Fault reactivation by fluid injection considering permeability evolution in damage zones: A case study of Guy-Greenbrier sequence

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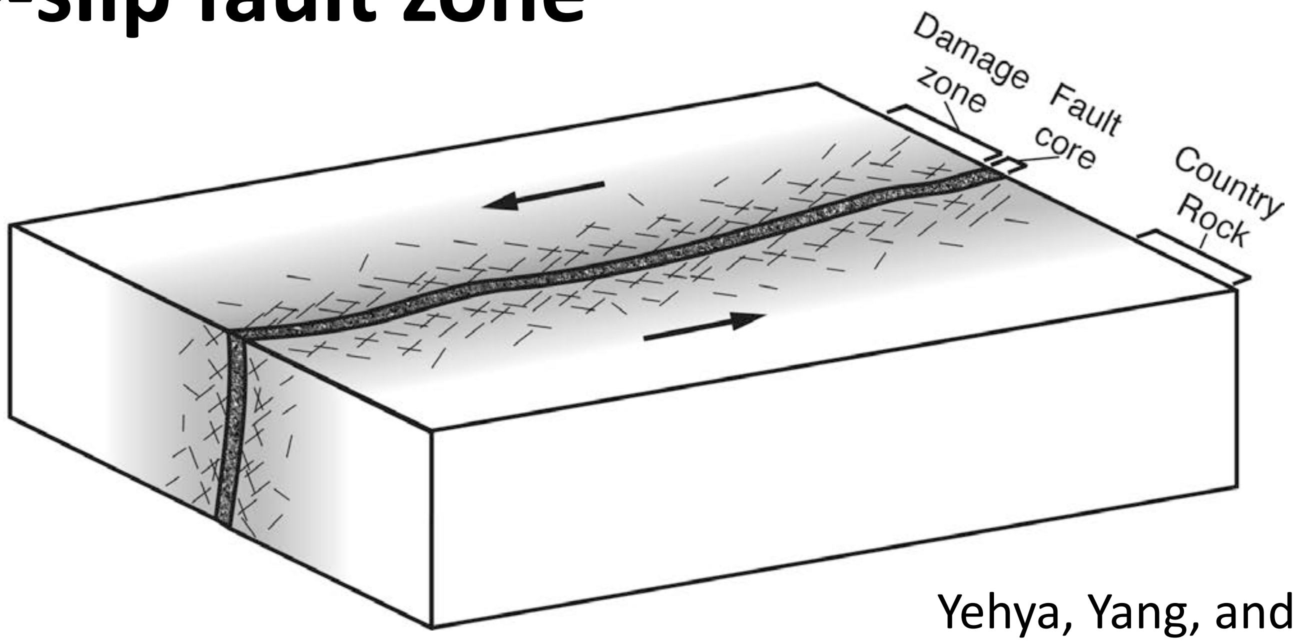
Schatzalp Workshop
March, 2019

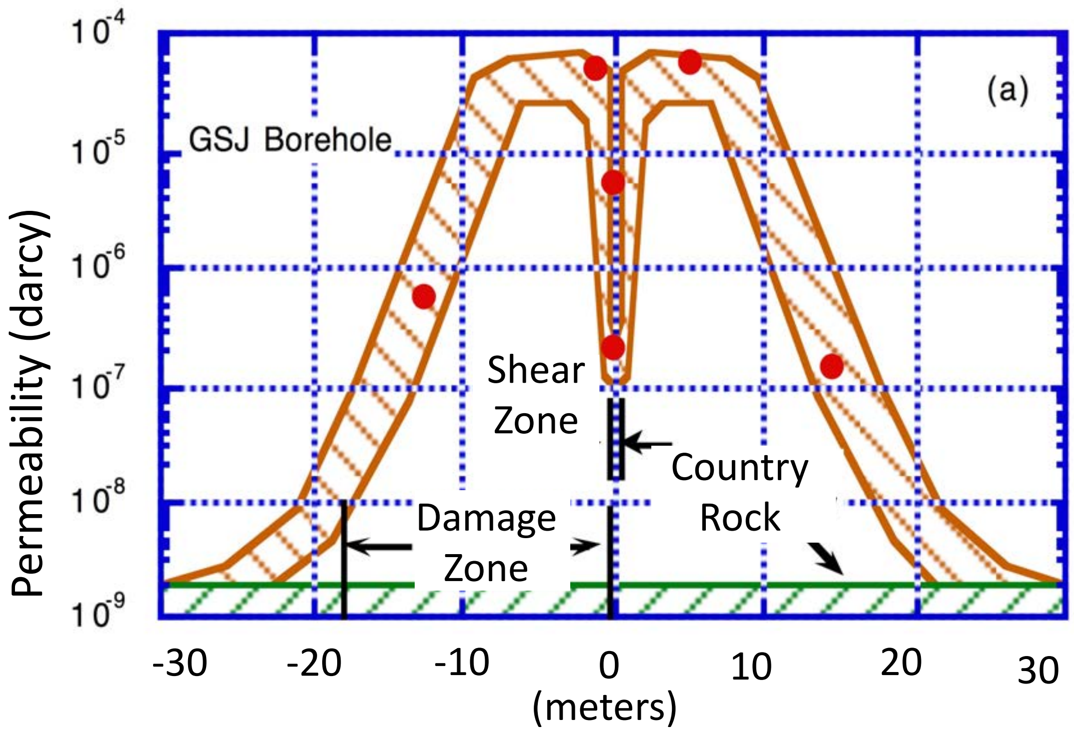
Schematic diagram of a representative strike-slip fault zone



Yehya, Yang, and Rice (2018)

- Includes a narrow, highly granulated, fault core (few cm scale thickness), and associated damage zones (10's of m scale).
- Coseismic damage zones generated by concentrated stresses near seismic rupture fronts.
- Longer-term broadening of damage zones may develop, driven by viscous post-seismic creep in response to tectonic forcing.

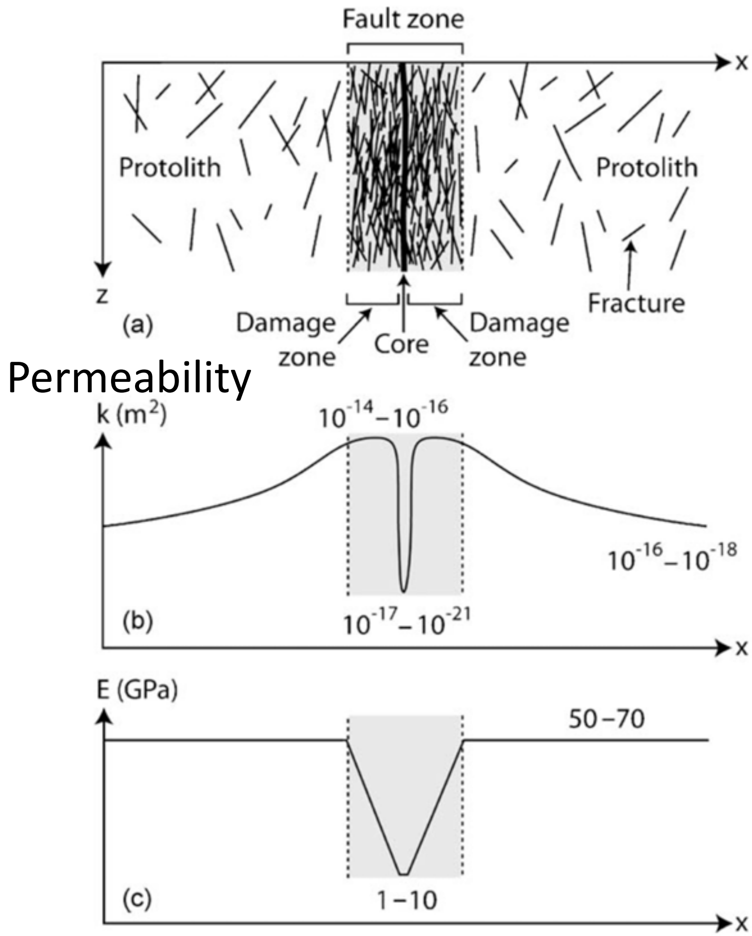
Measured permeability in relation to fault architecture



- Fault core:
  low permeability
- Damage zone:
  high permeability

Lockner et al. [USGS Open File Report 00-129, 2000]: Permeabilty measured on drill core taken from sites near fault strands slipped in 1995 Kobe earthquake

Model settings and testing



Cappa and Rutqvist (2010)

- We relate the permeability to the volumetric strain using a model developed and applied by Chin et al. (2000)
- Porosity:

$$\varphi(t) = 1 - (1 - \varphi_i)e^{-\varepsilon_{vol}(t)}$$

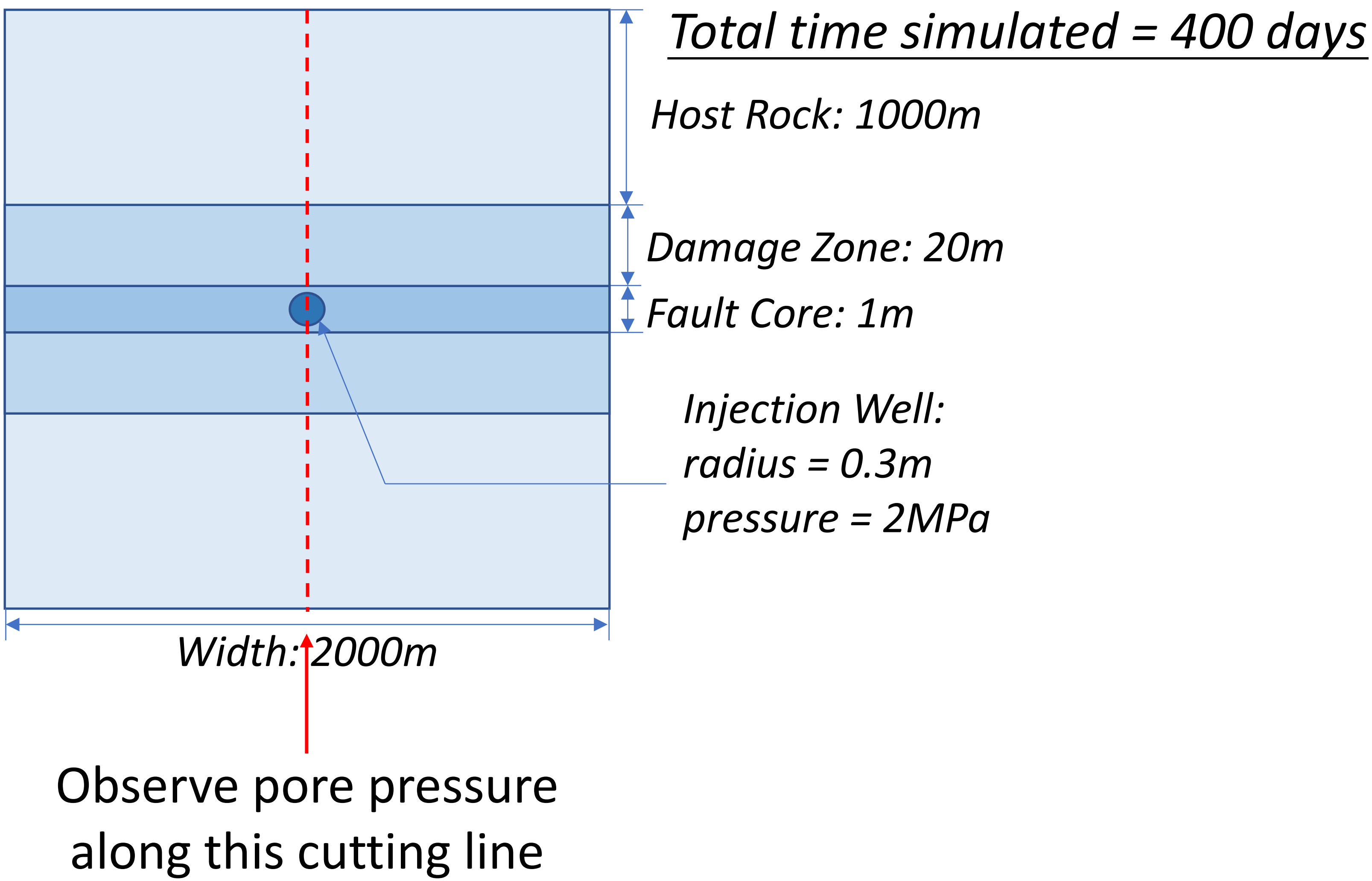
- Permeability:

$$k(t) = k_i \left(\frac{\varphi(t)}{\varphi_i}\right)^n$$

➢ Permeability k should be time dependent.

Model settings and testing

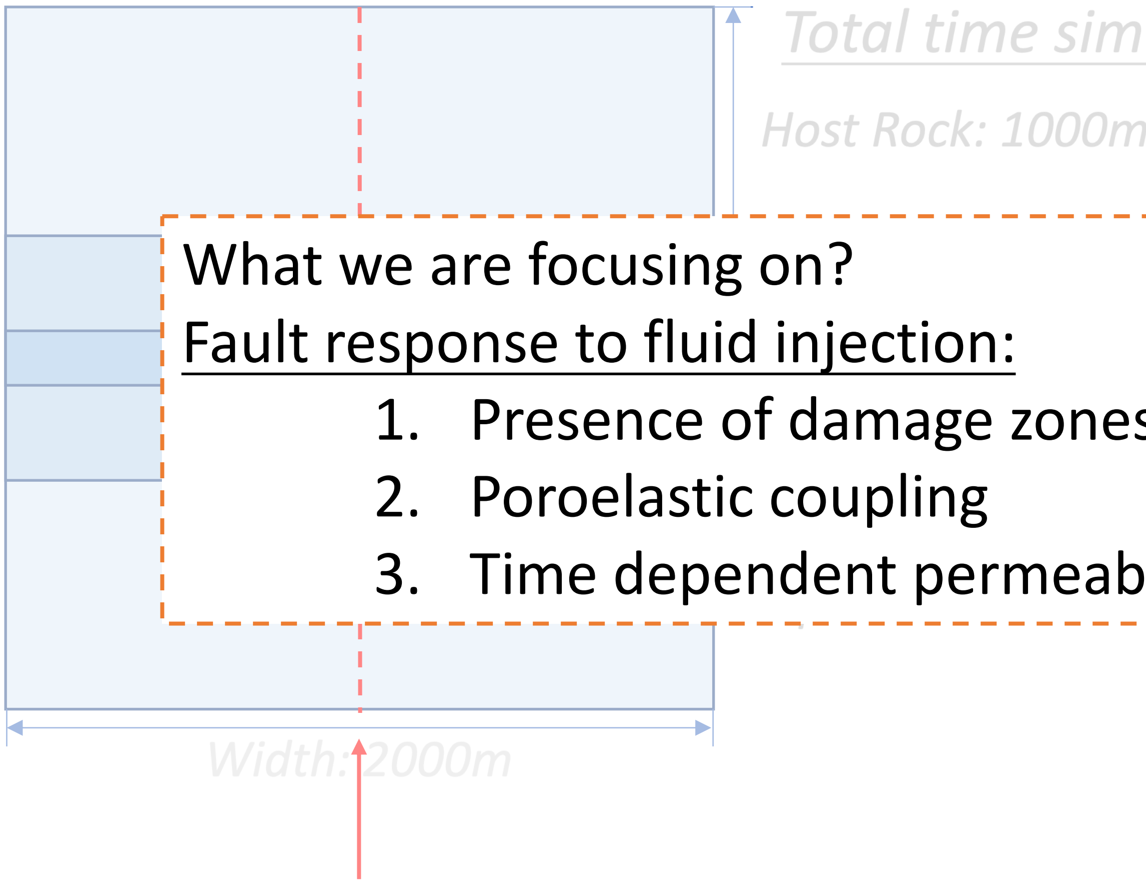
Fault’s Geometry Architecture: 2D Horizontal Plane (not to scale)



Model settings and testing

- Fault's Geometry Architecture: 2D Horizontal Plane (not toscale)

Total time simulated = 400 days



What we are focusing on?

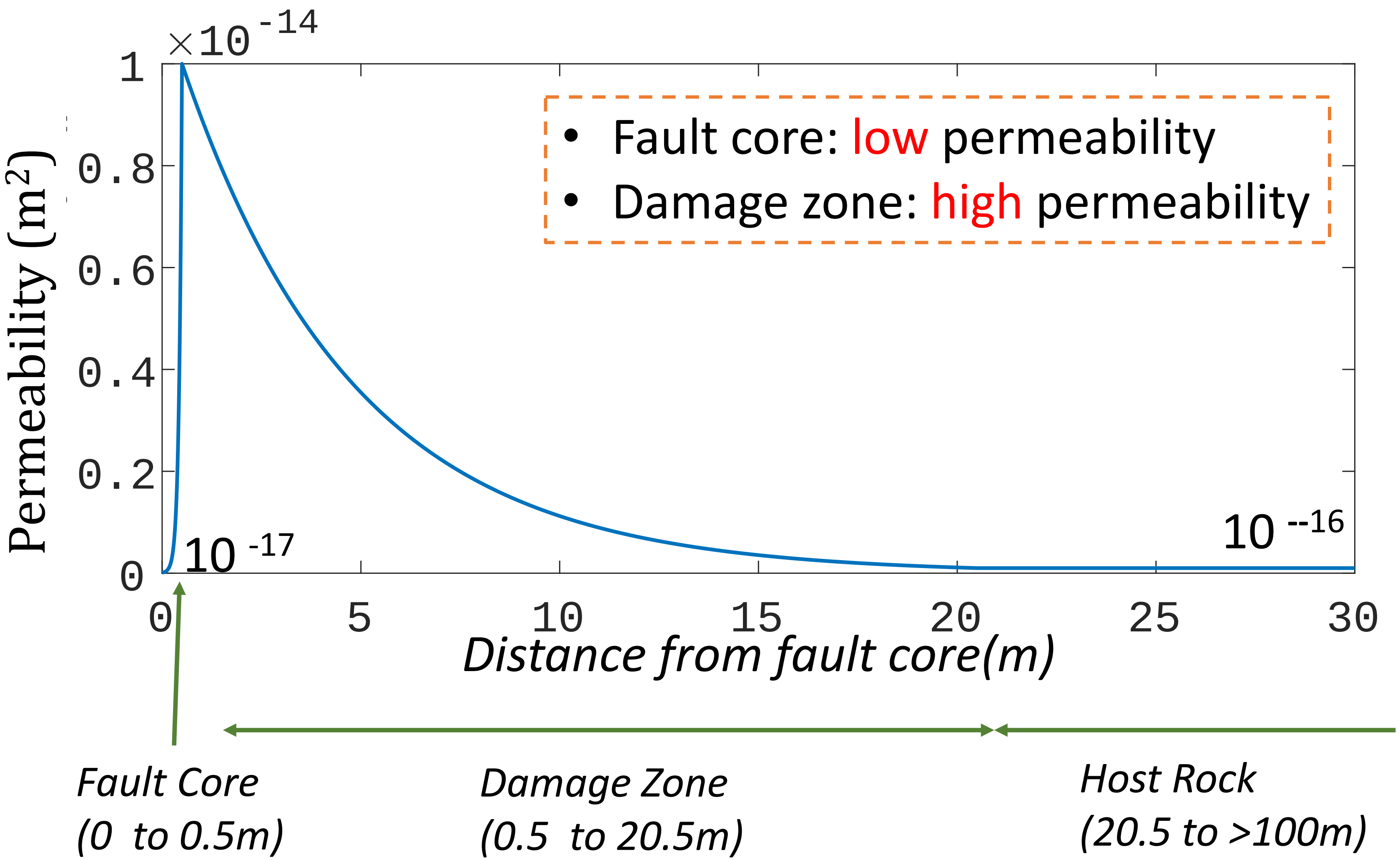
Fault response to fluid injection:

1. Presence of damage zones
2. Poroelastic coupling
3. Time dependent permeability

Observe pore pressure along this cutting line

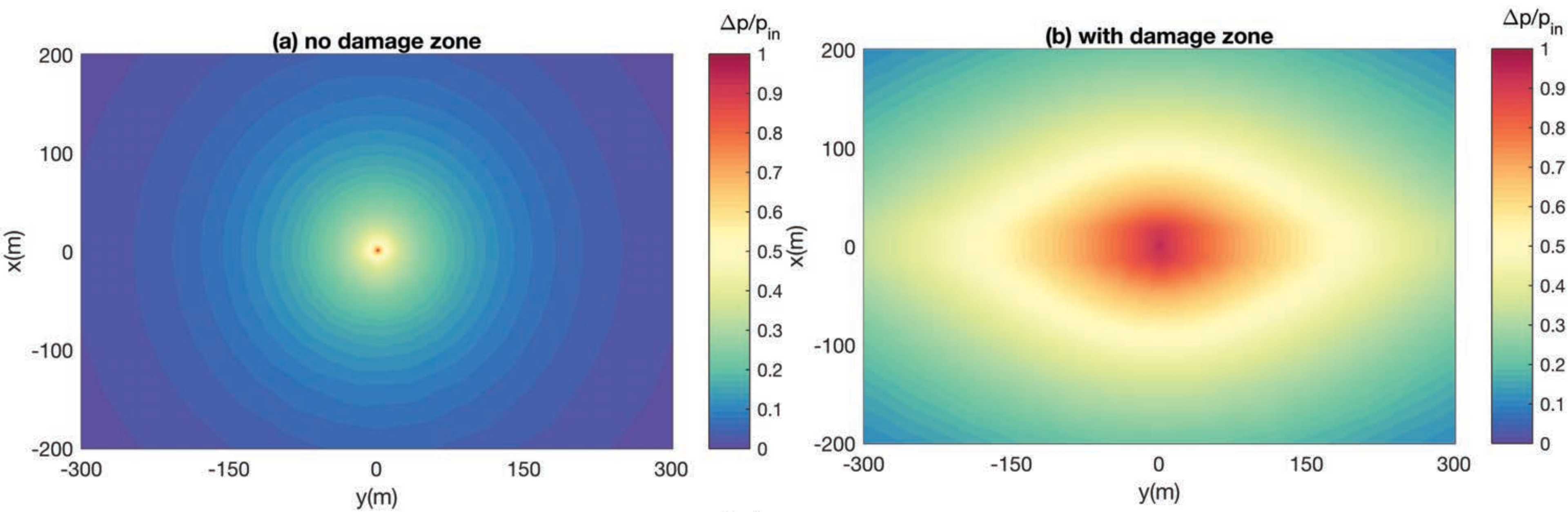
Model settings and testing

Permeability (in m^2) Variation in and near Fault Zone



Effect of damage zones on pressure diffusion

Pore pressure change ($\Delta p/p_{inject}$) after 40 days of injection:

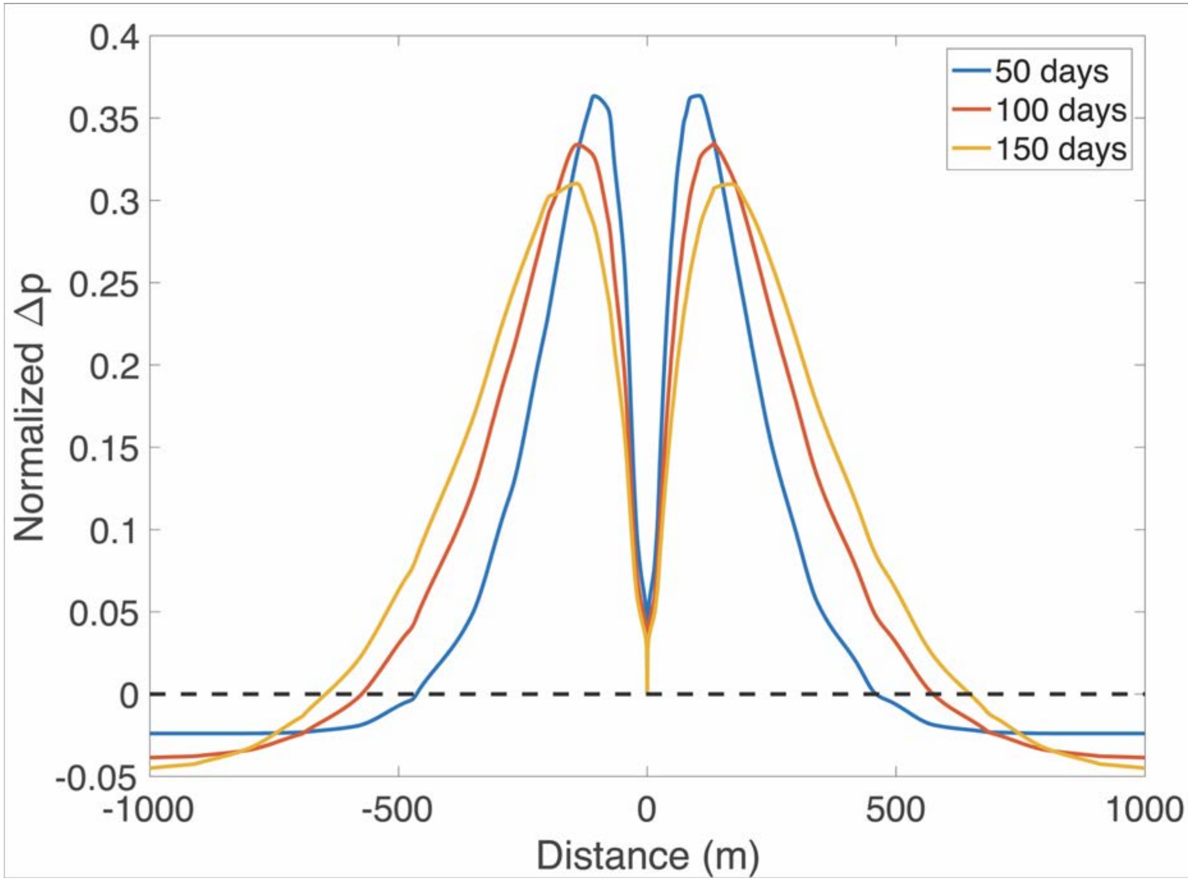


Model without damage zone

Model with high k damage zone

➢ The existence of high permeability (k) damage zones **facilitates** the pressure diffusion: **zones act as conduits** for fluid pressure changes.

Effect of poroelastic coupling

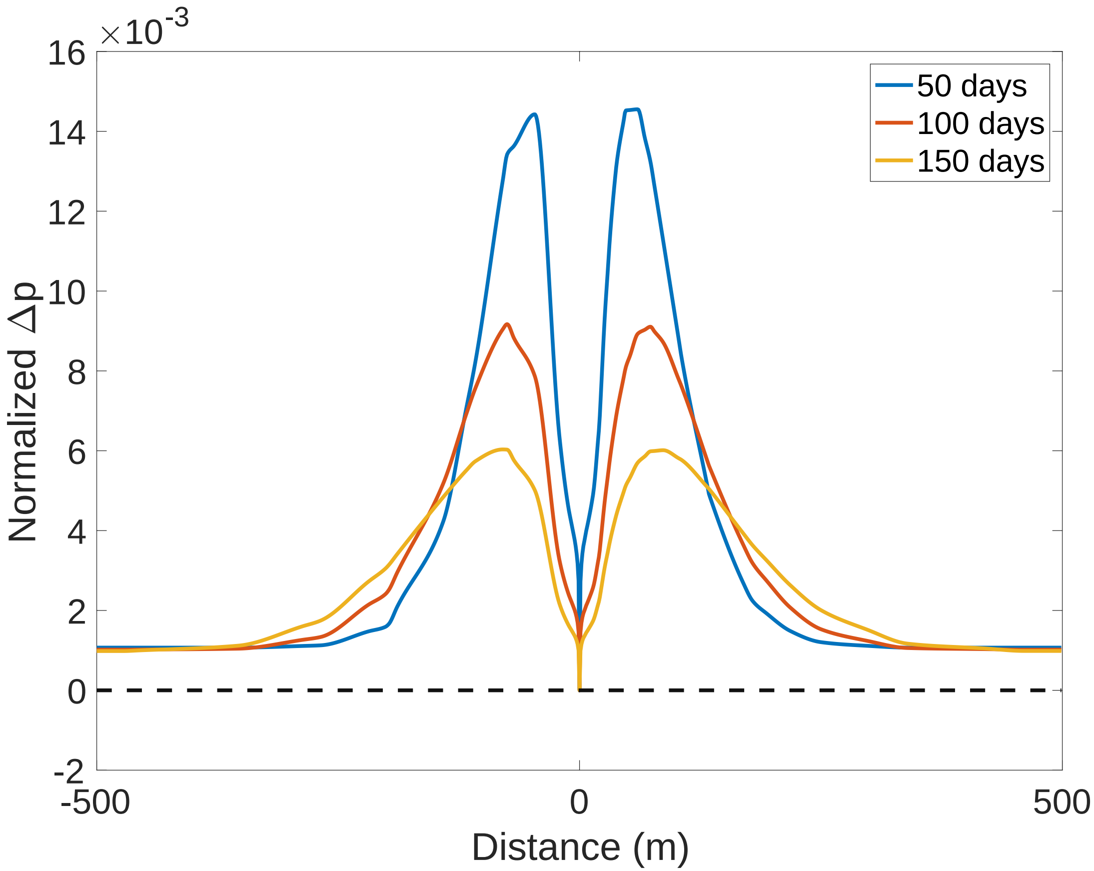


Pressure Difference Δp

"Uncoupled diffusion model" significantly **overestimates the near field pressure** while underestimates far field!

Plotted: Uncoupled diffusion model **–** Coupled poroelastic model

Effect of permeability evolution



Porosity:

$$\varphi(t) = 1 - (1 - \varphi_i)e^{-\varepsilon_{vol}(t)}$$

Permeability:

$$k(t) = k_i \left(\frac{\varphi(t)}{\varphi_i}\right)^n$$

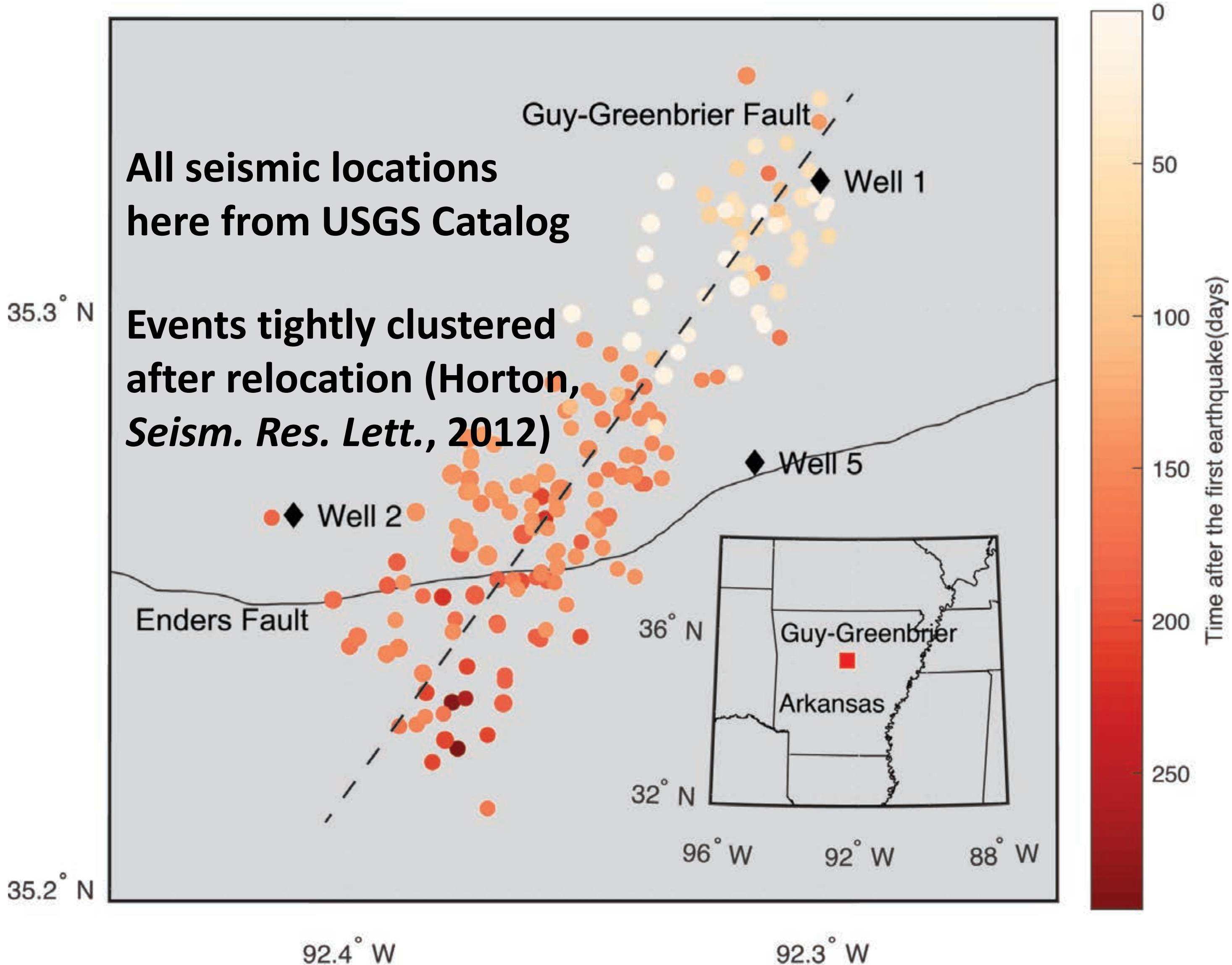
"time independent permeability model" **underestimates the whole field pressure** especially the near field!

Plotted: Pressure Difference Δp

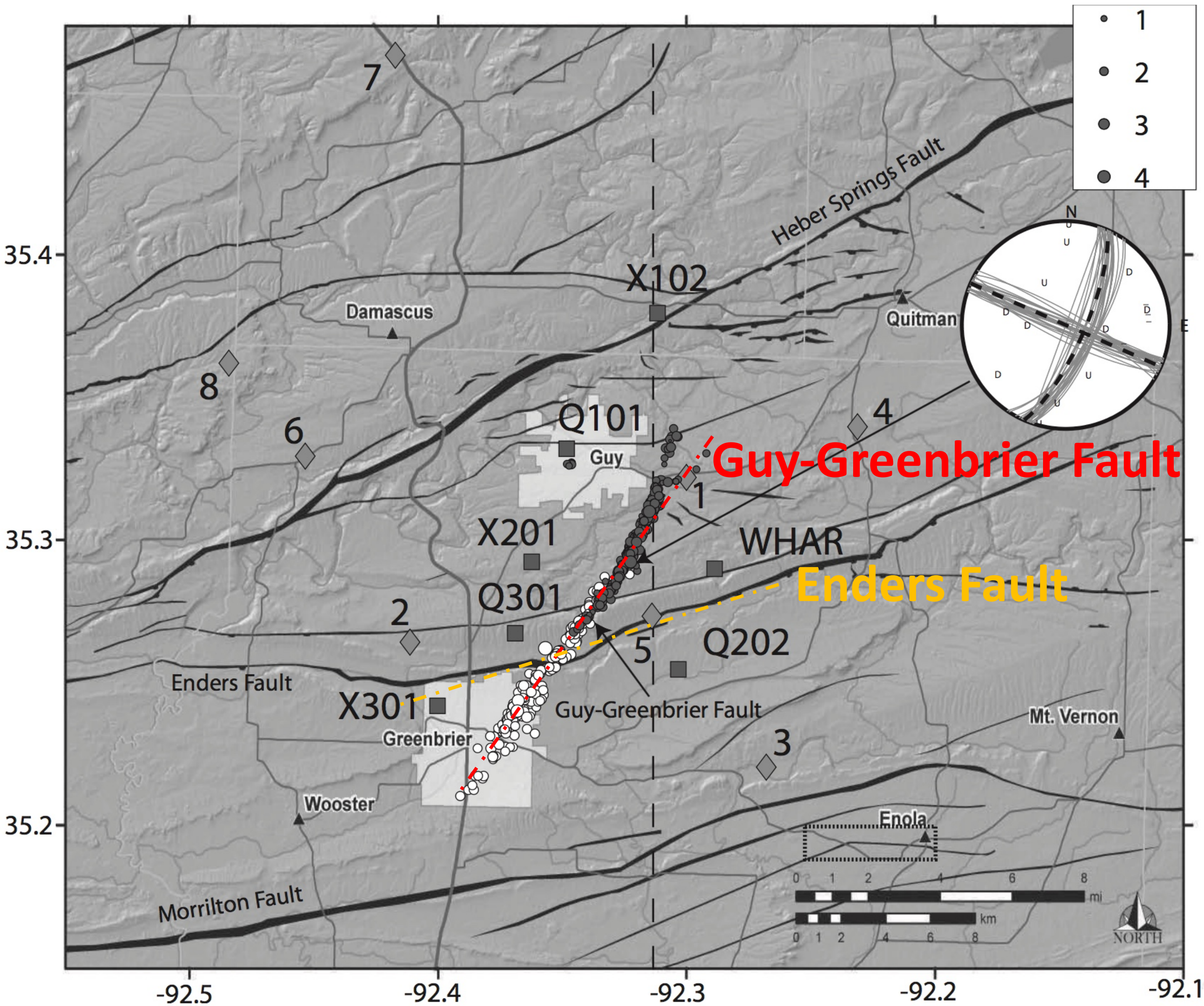
Time dependent k model	–	Time independent k model

Application: Arkansas, USA

A continuous swarm of small earthquakes illuminated a **previously undetected** fault, now called the "**Guy-Greenbrier Fault**"



Horton's relocations. Events clustered along a single structure, now called the Guy-Greenbrier Fault

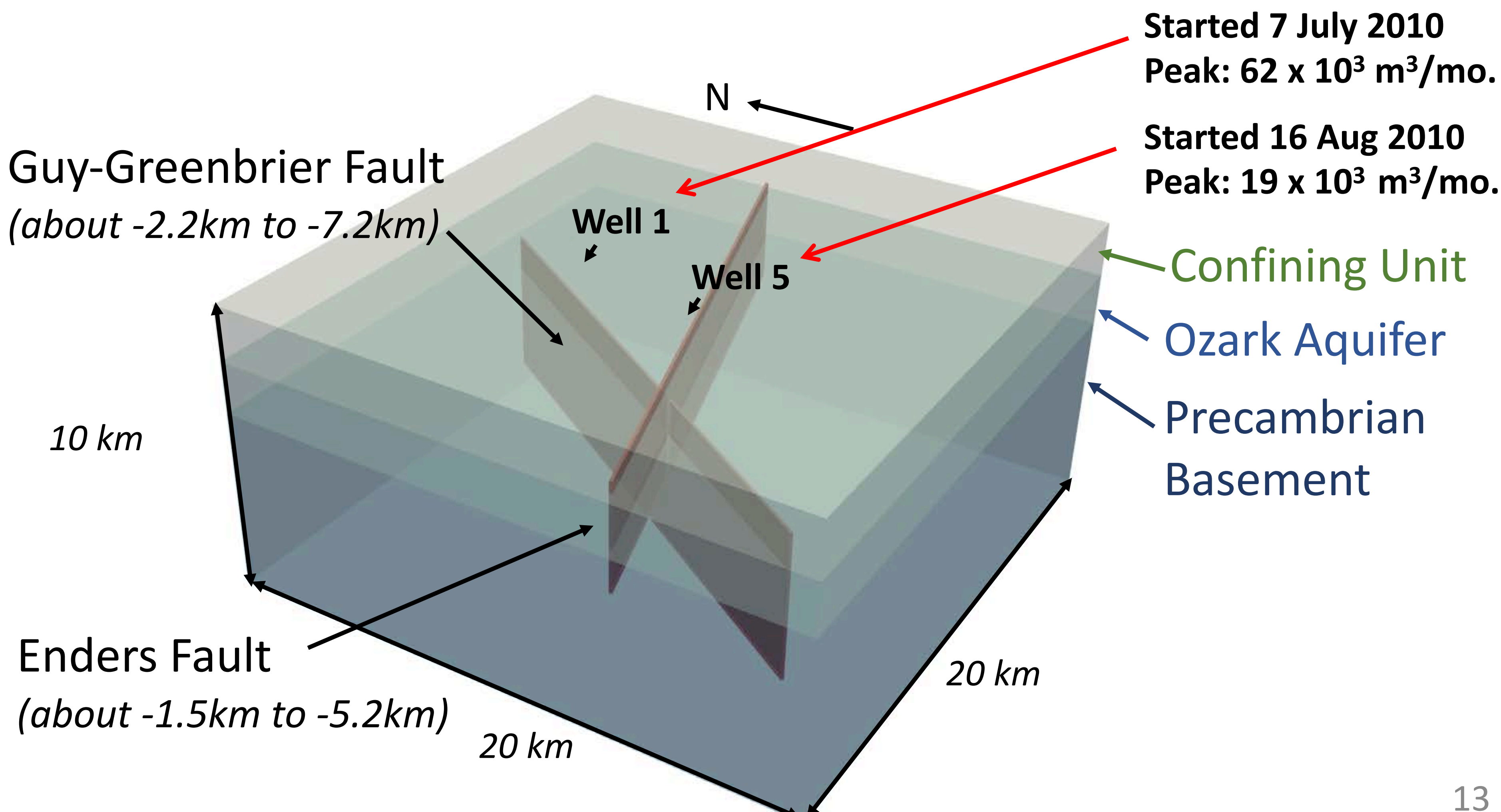


(Horton, *Seism. Res. Lett.*, 2012)

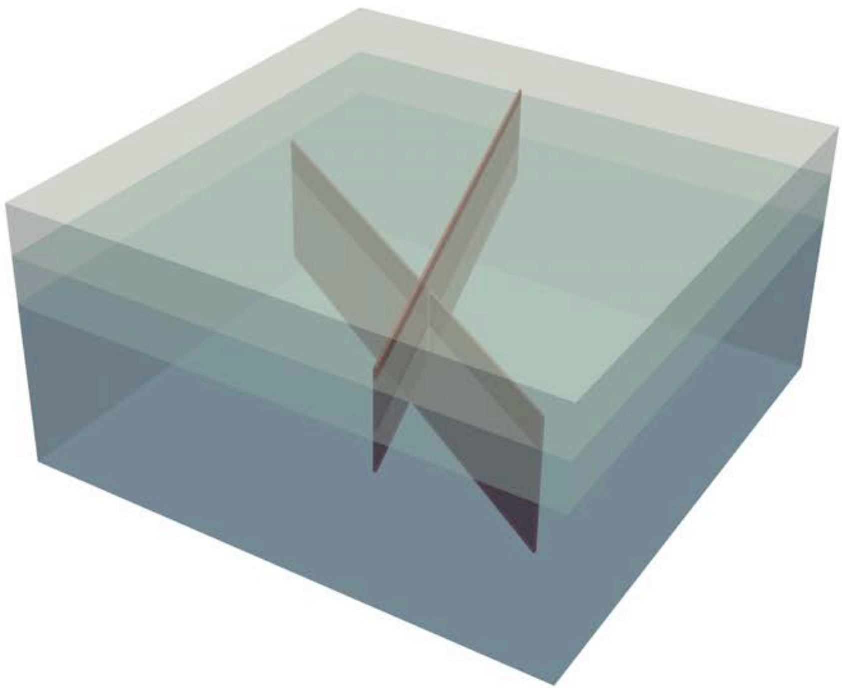
COMSOL FEM model:

An attempt to understand the nucleation of these events.

Include: Anisotropic damage zones surrounding fault core; Poroelastic coupling; Permeability evolution.



Permeability setting



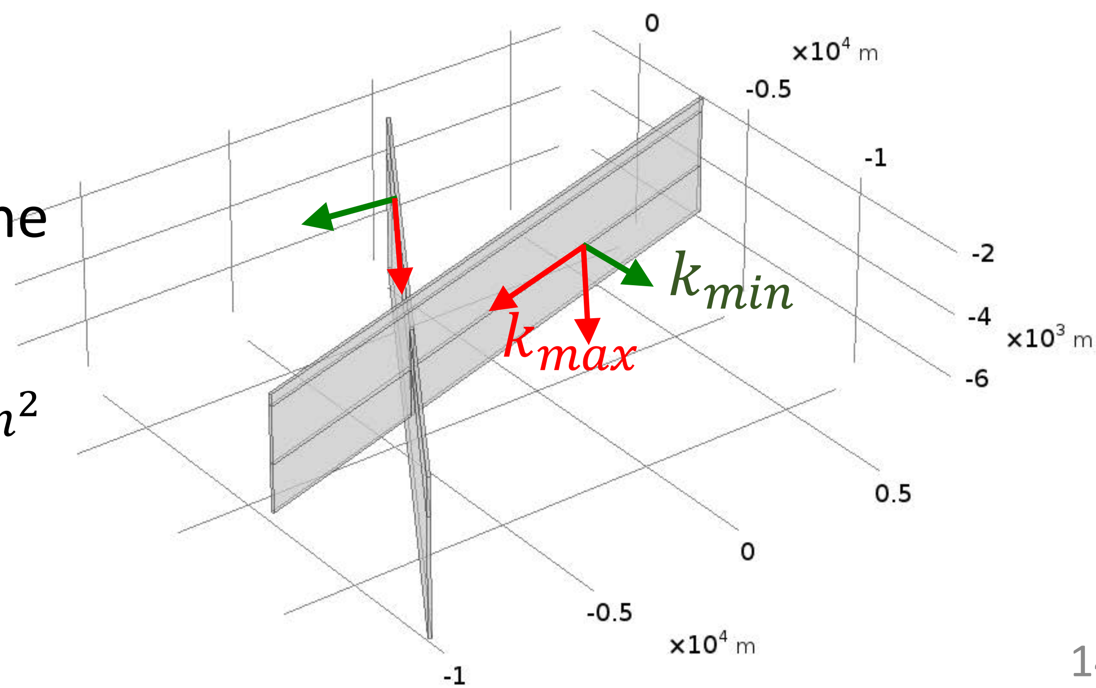
Permeability in the model

Layers	Permeability(m^2)
Confining Unit	10^{-16}
Ozark Aquifer	10^{-15}
Basement	10^{-21}

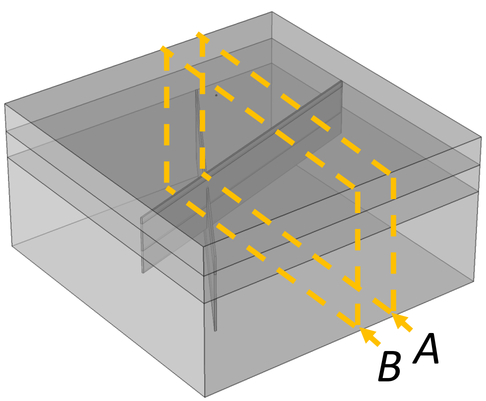
Permeability in the fault zone

$$k = \begin{pmatrix} 10^{-13} & 0 & 0 \\ 0 & 10^{-15} & 0 \\ 0 & 0 & 10^{-13} \end{pmatrix} m^2$$

$$k_{parallel} = 100 \times k_{normal}$$

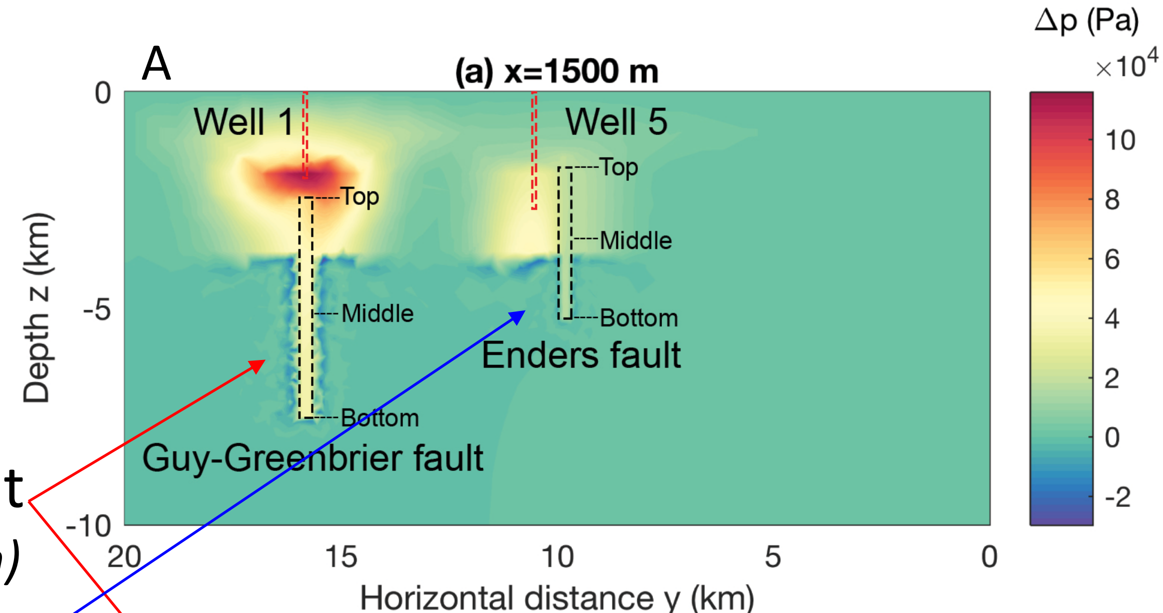


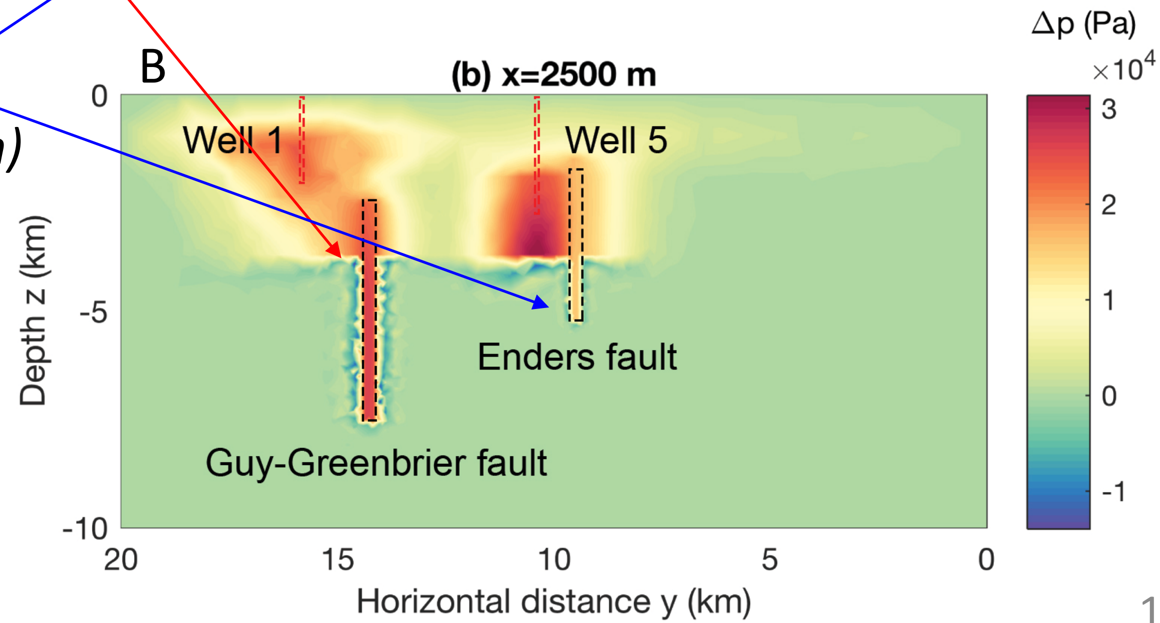
Pressure change on vertical cross-sections, approx. 1.5 yr later



Guy-Greenbrier Fault
(about -2.2km to -7.2km)

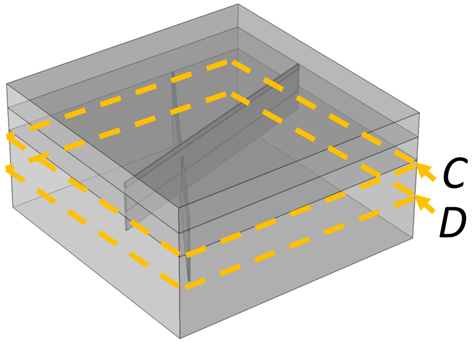
Enders Fault
(about -1.5km to -5.2km)



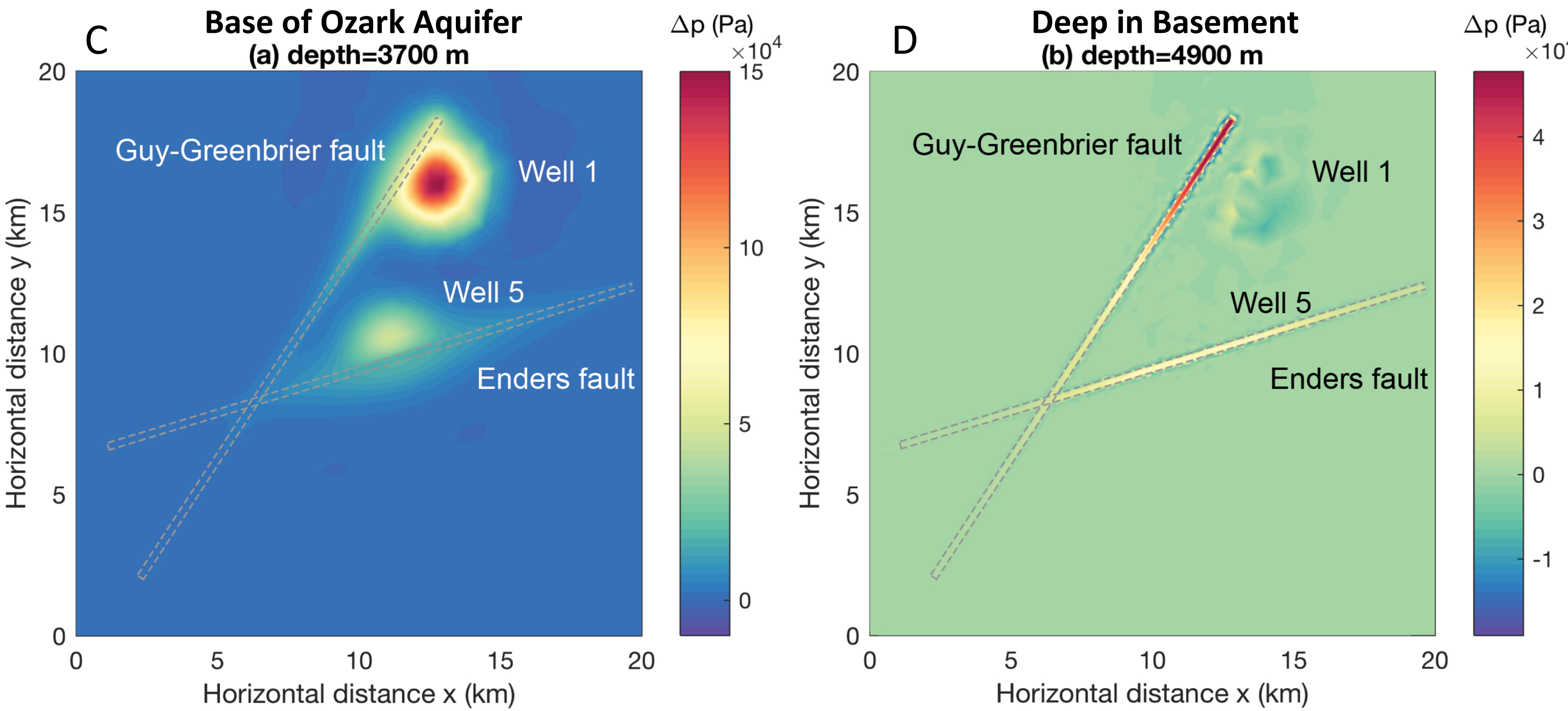


Enders fault acts as a barrier for horizontal fluid diffusion.

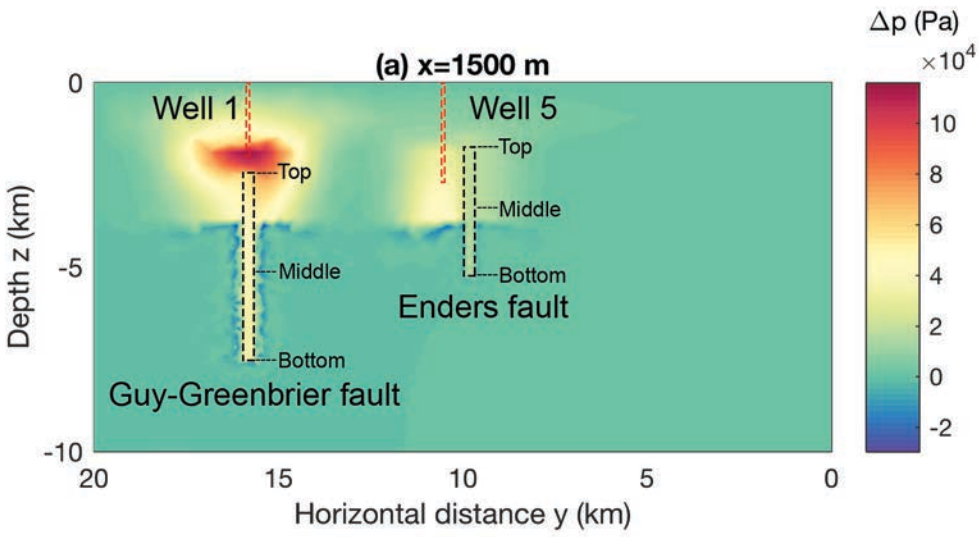
Pressure change on horizontal cross-sections, approx. 1.5 yr later

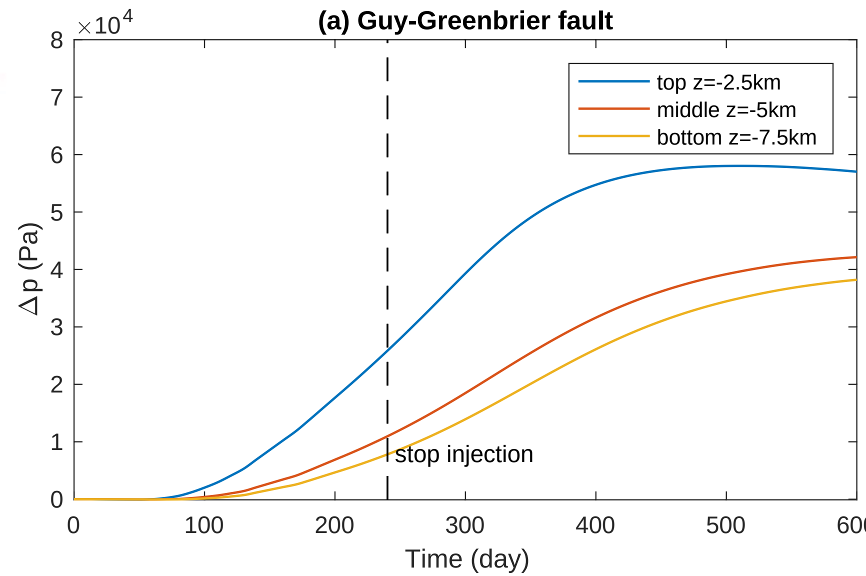


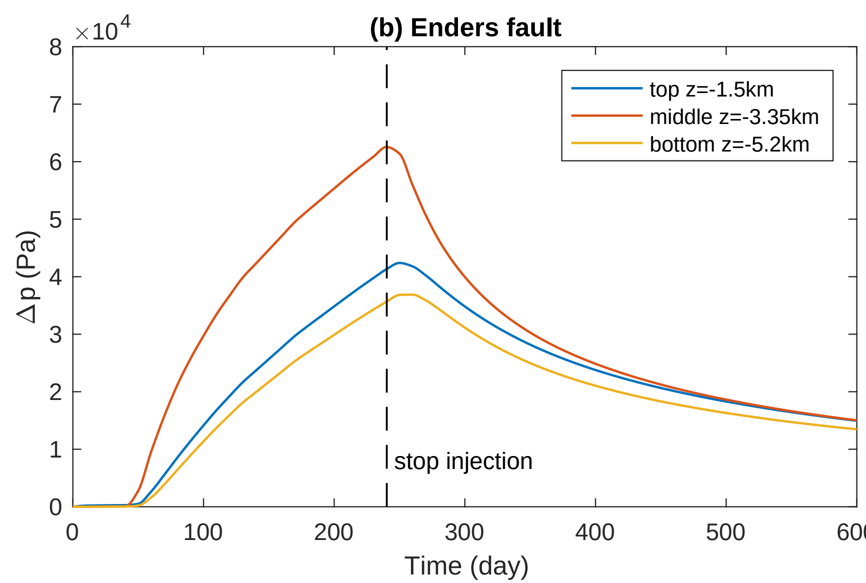
As depth increases, pore pressure change concentrates only on damage zones.



Pore pressure change in the faults

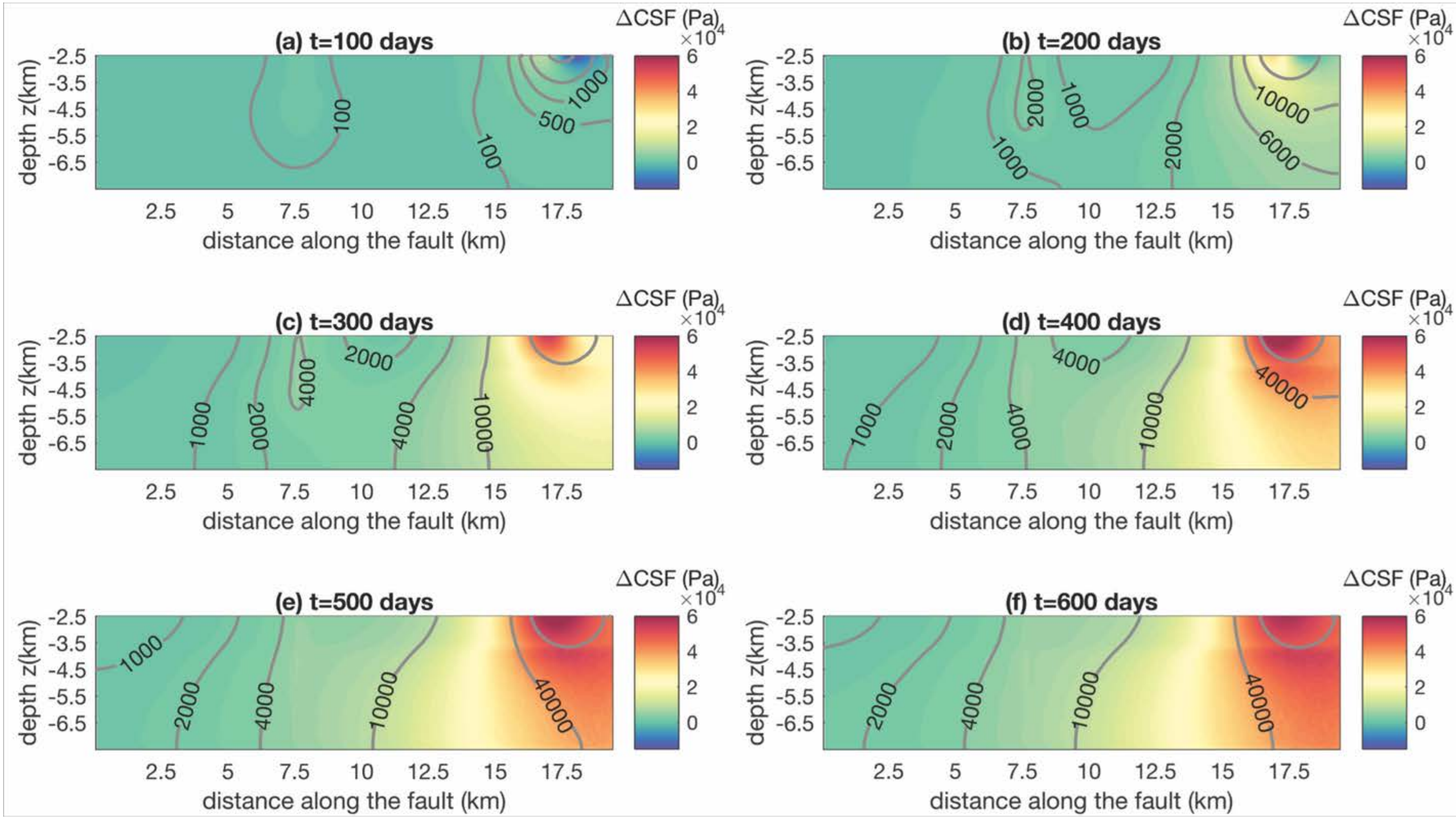






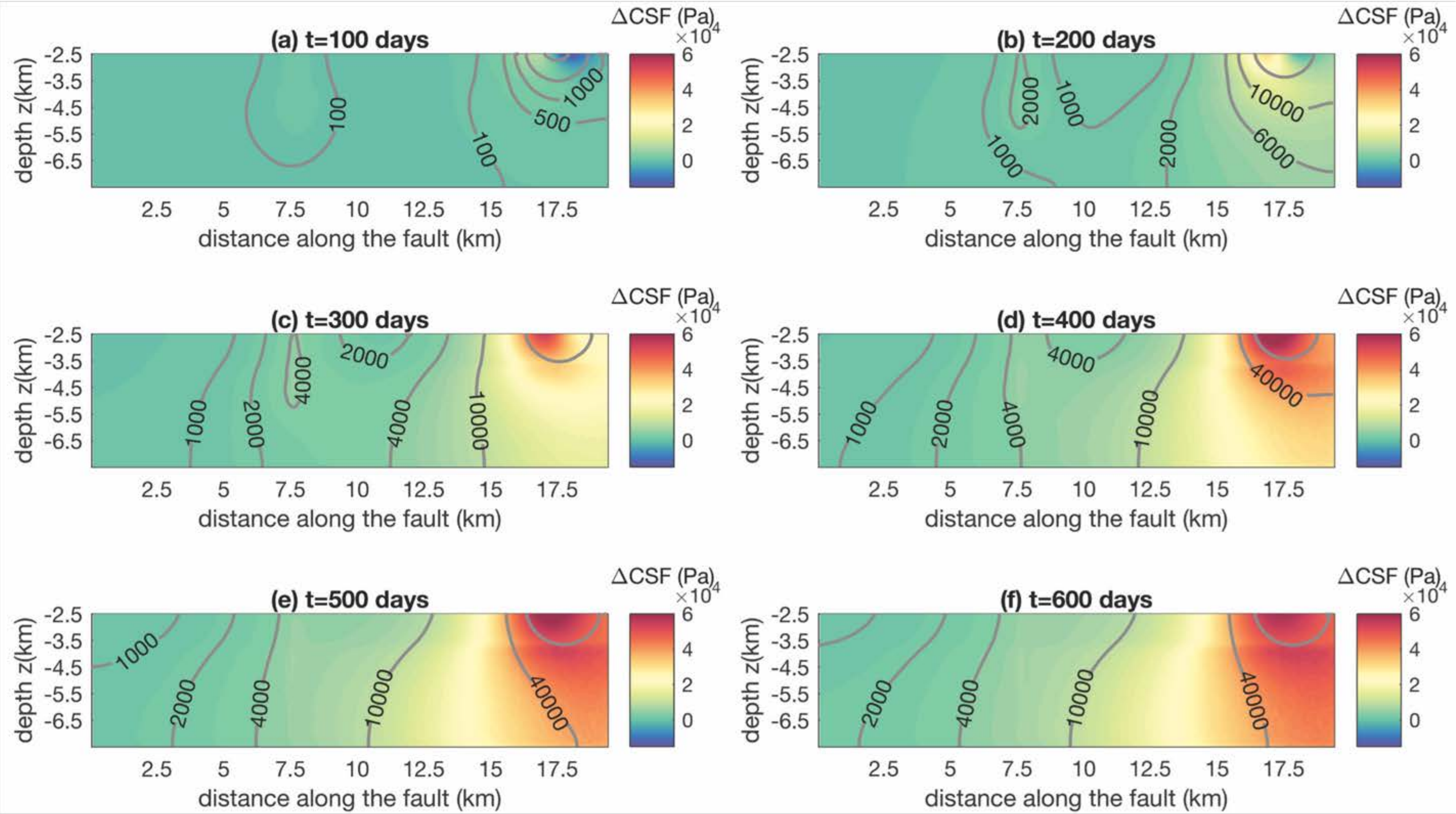
- Pore pressure keeps increasing after stopping injection in the Guy-Greenbrier fault.

Change in overall Coulomb stress: $\Delta CFS = \Delta\tau - f\left(\Delta\sigma - \Delta p\right)$



ΔCFS is positive → EQ is likely to be triggered. So, either an increase in shear stress, caused by the poroelastic effect, or an increase in pore pressure due to fluid diffusion, can trigger an EQ.

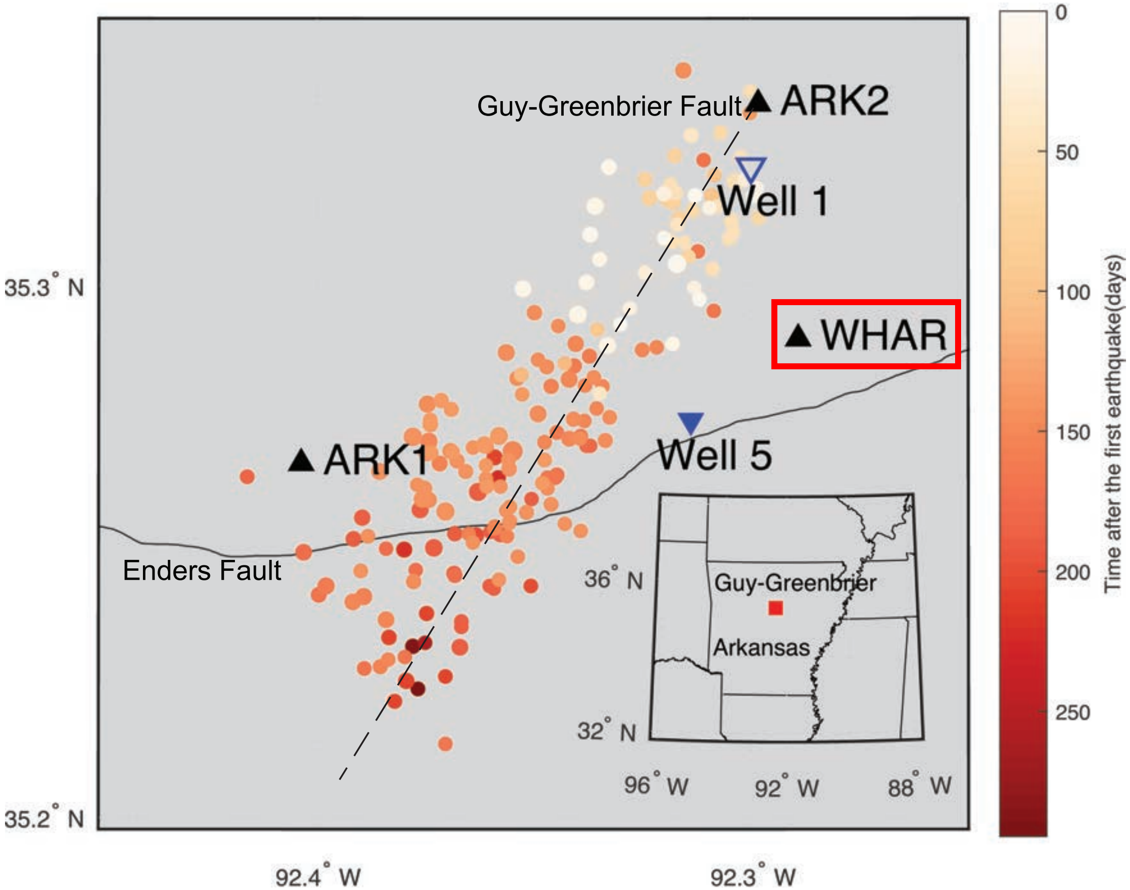
<u>Change in overall Coulomb stress:</u> $\Delta CFS = \Delta\tau - f\left(\Delta\sigma - \Delta p\right)$



With time, the increase in Δ*CFS* goes deeper along the fault and propagates along the southeast side of the fault, which is consistent with the seismicity propagation.

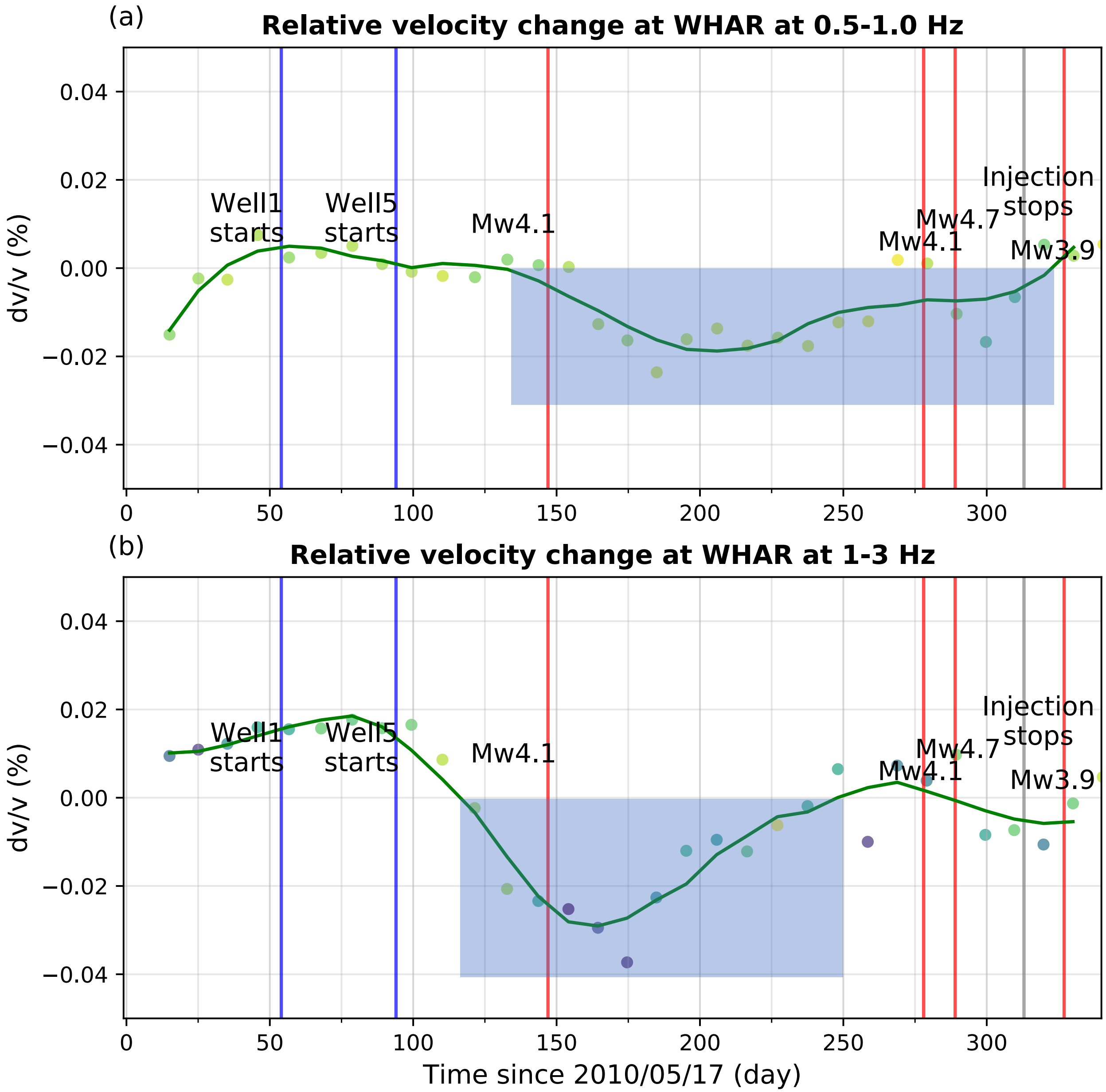
Monitor structure response: ambient noise

We use single-station correlation functions to monitor the structure velocity change after the injections.



- Use 11-month-long continuous waveform from station WHAR.
- Use Moving-Window Cross-Spectral (MWCS) to calculate the relative velocity change.

Relative velocity change: dv/v



0.5-1Hz:

- Lower frequency band shows longer velocity decrease.

1-3Hz:

- Higher frequency band could recover more quickly.

Conclusions:

- Spatial and temporal evolution of permeability affects the fault response to fluid injection.
- Damage zones create a conduit-like system to diffuse pore pressure along faults and transport fluids, and pressure elevations, to deeper levels.

Related paper:

Yehya, A., Yang, Z., & Rice, J. R.(2018). “Effect of fault architecture and permeability evolution on response to fluid injection”, *Journal of Geophysical Research: Solid Earth*, 123. https://doi.org/10.1029/2018JB016550

- Structure response can be monitored to provide more evidence to track underground flow.

Research supported at Harvard by the NSF-EAR Geophysics Program (Grant EAR-1315447) and by the NSF Materials Research Science and Engineering Center (Contract DMR-0820484)