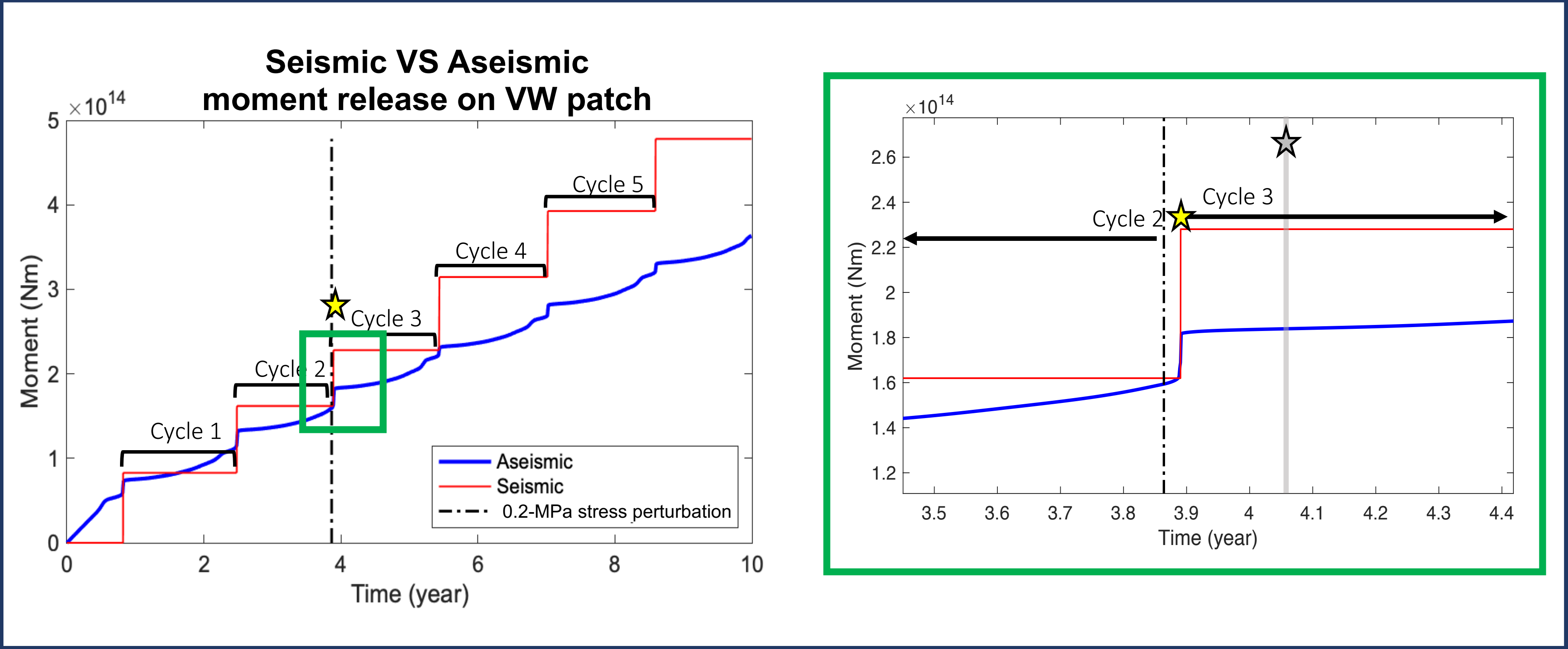
Substantial aseismic moment is released right after the perturbation; the fault returned to stable loading; the “triggered” earthquake is delayed.



III: Aseismic slip also occurred when earthquakes are advanced.

0.2 MPa pore-pressure change at **85%** of the cycle:

Aseismic moment is also released right after the perturbation, which triggered an earthquake almost instantaneously.

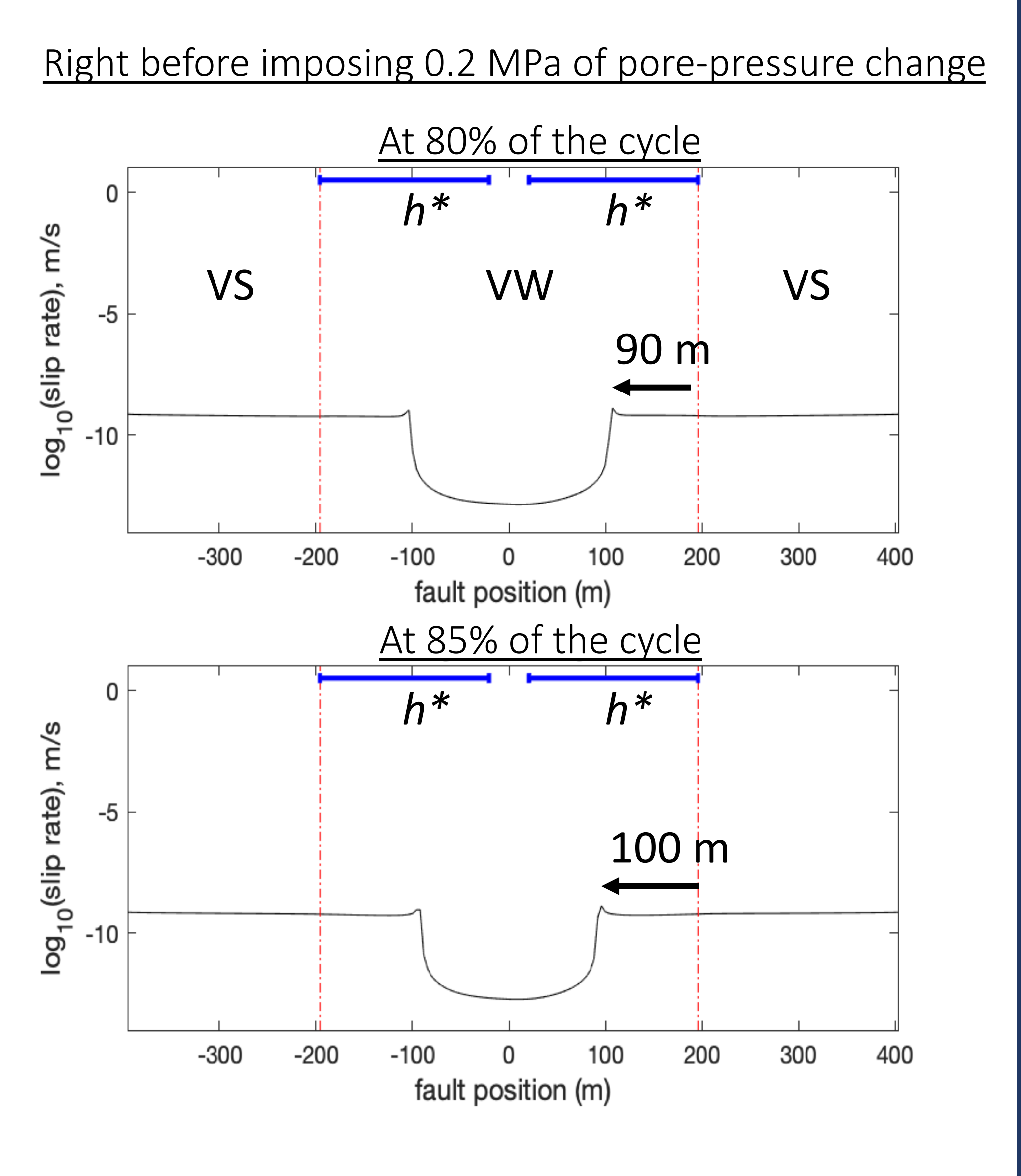


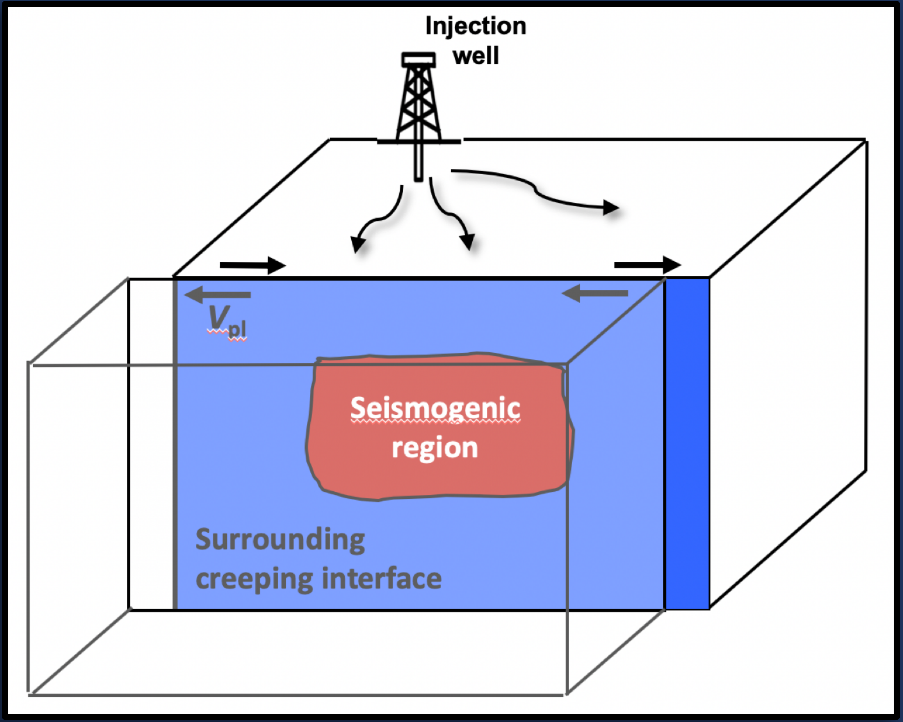
Critical nucleation size h*

Slip only accelerates into an earthquake if the width of the region creeping within the seismogenic (VW) zone becomes comparable to the nucleation size h^*.

State of stress on the fault

The state of stress on the fault at the moment of perturbation controls the extent of aseismic response.




Injection well
V_{pl}
Seismogenic region
Surrounding creeping interface