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

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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.

Yehya, Yang, and Rice (2018)
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]: Permeability measured on drill core taken from sites near fault strands slipped in 1995 Kobe earthquake
Model settings and testing

- 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)

- **Total time simulated** = 400 days
- **Host Rock**: 1000m
- **Damage Zone**: 20m
- **Fault Core**: 1m
- **Injection Well**:
  - radius = 0.3m
  - pressure = 2MPa

Observe pore pressure along this cutting line

Width: 2000m

[Diagram showing fault geometry with specified dimensions.]
Model settings and testing

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

What we are focusing on?

Fault response to fluid injection:
1. Presence of damage zones
2. Poroelastic coupling
3. Time dependent permeability

Total time simulated = 400 days
Host Rock: 1000m

Width: 2000m

Observe pore pressure along this cutting line
Model settings and testing

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

- Fault core: low permeability
- Damage zone: high permeability
Effect of damage zones on pressure diffusion

Pore pressure change ($\Delta p/p_{inj}$) 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

“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:

- 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”.

All seismic locations here from USGS Catalog

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

COMSOL FEM model:
An attempt to understand the nucleation of these events. Include: Anisotropic damage zones surrounding fault core; Poroelastic coupling; Permeability evolution.

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

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

10 km

20 km

20 km

Confining Unit
Ozark Aquifer
Precambrian Basement

Well 1
Well 5

Started 7 July 2010
Peak: $62 \times 10^3$ m$^3$/mo.

Started 16 Aug 2010
Peak: $19 \times 10^3$ m$^3$/mo.
Permeability setting

Permeability in the fault zone

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

\[ k_{parallel} = 100 \times k_{normal} \]

Permeability in the model

<table>
<thead>
<tr>
<th>Layers</th>
<th>Permeability ( (m^2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confining Unit</td>
<td>( 10^{-16} )</td>
</tr>
<tr>
<td>Ozark Aquifer</td>
<td>( 10^{-15} )</td>
</tr>
<tr>
<td>Basement</td>
<td>( 10^{-21} )</td>
</tr>
</tbody>
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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.
As depth increases, pore pressure change concentrates only on damage zones.

Base of Ozark Aquifer (a) depth=3700 m

Deep in Basement (b) depth=4900 m

Guy-Greenbrier fault
Well 1
Well 5
Enders fault

Pressure change on horizontal cross-sections, approx. 1.5 yr later
Pore pressure change in the faults

- Pore pressure keeps increasing after stopping injection in the Guy-Greenbrier fault.
Change in overall Coulomb stress: \( \Delta CFS = \Delta \tau - f(\Delta \sigma - \Delta p) \)

\( \Delta CFS \) is positive \( \rightarrow \) 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.
Change in overall Coulomb stress: \[ \Delta CFS = \Delta \tau - f(\Delta \sigma - \Delta p) \]

With time, the increase in \( \Delta CFS \) 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:**


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

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