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

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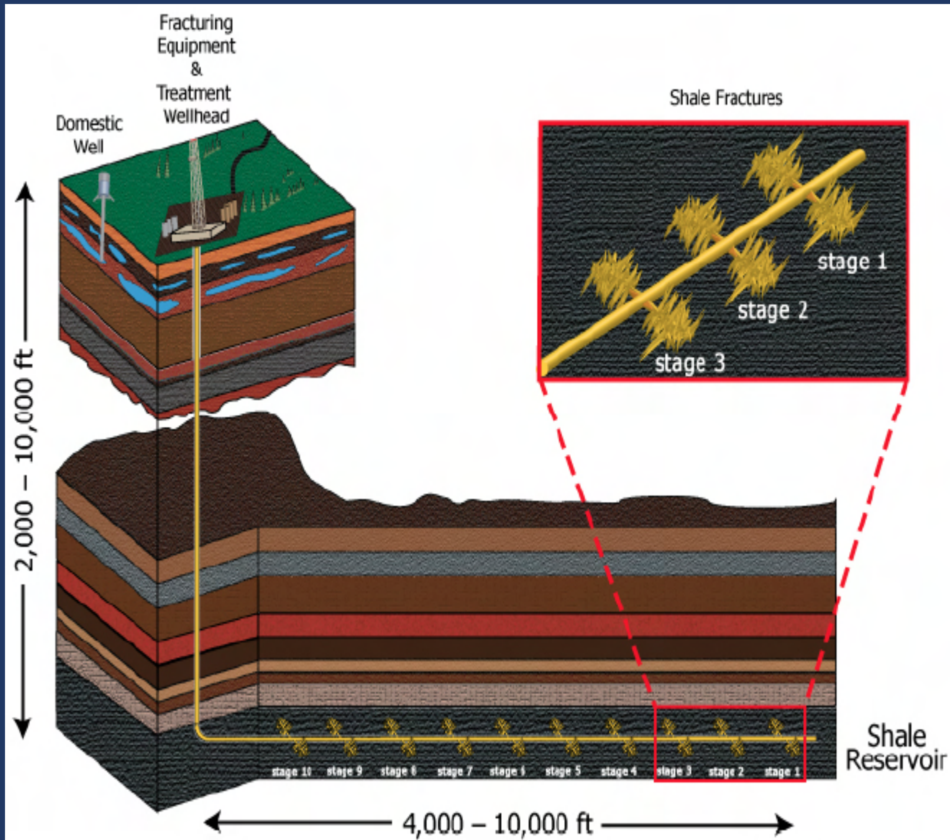
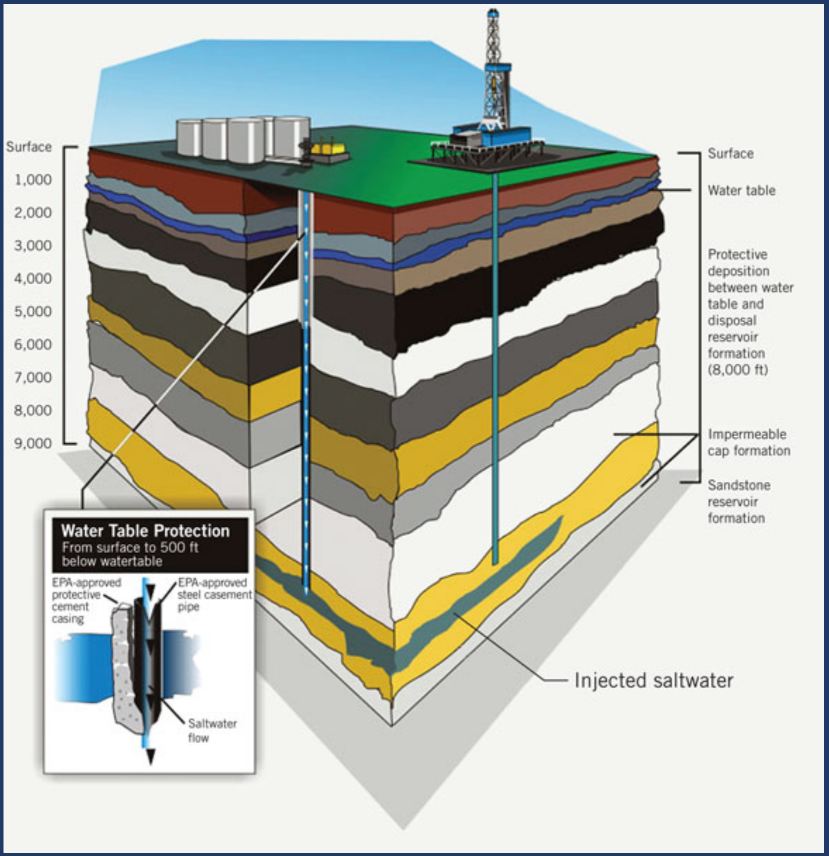
Injection-induced earthquakes: Earthquakes induced by fluid injection related to energy technologies including oil and gas production, geothermal energy, carbon storage, mining activity and reservoir impoundment.

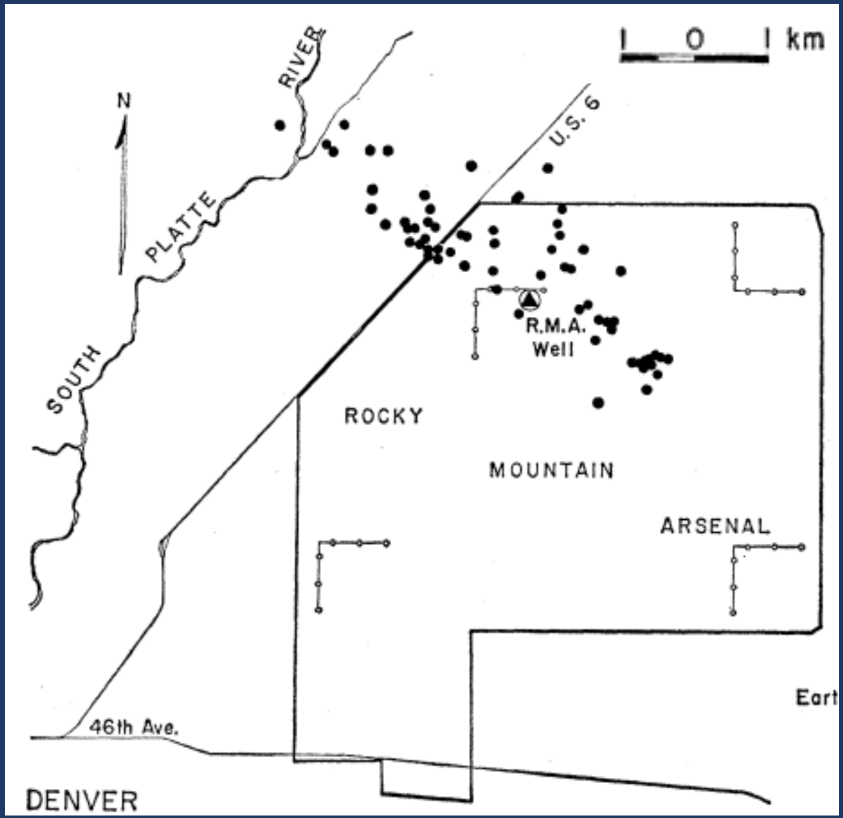
Hydraulic Fracturing

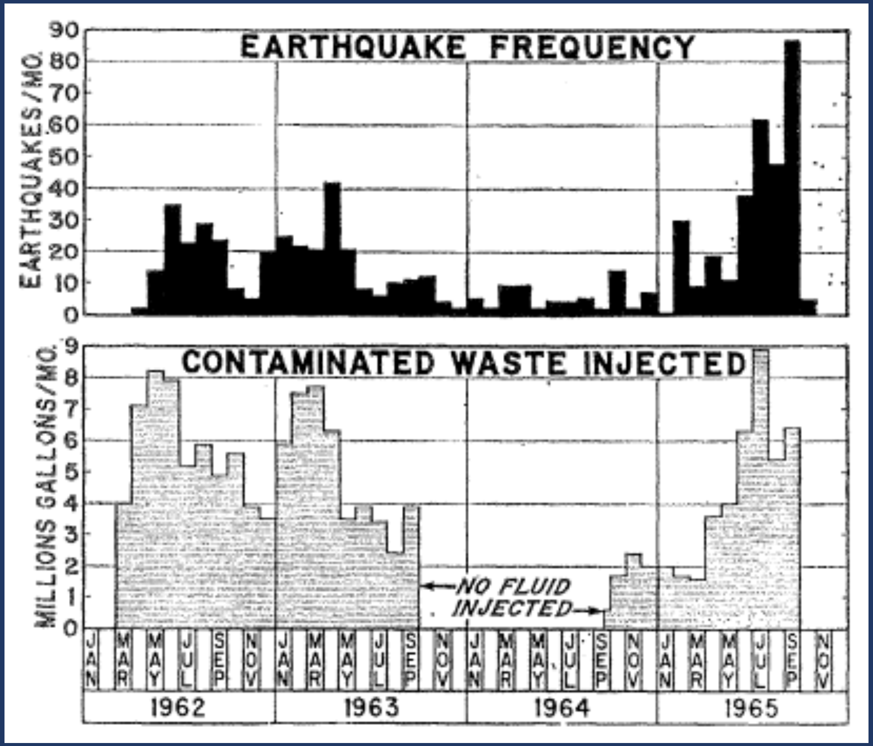


Deep Injection Wells



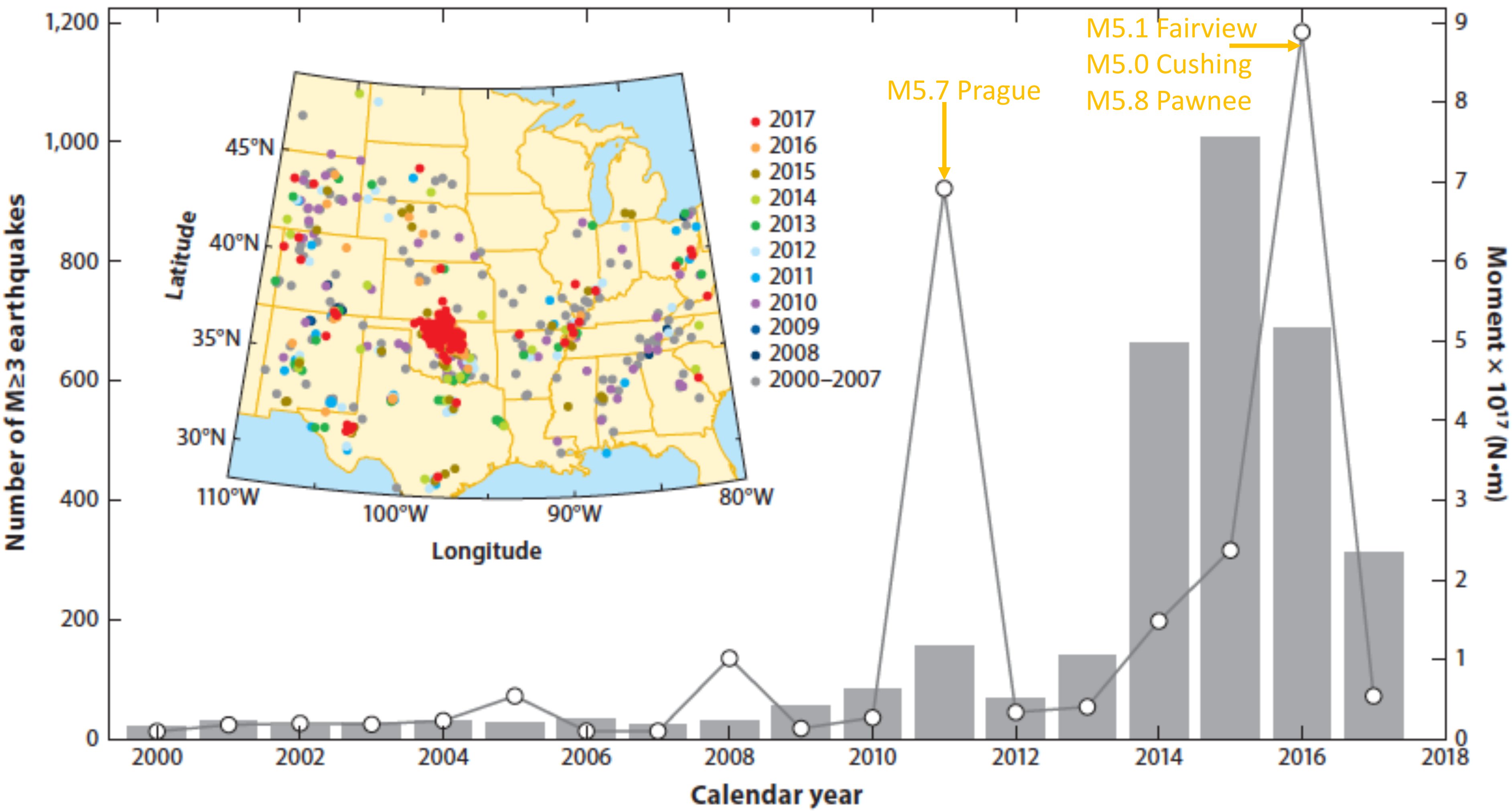
The famous example of the 1960s Denver earthquakes



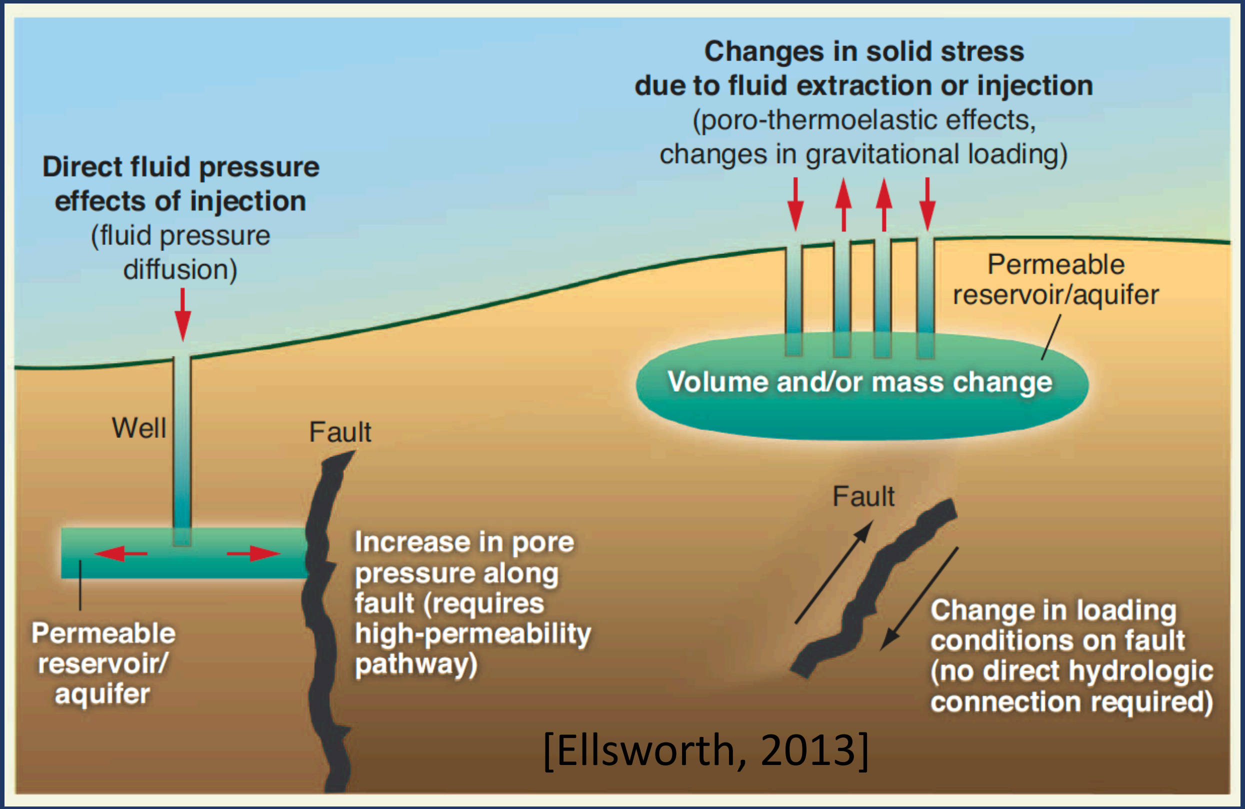


[Healy et al., 1968]

M>3 earthquakes in the central US (2000-2017)



[Keranen and Weingarten, 2018]



- 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 earthquake characteristics and ground motions?

- Are earthquakes always a direct response of fluid injection?

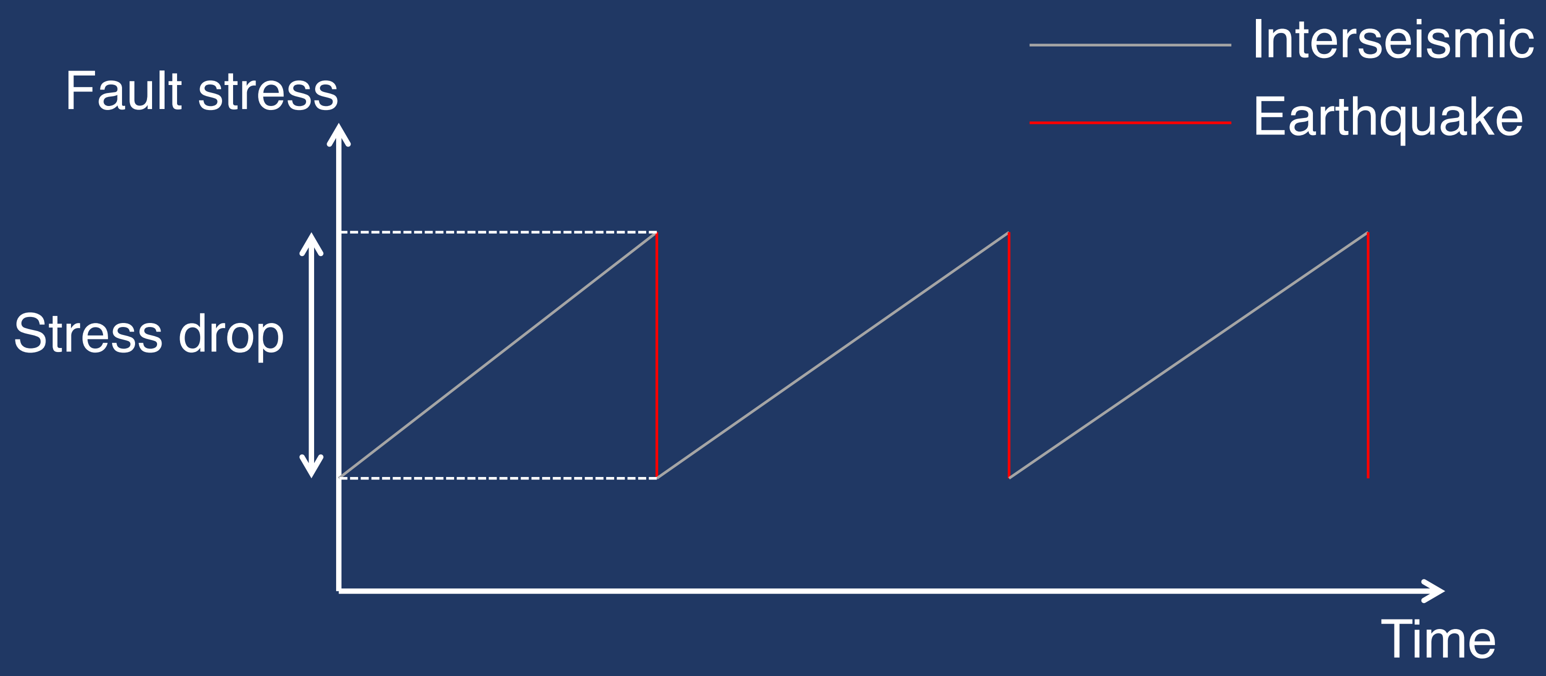
Overview

- Stress drop analysis of induced and tectonic earthquakes
- Magnitude-frequency distribution and rupture directivity analysis of induced earthquakes
- Simulations of earthquakes cycles on faults with normal and shear stress perturbations

$\Updownarrow$

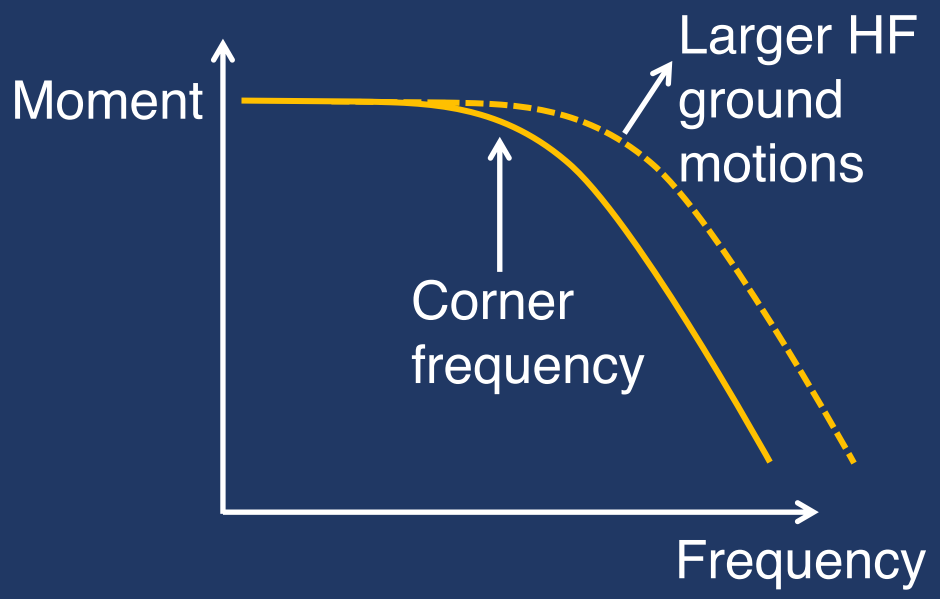
- How large is the change of fluid pressure or poroelastic stress? Will it cause a significant change of earthquake stress release?
- Can fluid migration leave a signature in earthquake characteristics and ground motions?
- Are induced earthquakes always a direct response of fluid injection?

I: Stress drop is how much fault stress is released during an earthquake.



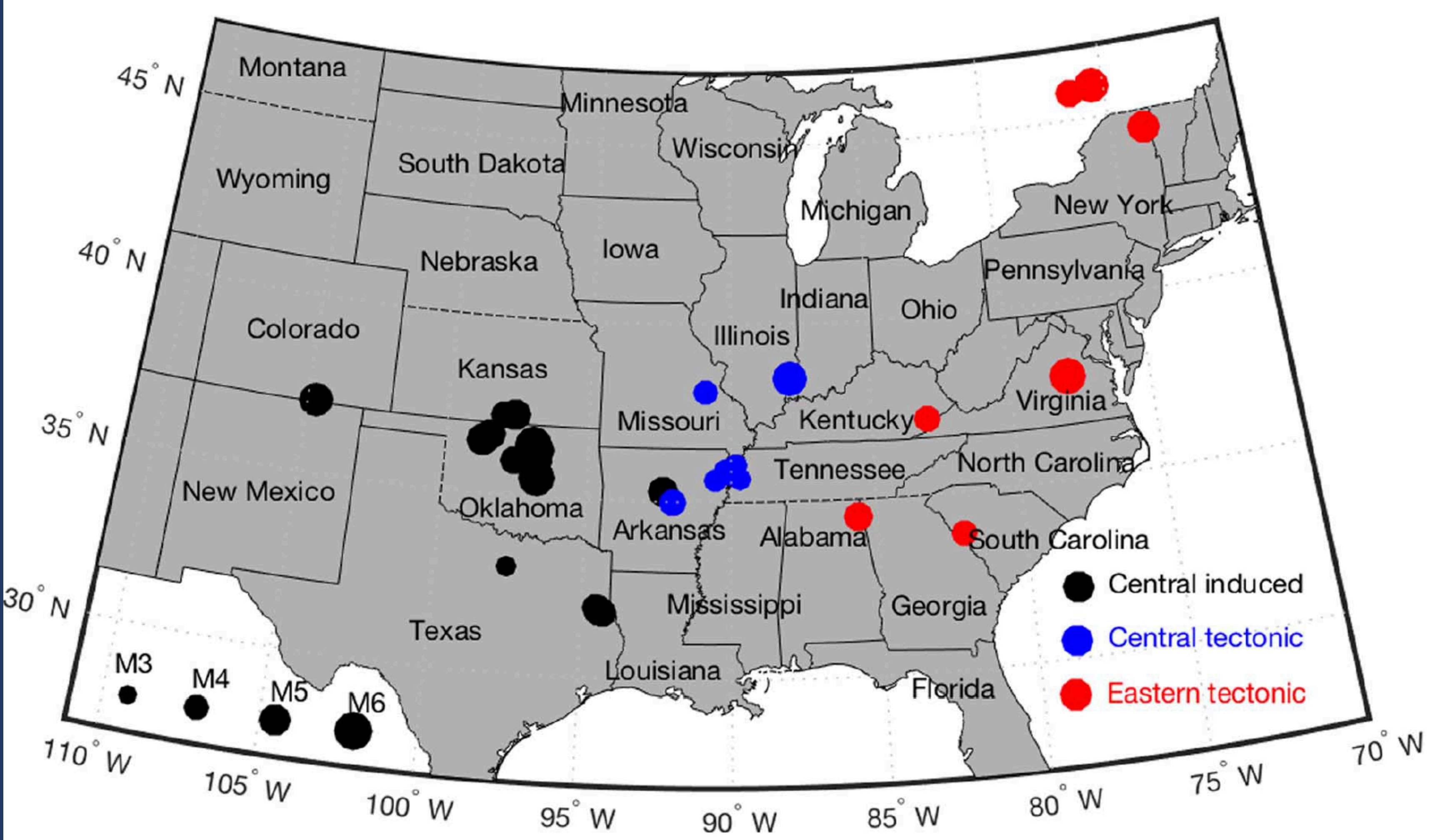
I: Stress drop can be measured from the far-field displacement spectrum.

Source displacement spectrum recorded in far field



Large stress drops lead to large corner frequency and HF ground motions.

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



[Huang, Ellsworth and Beroza, 2017]

I: Source effect is isolated from path effect using the spectral ratio approach with eGfs

$$\frac{u_1(f)}{u_2(f)} = \frac{M_{01}}{M_{02}}\left(\frac{1+(\frac{f}{f_{c2}})^2}{1+(\frac{f}{f_{c1}})^2}\right)$$

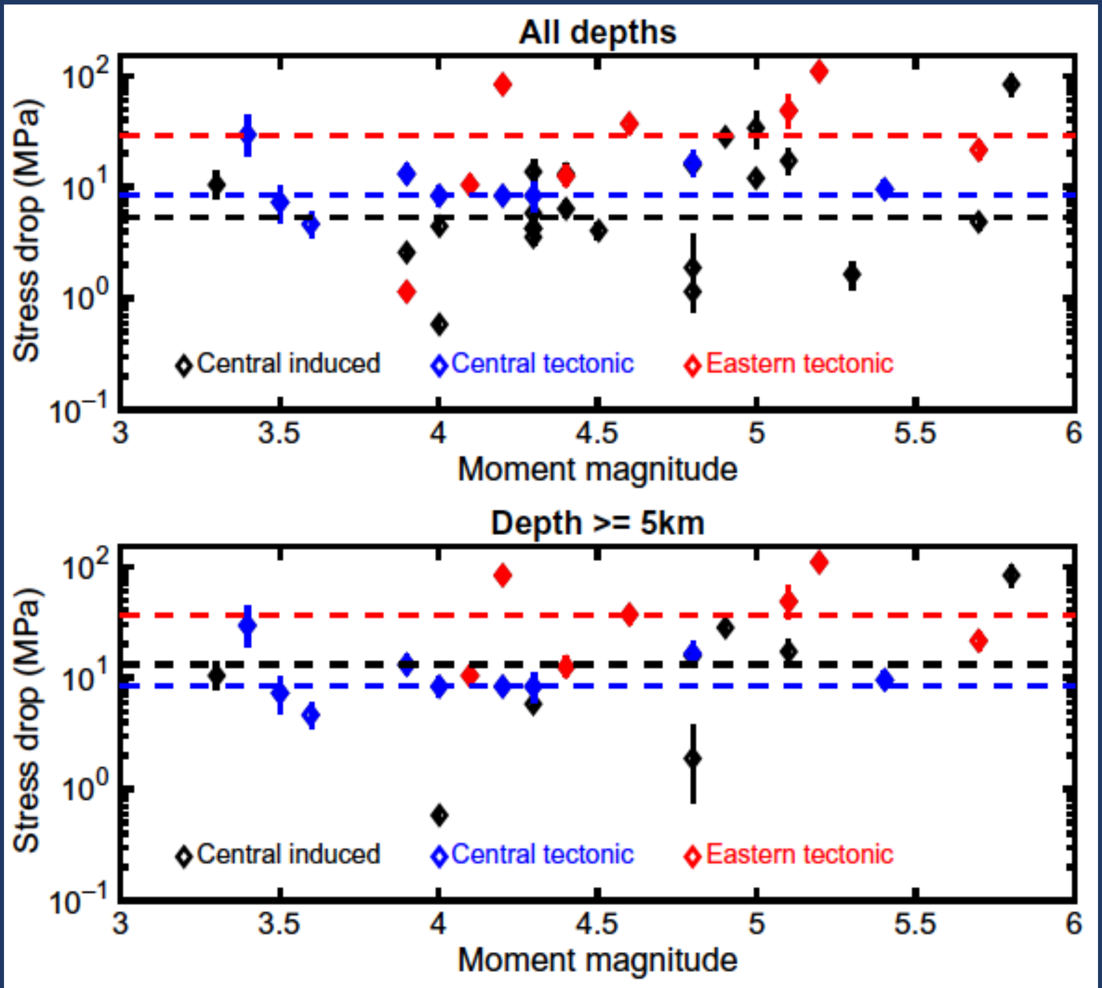
Spectral ratio

Moment ratio

Corner frequency of the eGf

Corner frequency of master event

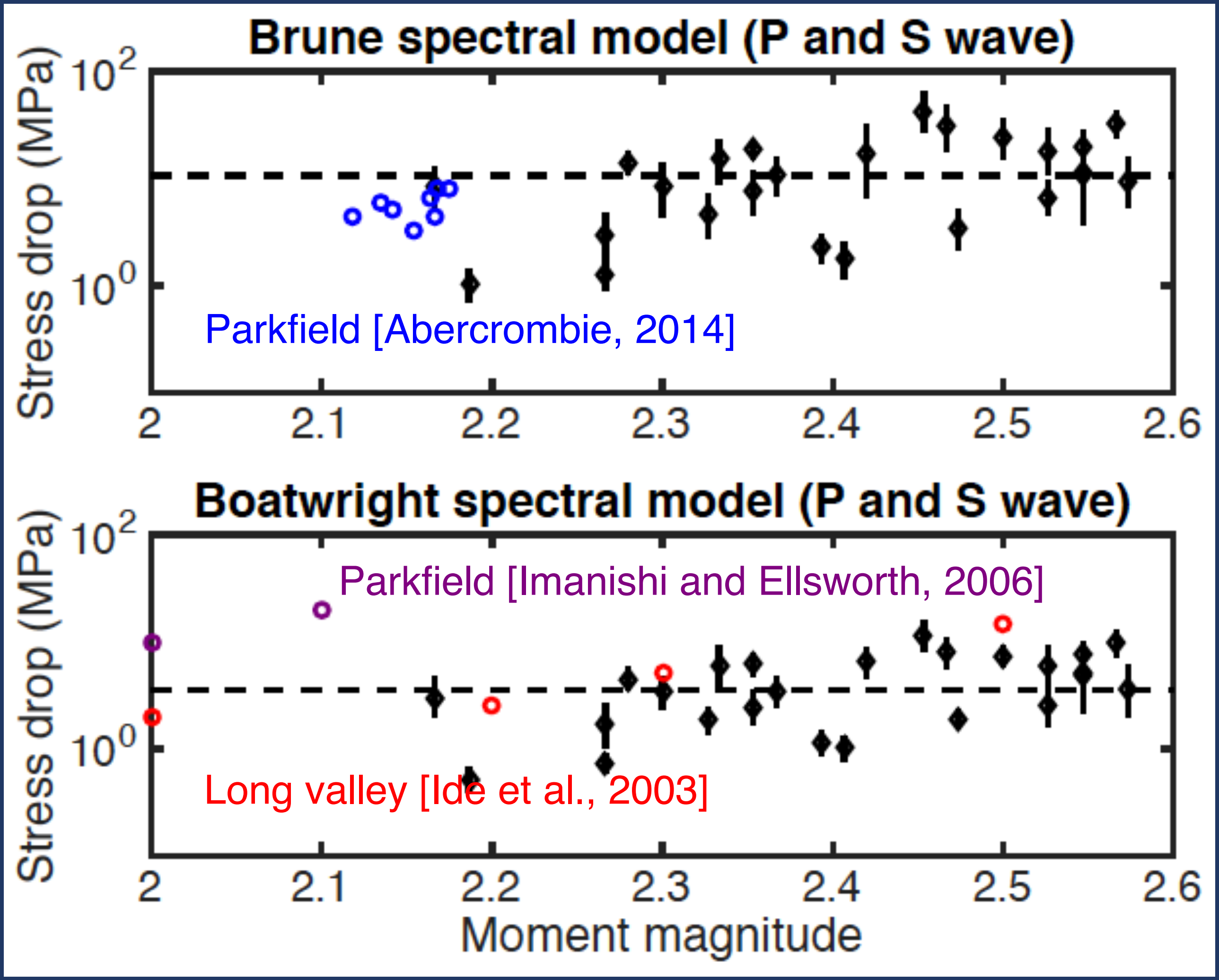
I: Stress drop results



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

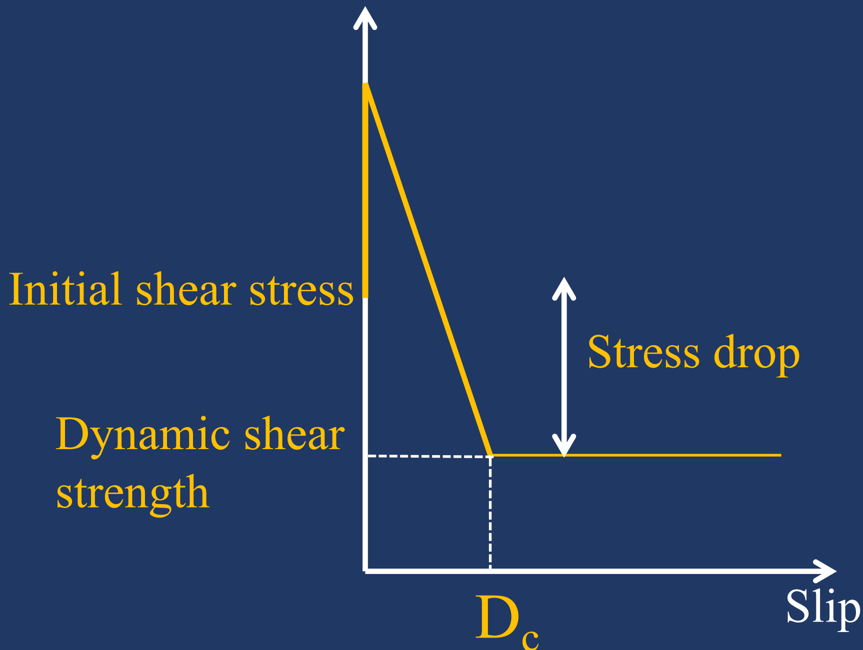
[Huang, Ellsworth and Beroza, 2017]

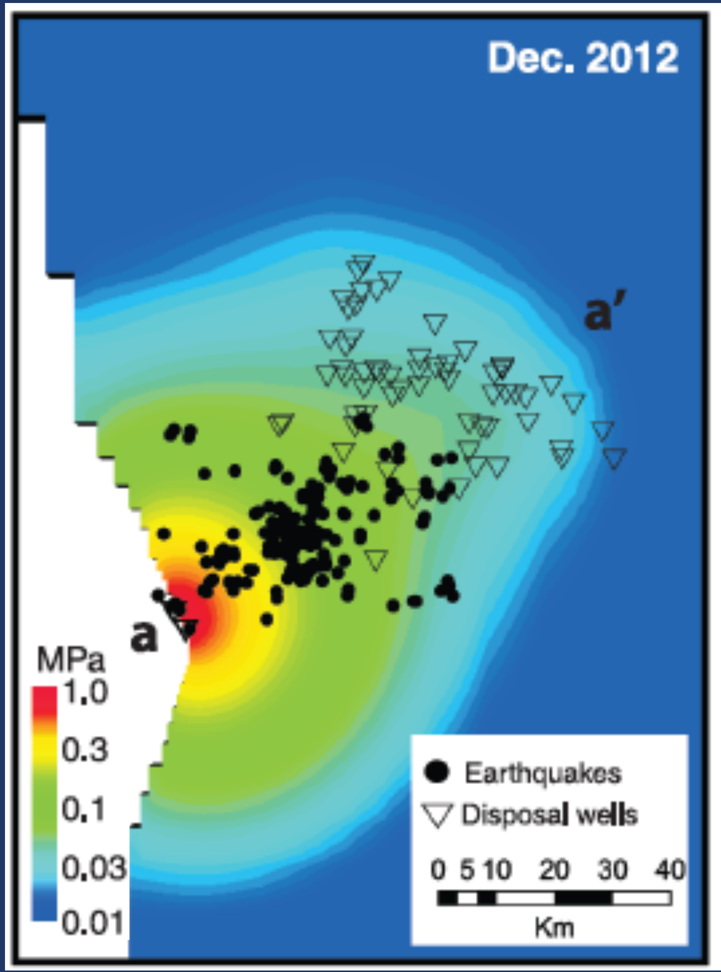
I: Stress drop results



[Huang, Beroza, and Ellsworth, 2016]

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



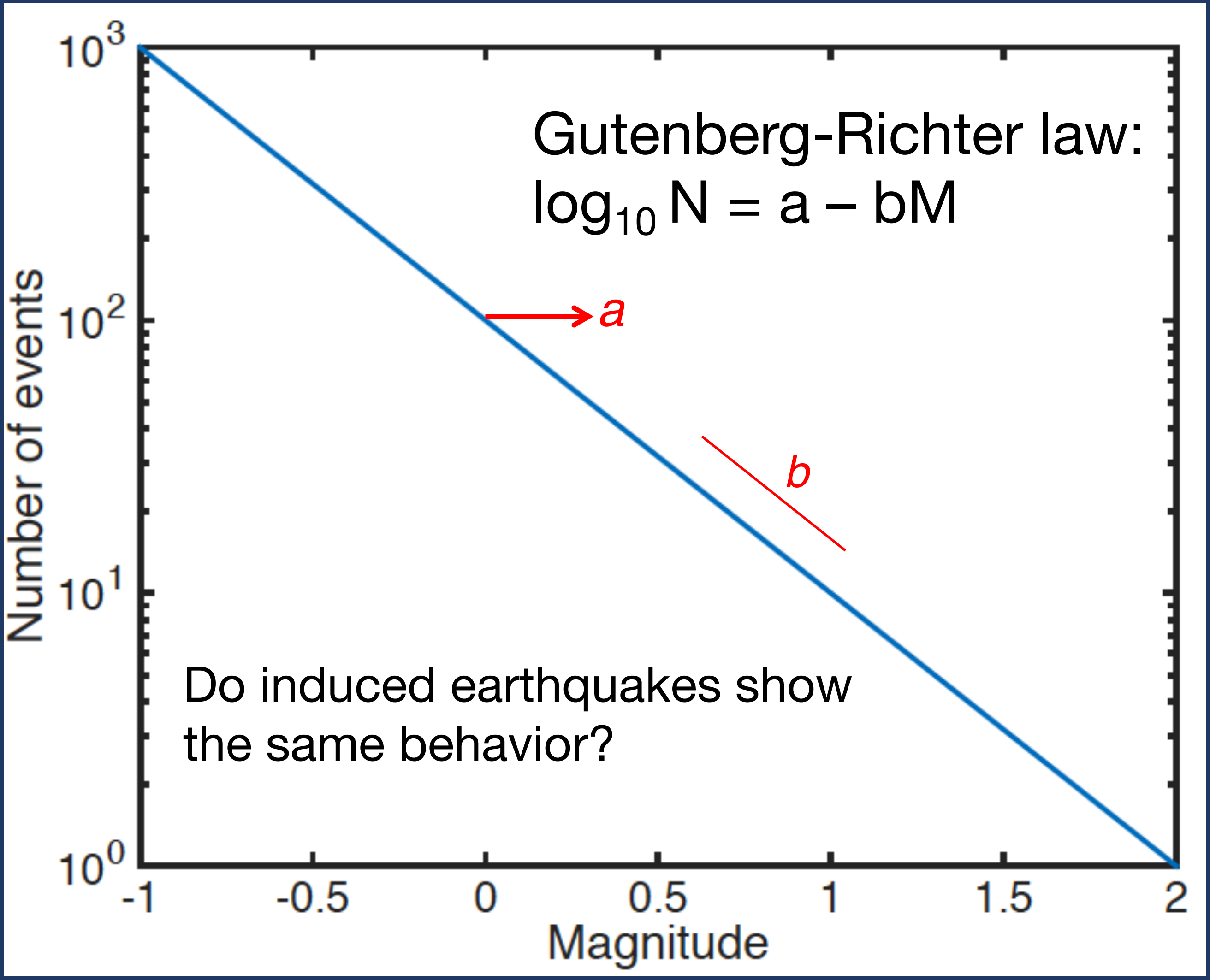


[Keranen, et al., 2014]

- The difference between stress drops of induced and tectonic earthquakes is pore pressure x dynamic friction coefficient.

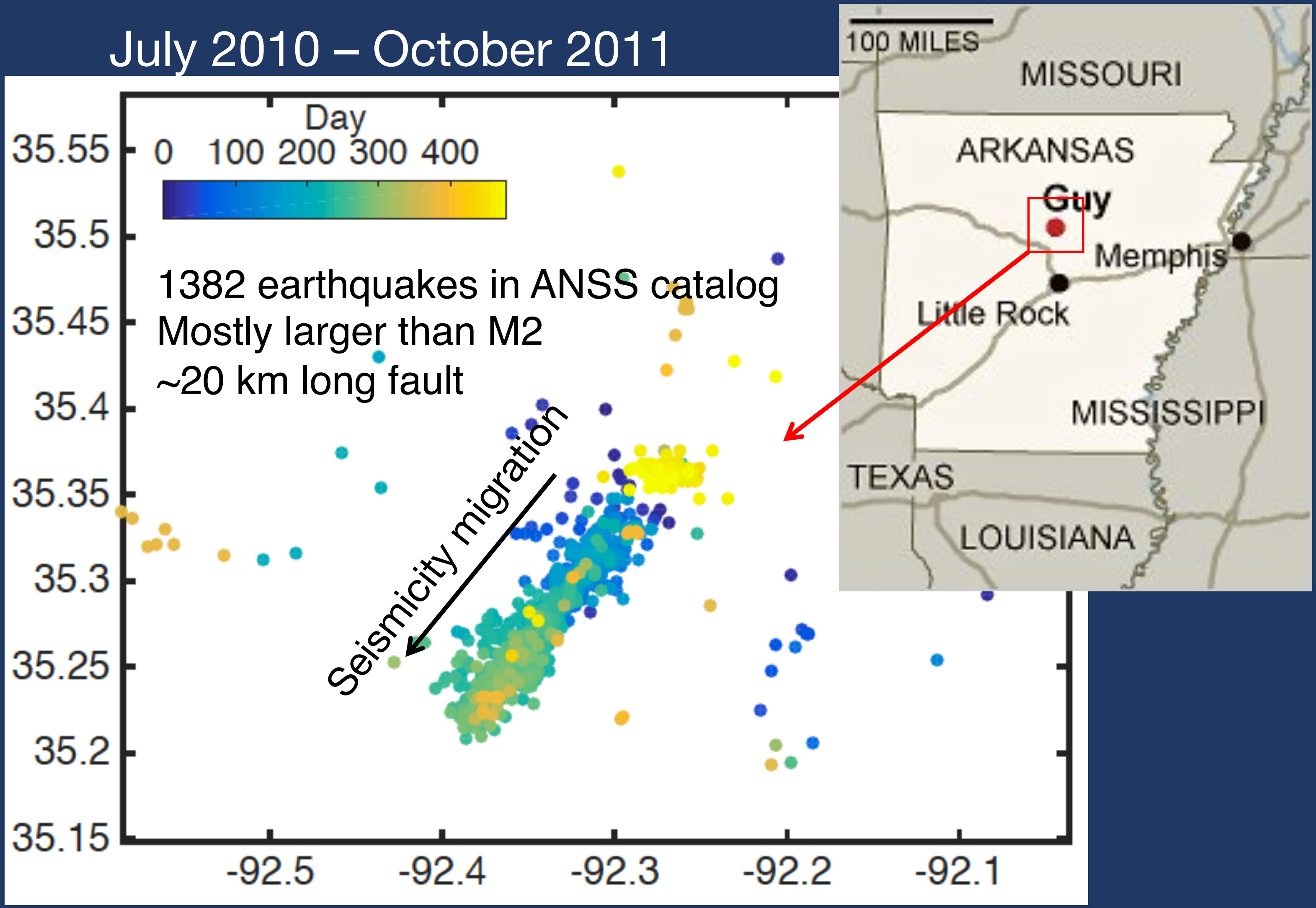
- Stress drop is mainly controlled by tectonic stress.

II: Can fluid migration leave a signature in earthquake characteristics?



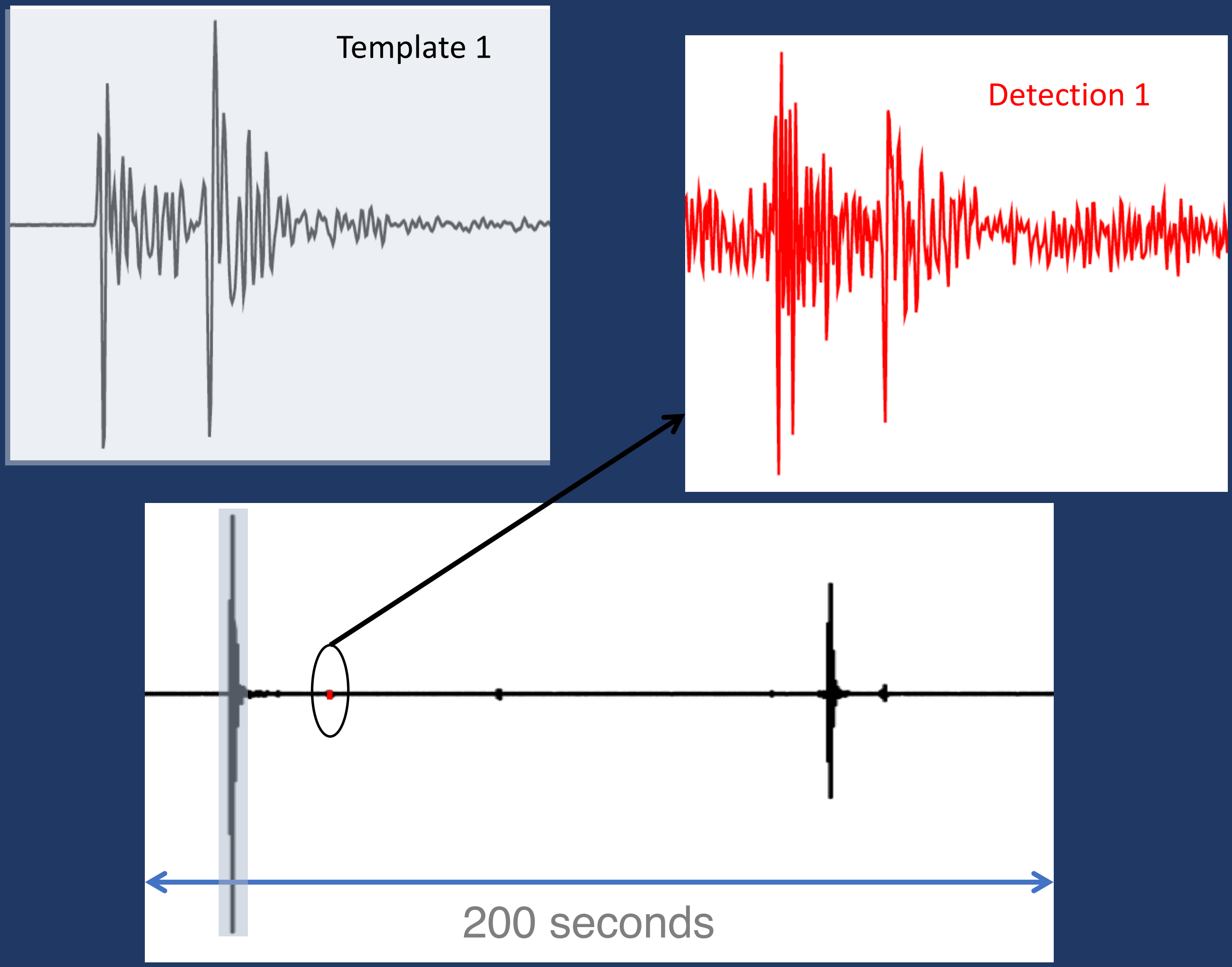
II: We apply template matching to the Guy-Greenbrier sequence

July 2010 – October 2011



[Huang and Beroza, 2015]

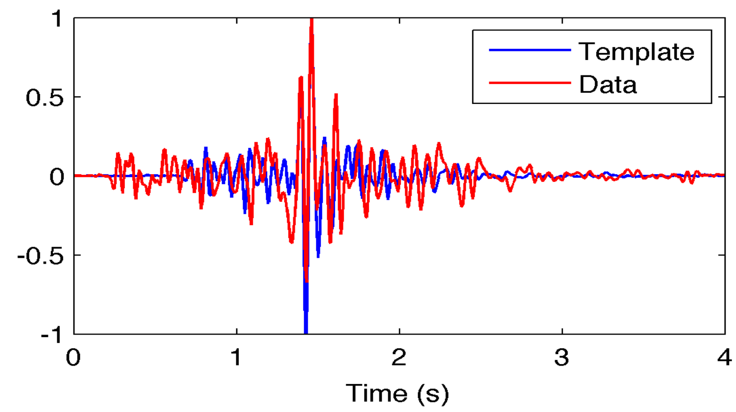
II: We apply template matching to the Guy-Greenbrier sequence

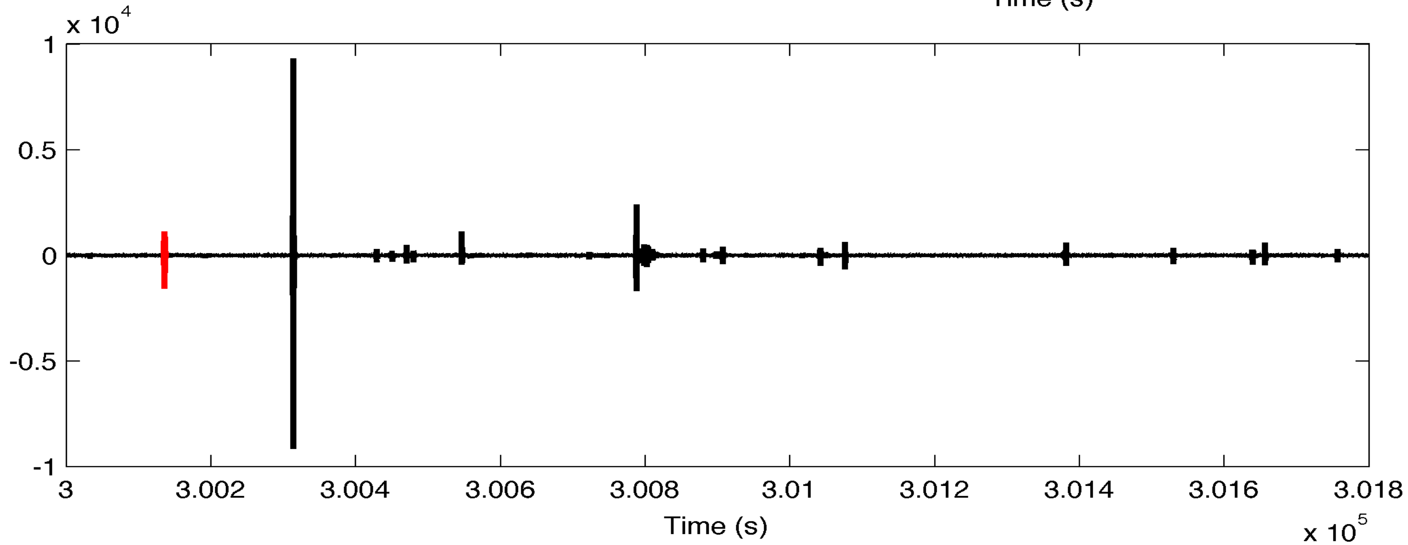


II: We apply template matching to the Guy-Greenbrier sequence

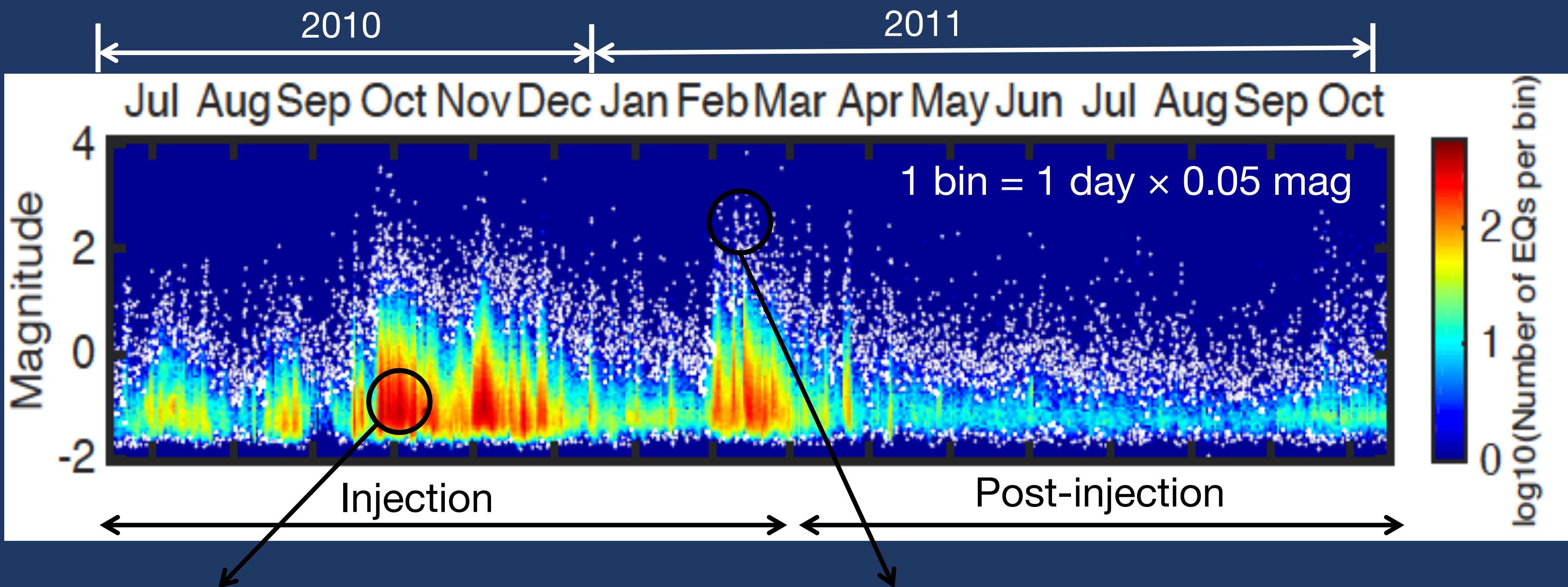
50 earthquakes are detected.

Most of them are small and have low signal to noise ratios.





II: The new catalog includes ~ 460,000 quakes



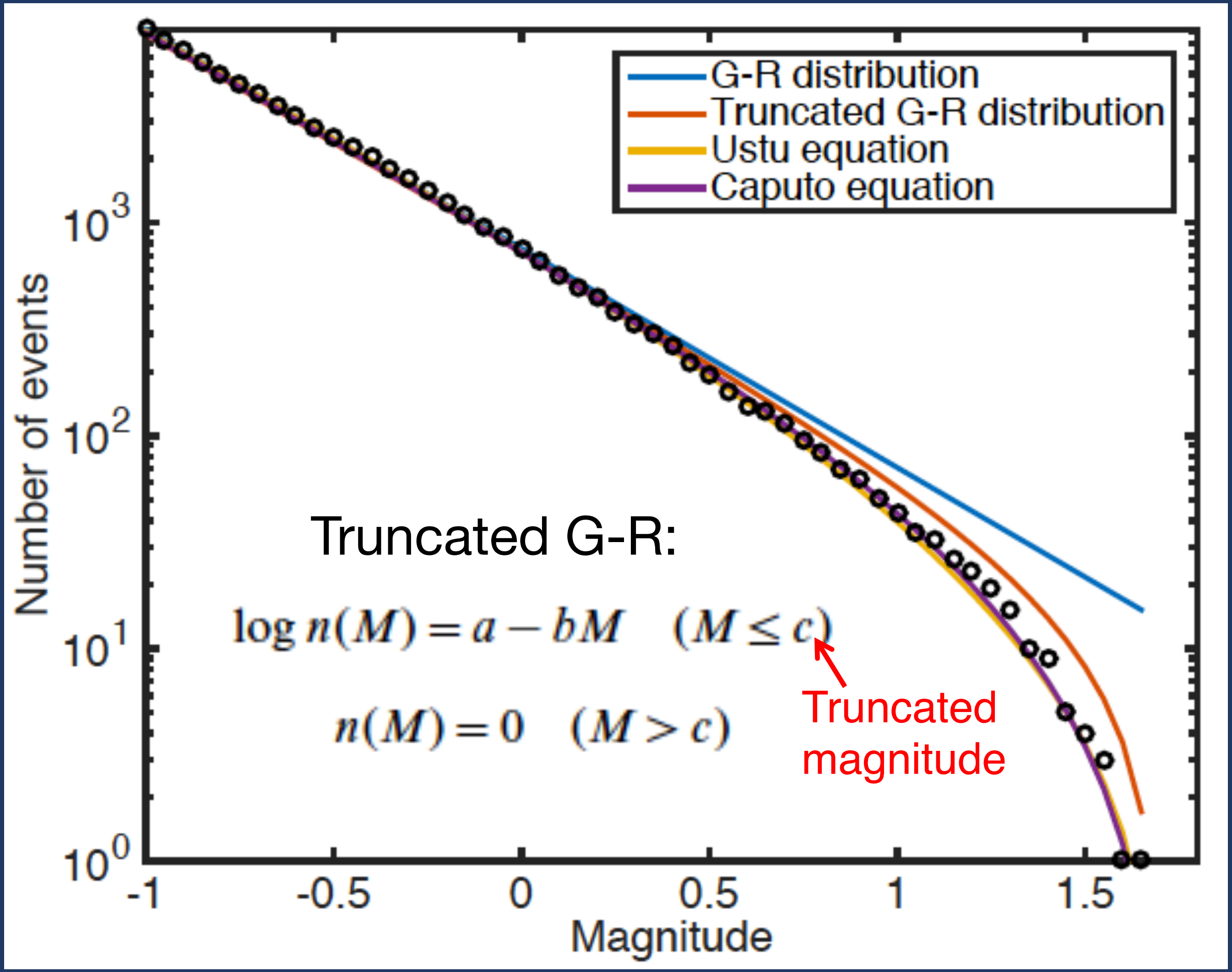
Red means >100 quakes/bin

White dot means 1 quake/bin

[Huang and Beroza, 2015]

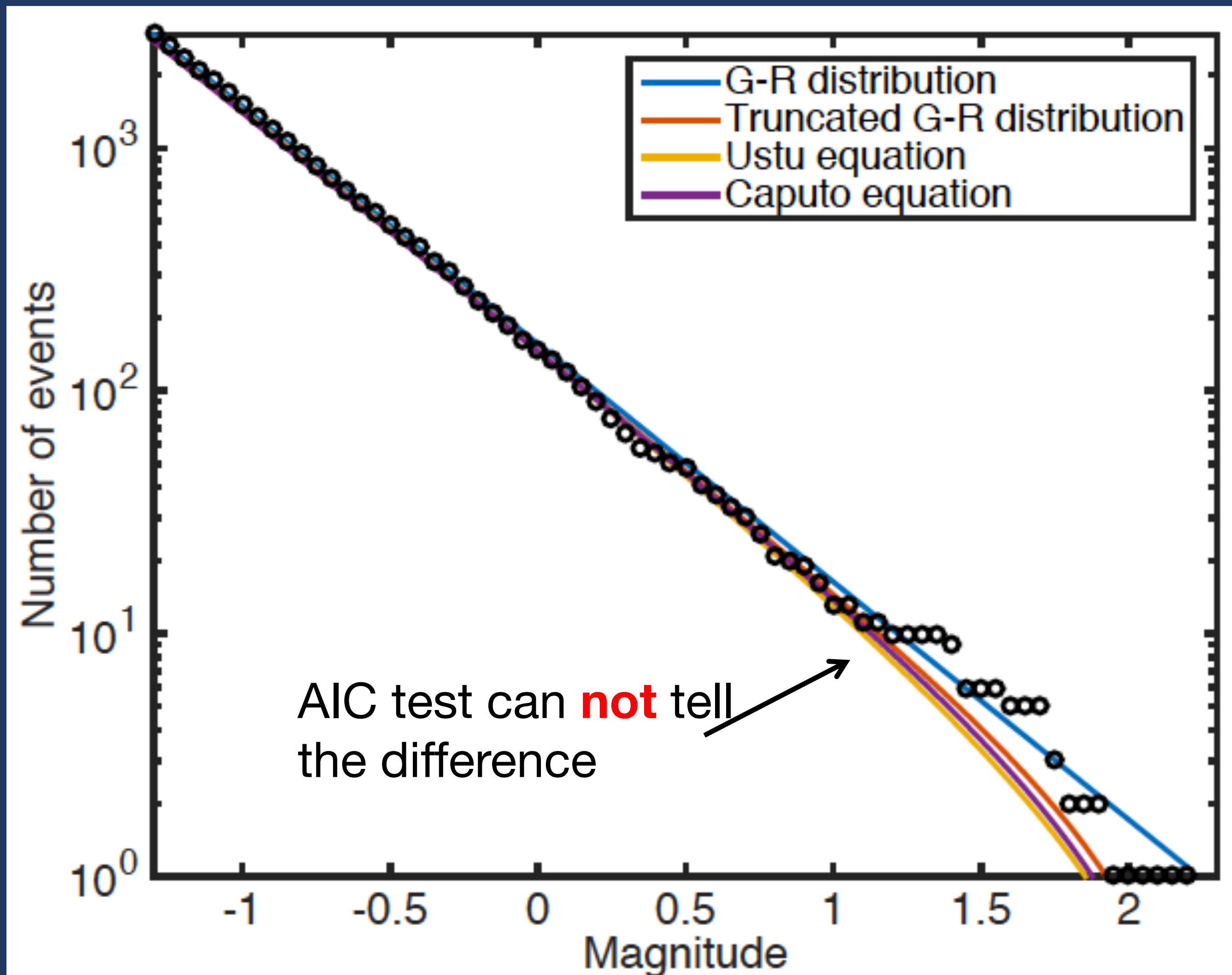
II: Magnitude-frequency distribution of induced earthquakes is not Gutenberg-Richter

July 2010

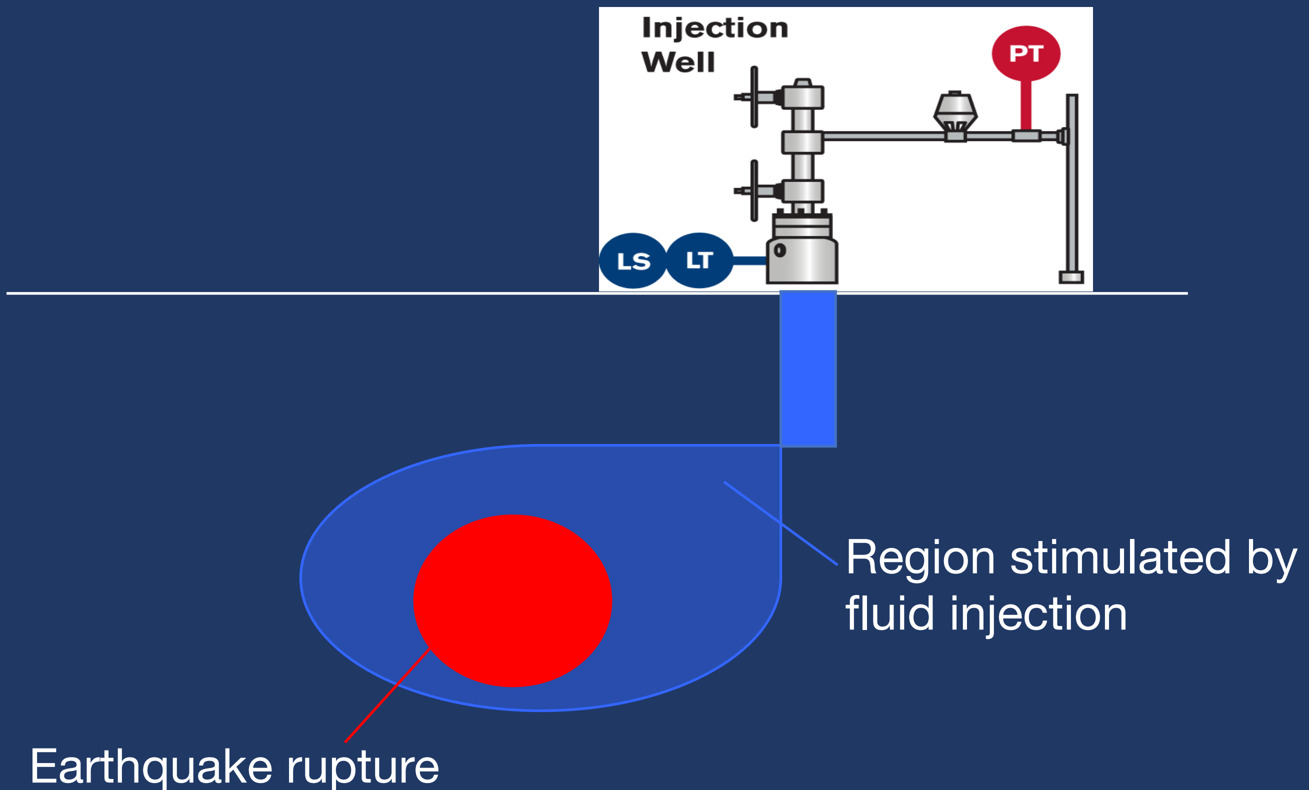


II: Earthquakes went back to Gutenberg-Richter during post-injection

July 2011

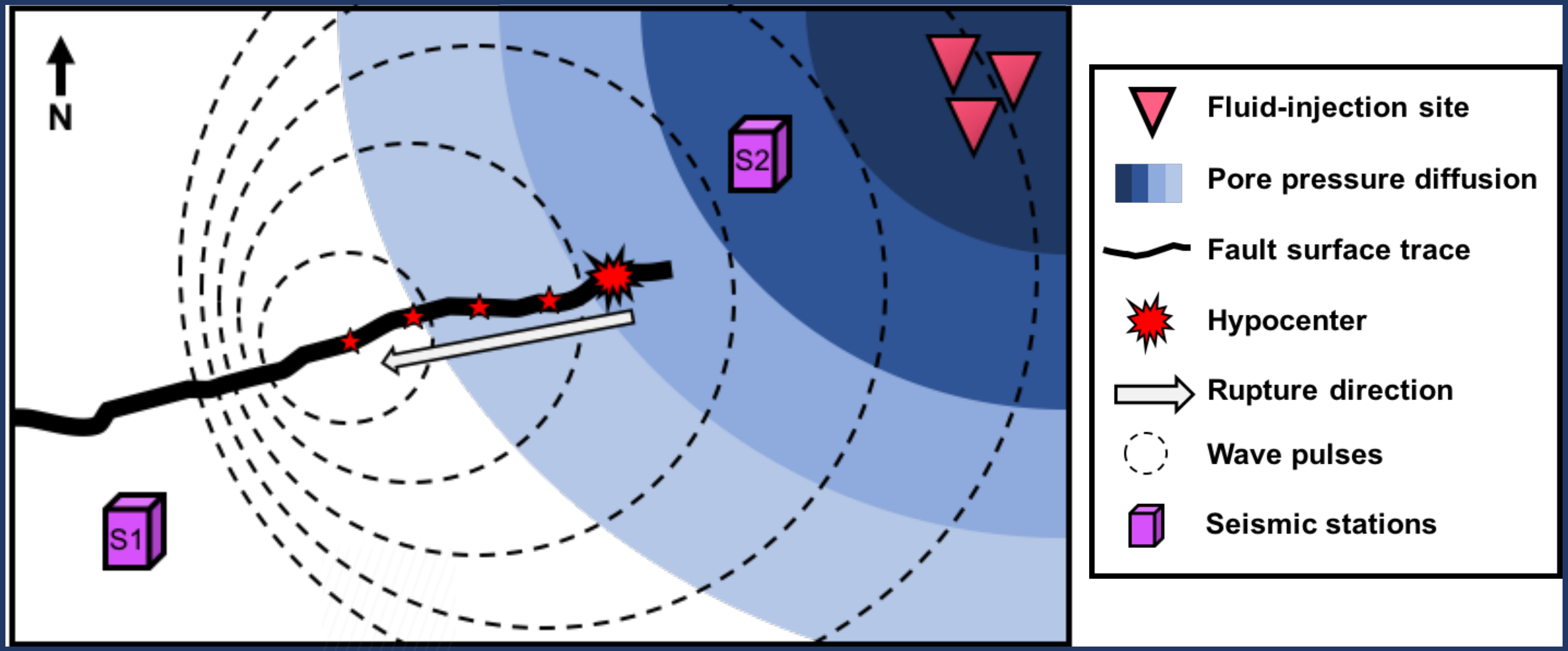


II: The deficiency of large earthquakes during injection suggests an upper bound of earthquake size related to fluid injection.



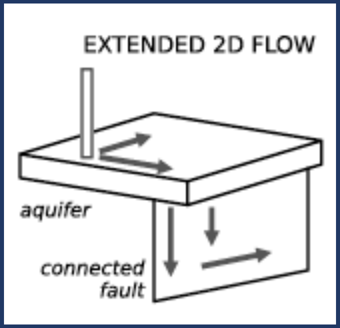
For a fault with low stress, earthquakes will tend to stay inside the blue area.

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

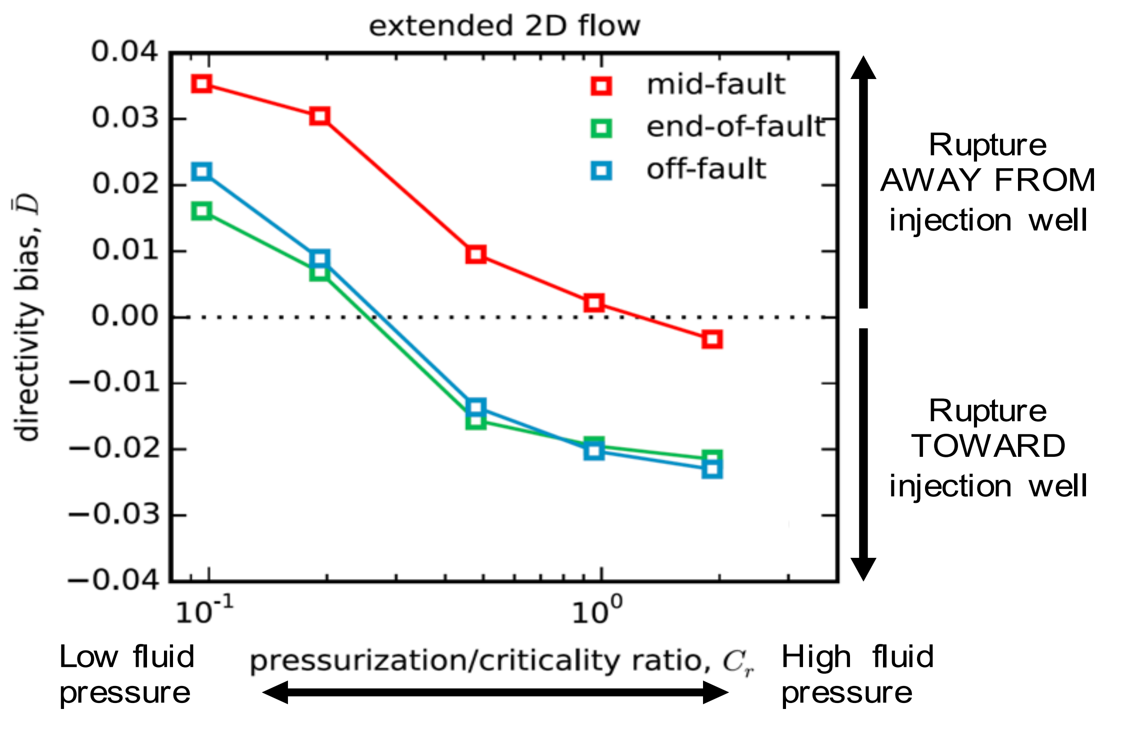


Rupture tends to propagate away from injection sites for uniform fault stress conditions.

II: Earthquake models with heterogeneous stress

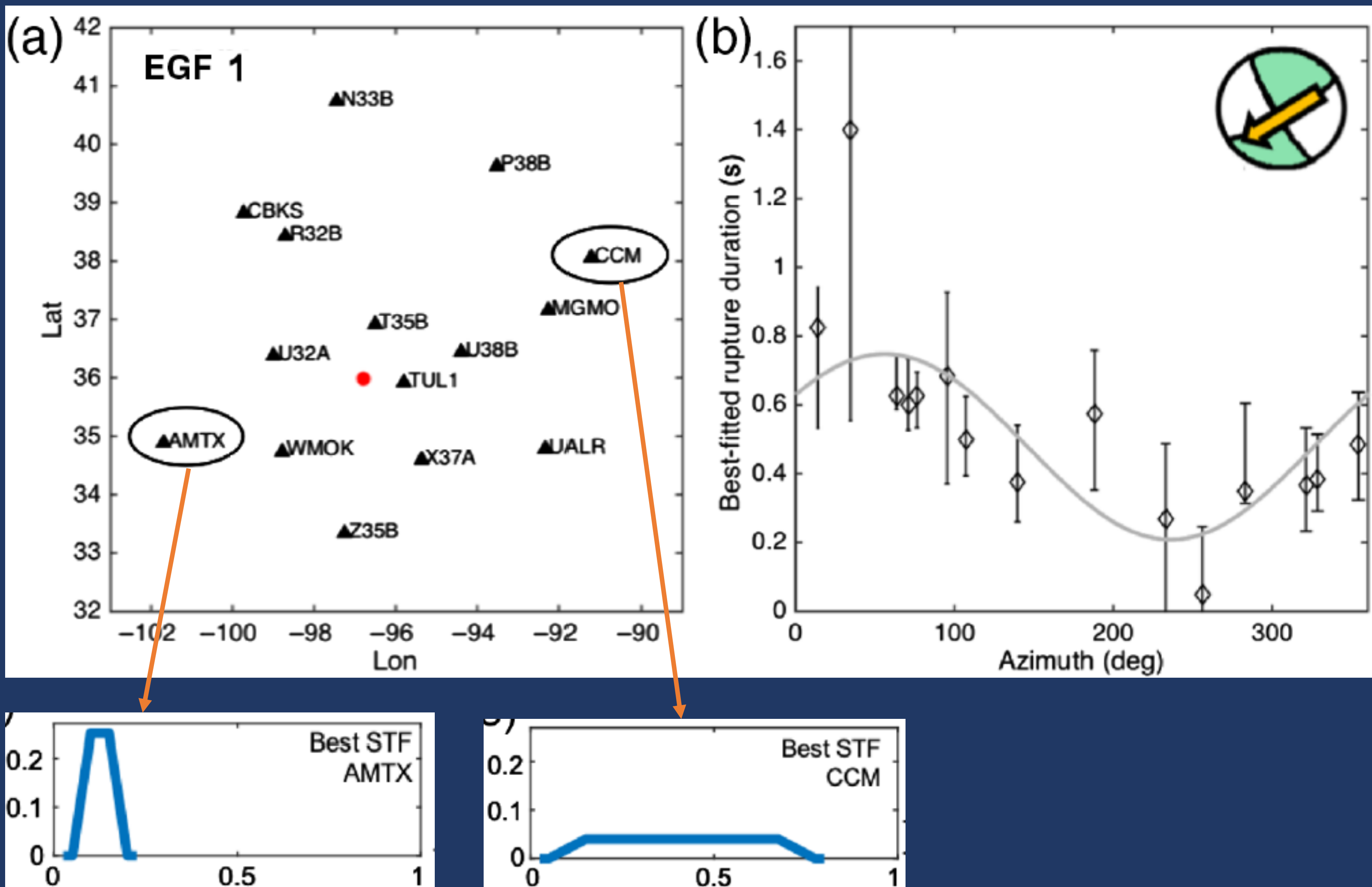


Off-fault injection favors rupture towards injection wells when pressure is high, but rupture away from wells when pressure is low.



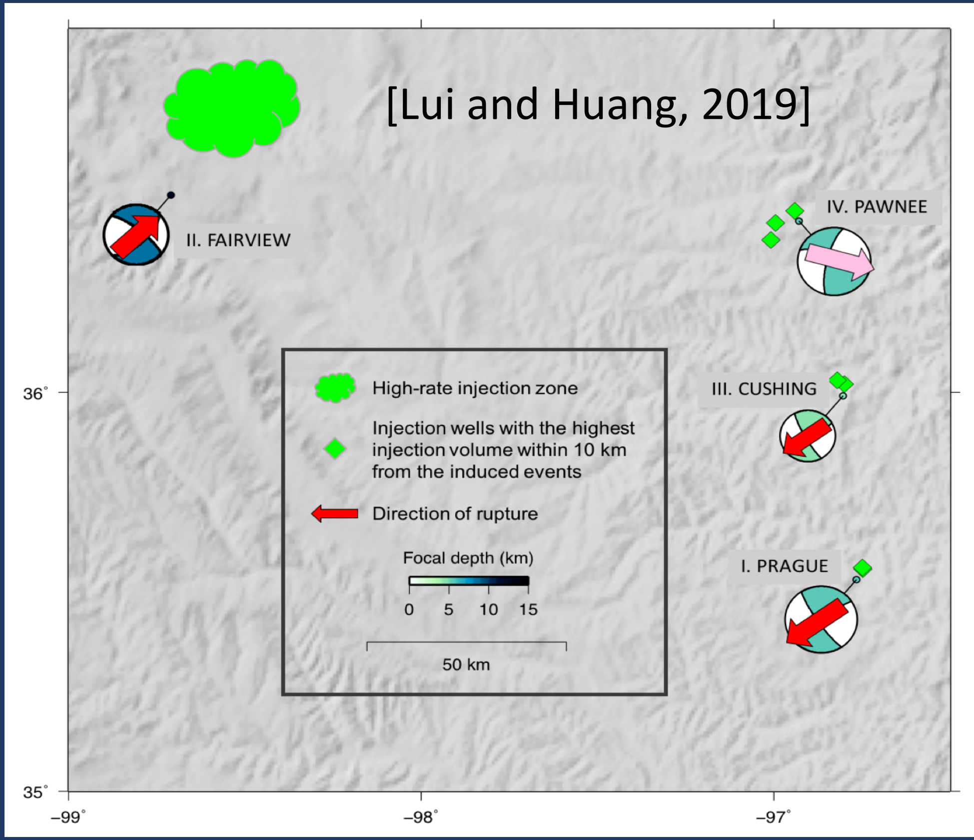
[Dempsey and Suckale, 2016]

II: The 2016 M_w 5.0 Cushing earthquake



[Lui and Huang, 2019]

II: Rupture directivity of major Oklahoma earthquakes



Prague: 1800 m^3/month

Cushing: 8.9×10^4 m^3/month

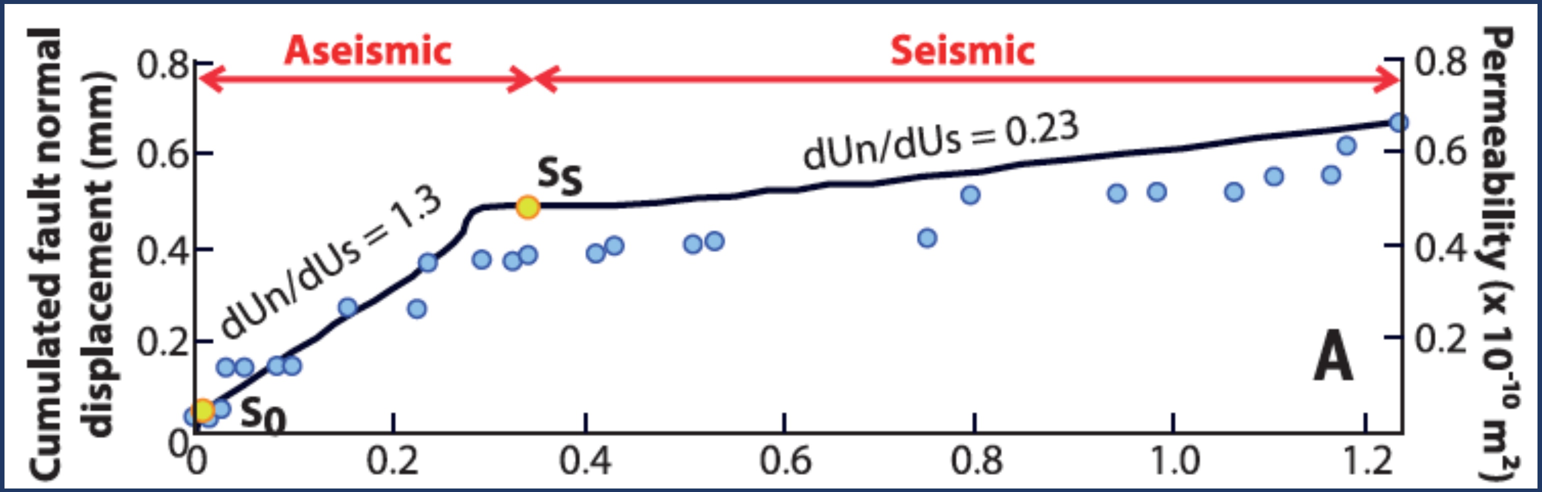
Pawnee: 5.1×10^4 m^3/month

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.

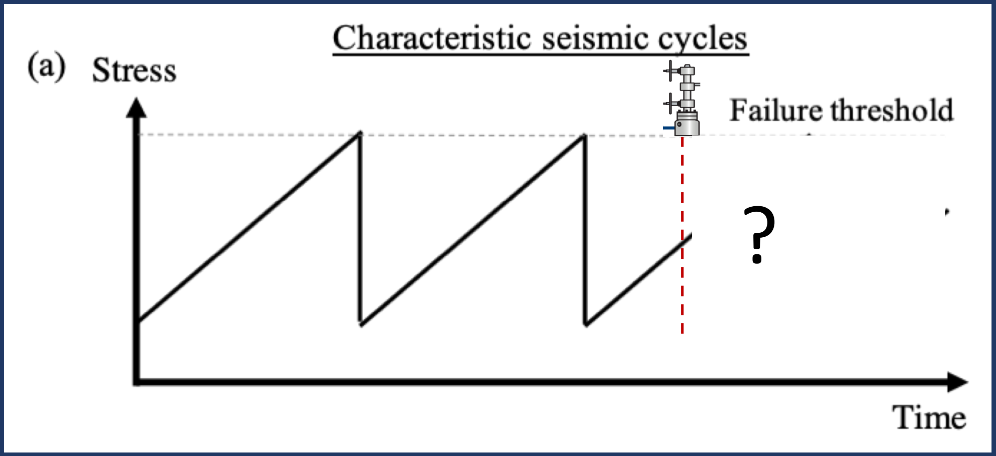
III: Are induced earthquakes always a direct response to fluid migration?

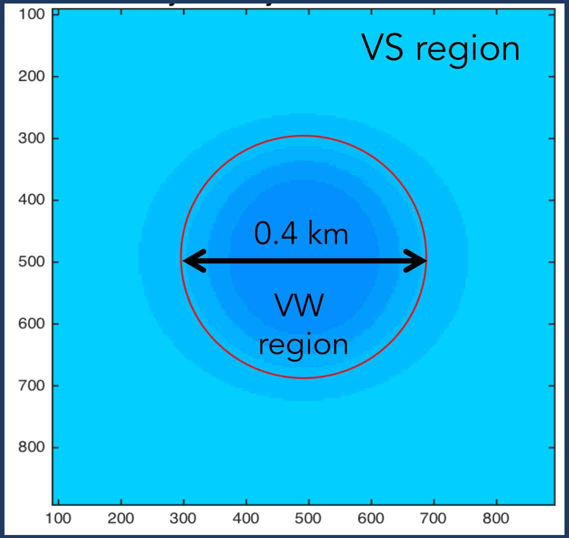


[Guglielmi et al., 2015]

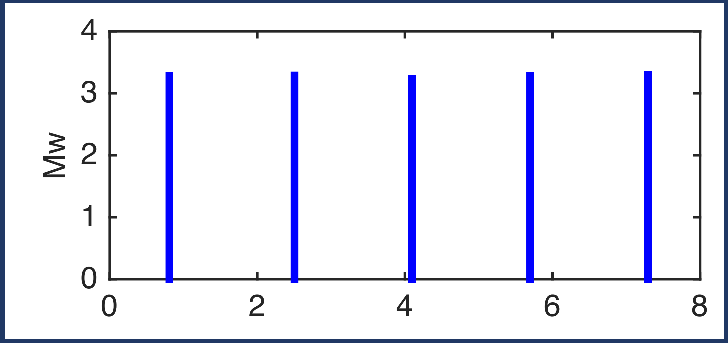
"In average, the energy budget shows that less than 0.1 % of the injection energy induces deformation, whose aseismic component is more than 99.9 %."

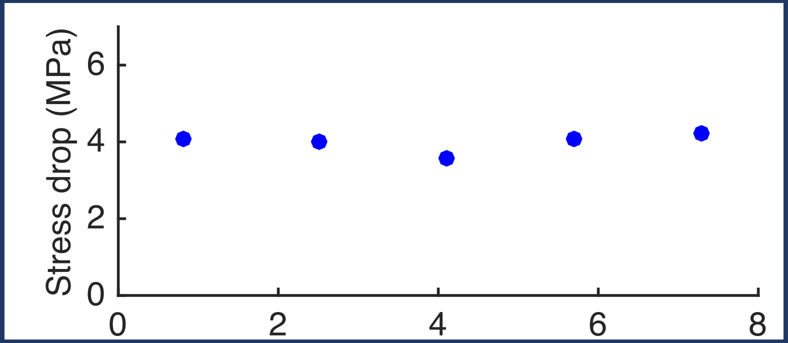
III: Earthquake cycle models with stress perturbation





Unperturbed/Tectonic case:





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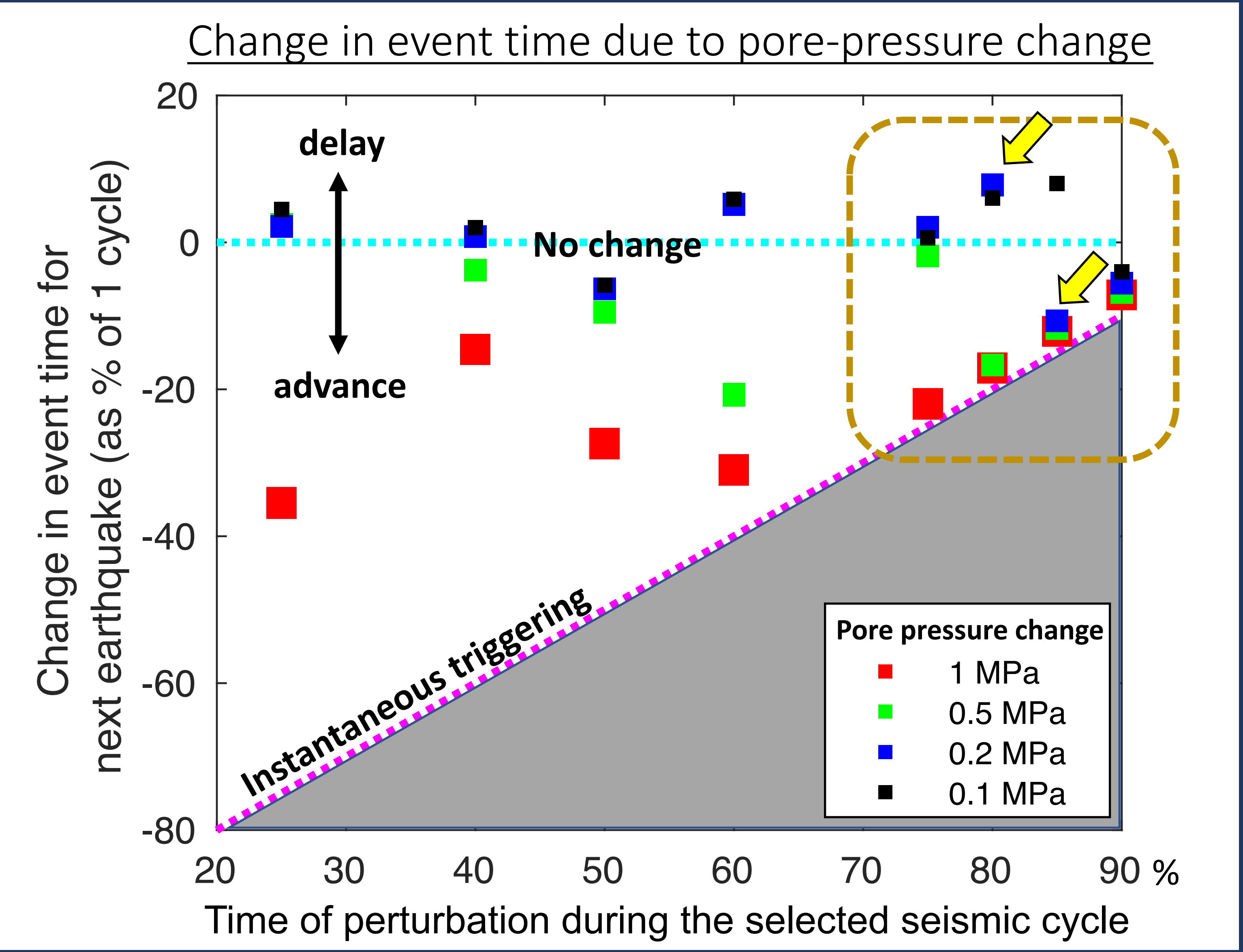
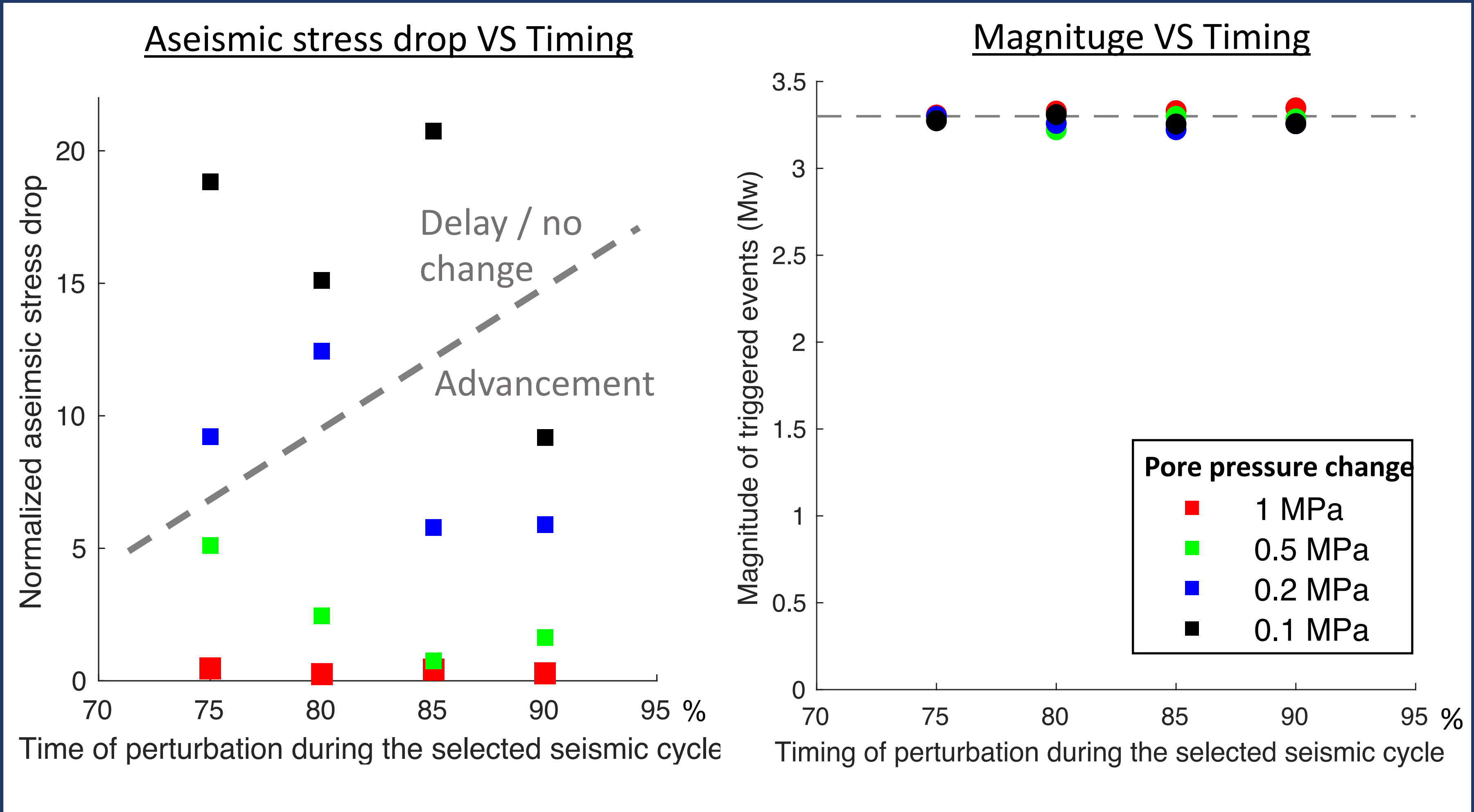
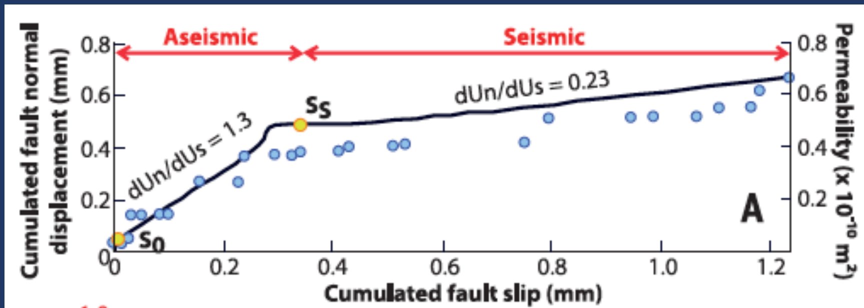
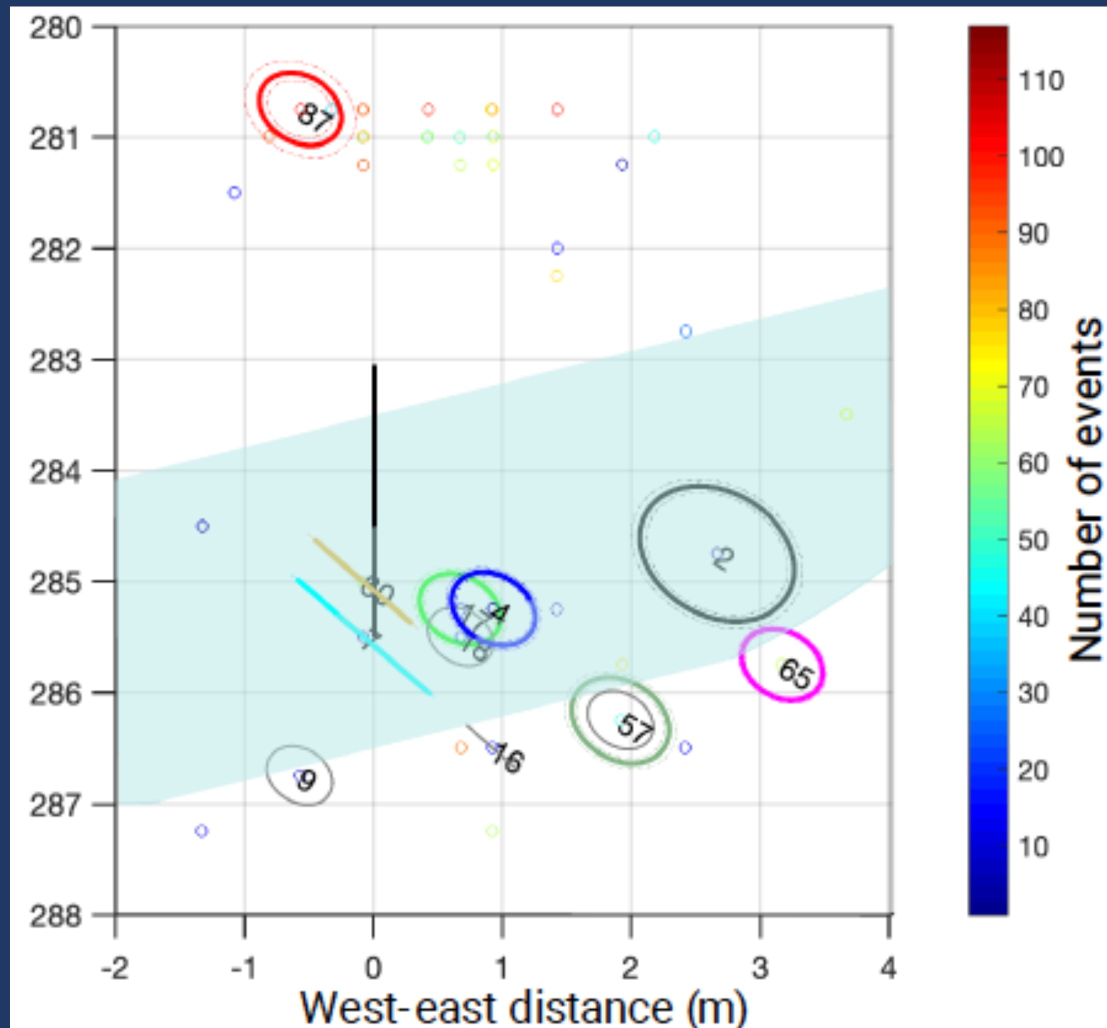


III: Aseismic stress release vs. time of perturbation



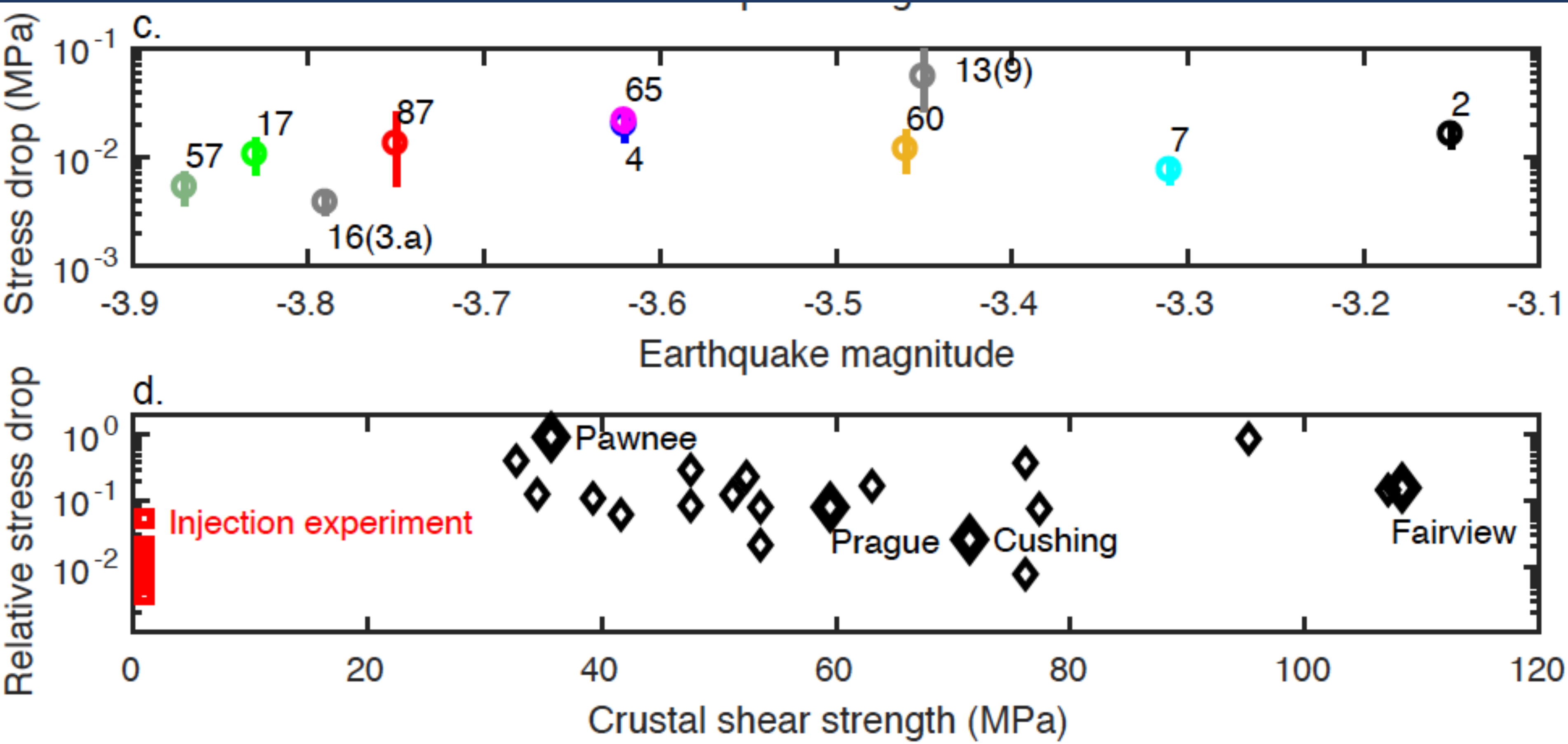


Could we tell large aseismic slip from earthquake source parameters?



[Huang, DeBarros, and Cappa, 2019]

III: Relative stress drops of microseismicity fall in the low end of those of central US earthquakes



[Huang, DeBarros, and Cappa, 2019]

Summary

- We find moderate induced and tectonic earthquakes in the central US have similar stress drops, indicating a small pore pressure change on faults.
- Earthquakes deviated from the Gutenberg-Richter distribution during fluid injection, suggesting an upper bound of earthquake size caused by fluid pressure.
- 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.