Induced Fault Reactivation and Hydraulic Diffusivity Enhancement: Insights from Pressure Diffusion Inversion in Laboratory Injection Tests

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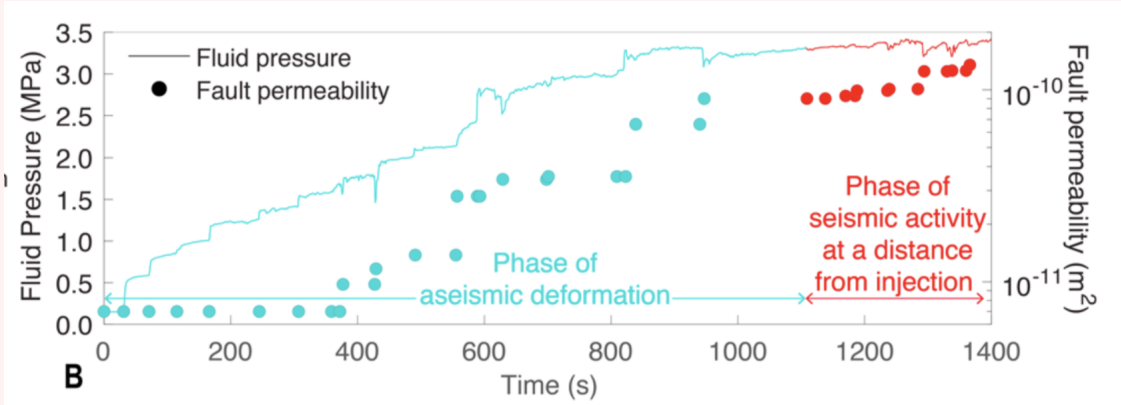
- Several observations show an increase of fault's permeability with effective stress reduction and slip accumulation: **Fully coupled process**

  Example: Permeability Increase observed during in-situ induced fault reaction reactivation experiments

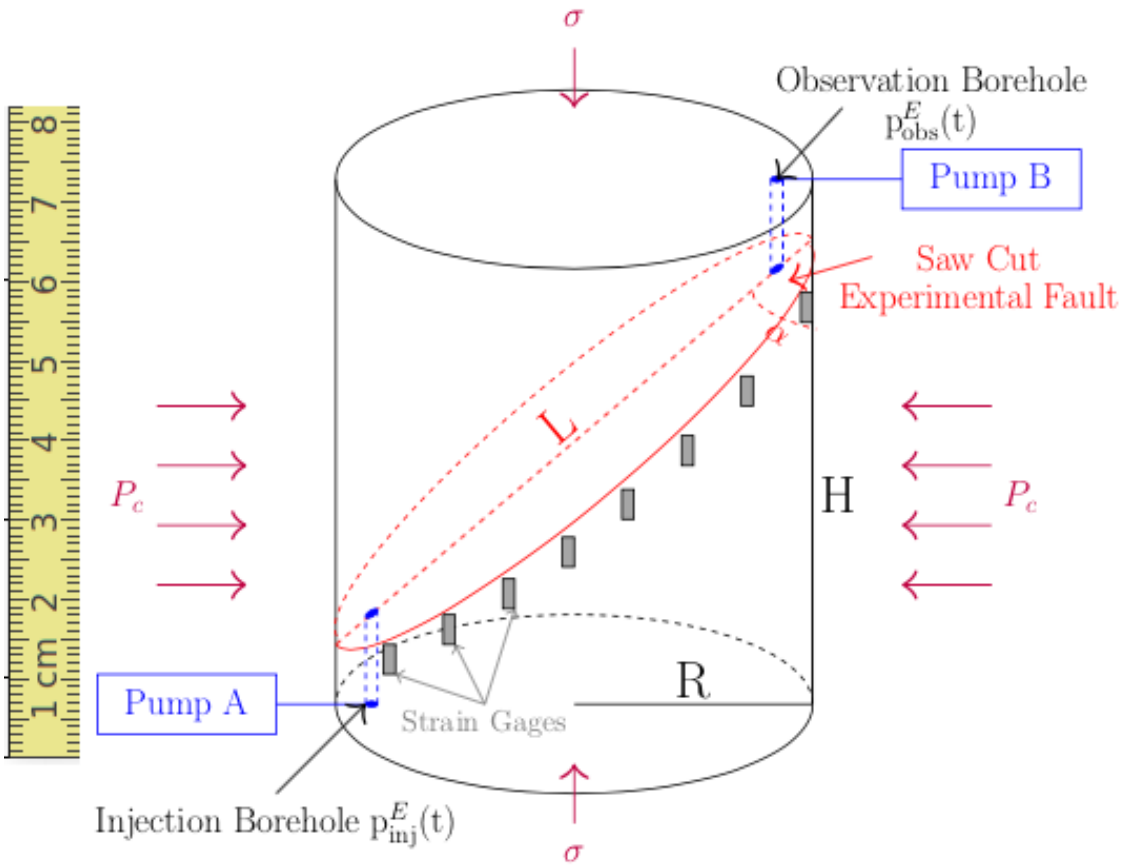


modified from (Cappa *et al*, JGR 2018)

- **Problem:** Changes is the Permeability or Hydraulic Diffusicity are still not fully explored nor understood.

- **GOAL: Investigate Hydraulic Diffusivity Changes** using **Laboratory Injection Experiments** and **Pressure Inversion Techniques**

Fault Slip Reactivation Experiments

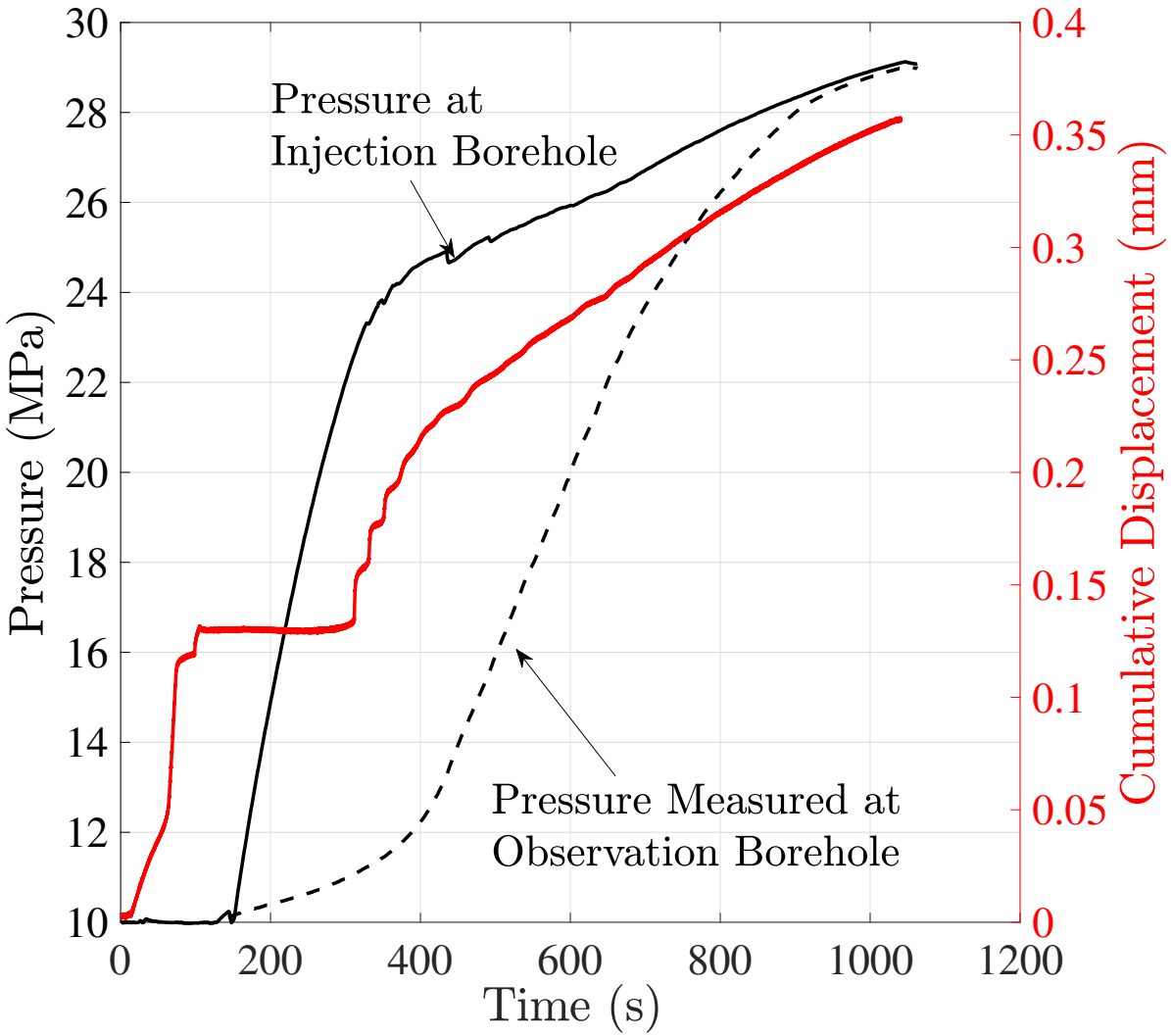


Collaboration with François Passelègue, from EPFL Lausanne

Experiments

- Saw cut fault at 30°
- **Fluid is injected from Pump A**
- Constant injection pressure rate
- **Pump B is sealed** and used to measure the pressure
- Test of **3 confining pressure**: 30, 60 and 95 MPa

Experimental Data: Example at 30 MPa



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Observations

- Two measures of pore pressure
- Average displacement along the fault

GOAL

Find Diffusivity vector D(x,y,t) that can explain the Data

Methodology: Diffusivity Inversion

Direct Problem: Non-linear 2-D Diffusion Equation (No mechanical coupling)

$$\frac{\partial \mathrm{p}}{\partial \mathrm{t}} = \boldsymbol{\nabla} \cdot D \nabla \mathrm{p}, \qquad \frac{\partial p}{\partial n} = 0 \ \& \ p(x_{\mathrm{Inj}}, t) = p_{\mathrm{inj}}(t),$$

As we have only two measures of pressure: Choose to invert an **Effective Diffusivity vector D(t)**

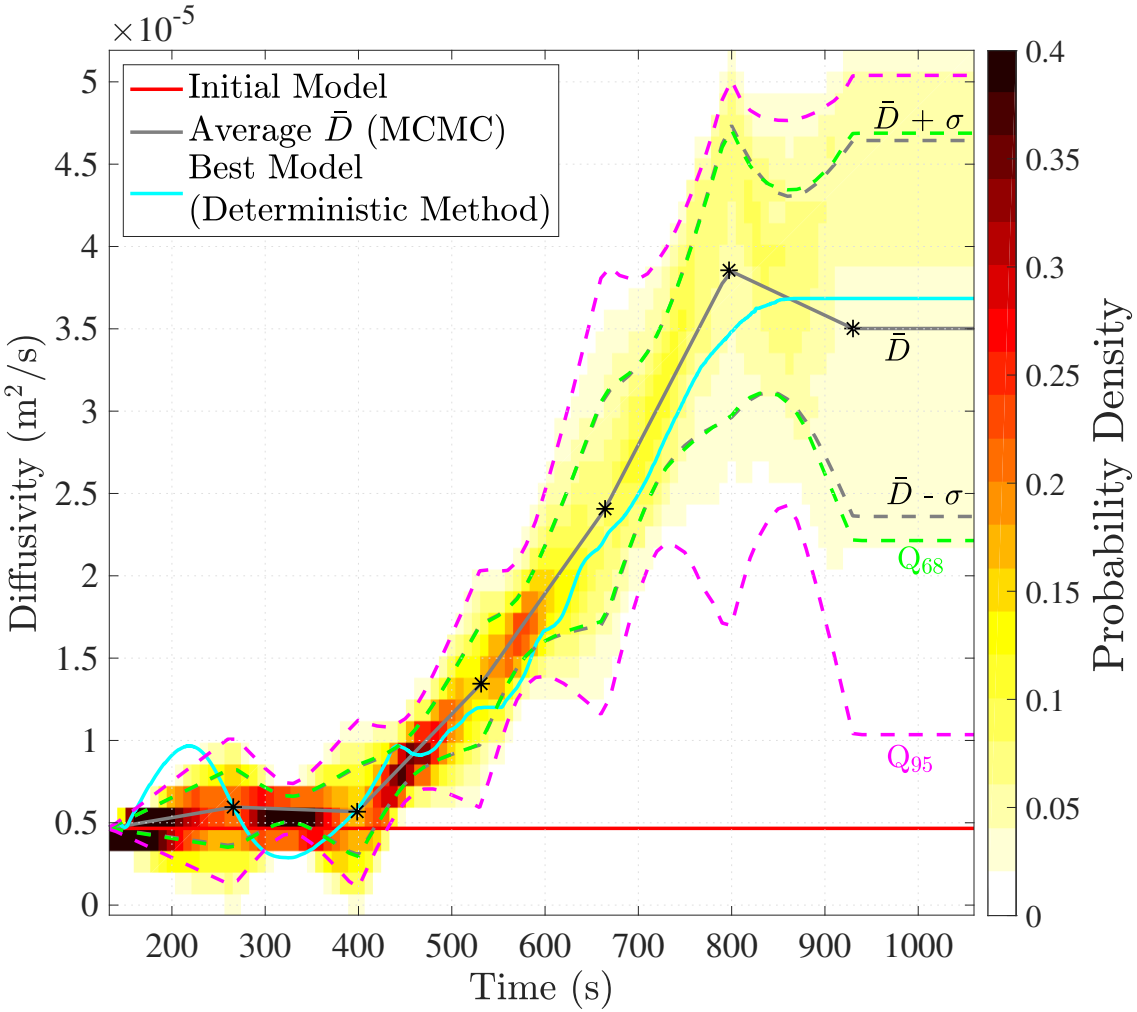
Deterministic Approach

- Adjoint State Method (Plessix, 2006)
- Iterative Approach
- Estimate the **Best Model**

Probabilistic Approach

- Markov Chain Monte Carlo Algorithm (Metropolis et al, 1953, Hastings, 1970)
- Large number of forward computations
- Estimate the **Associated Uncertainties**

Methodology: Application



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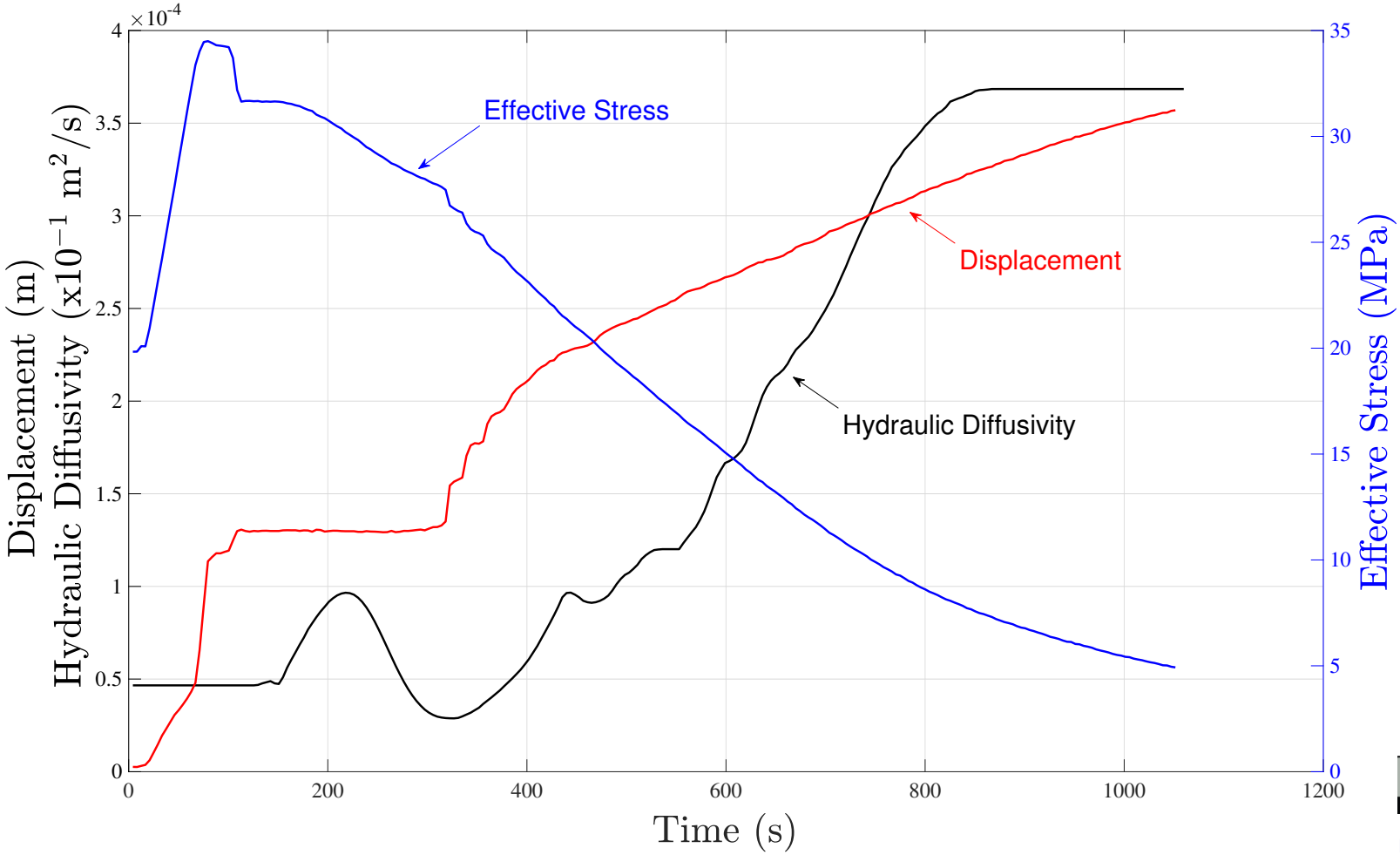
HIGHLIGHTS

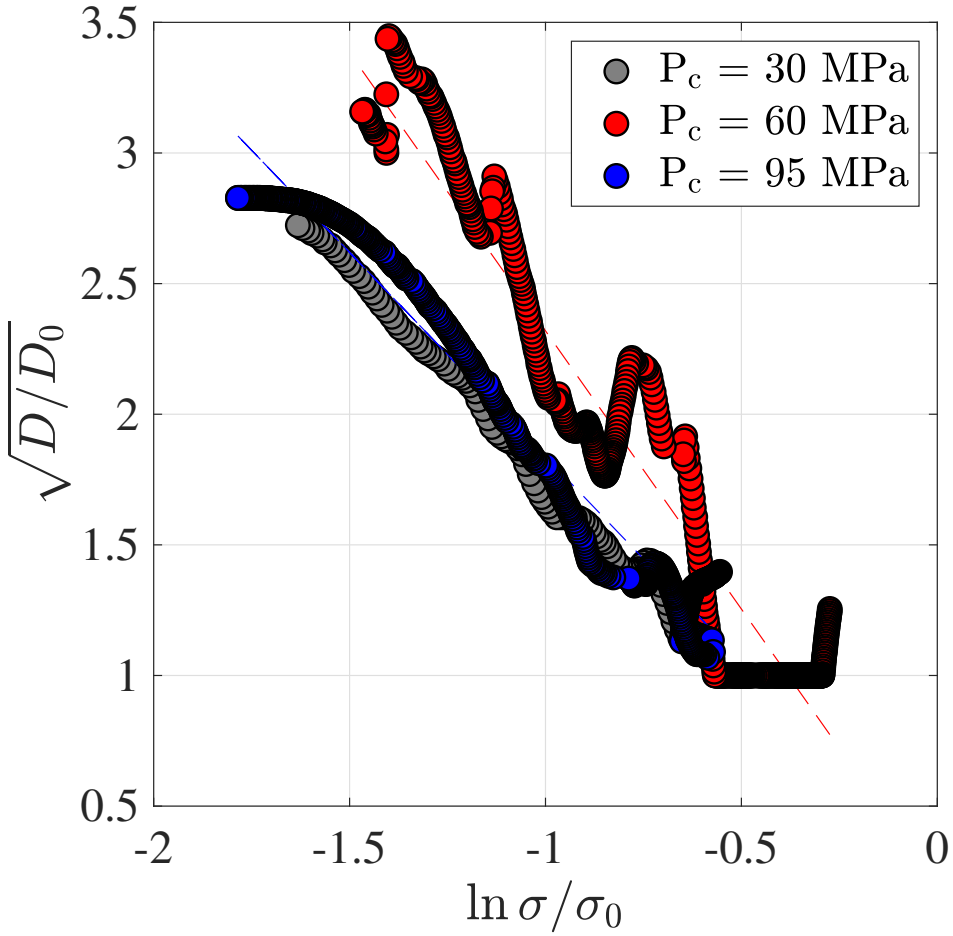
- Method is quite **Effective**
- Solution is well constrained in the domain [400–800] seconds
- Increase in almost one order of magnitude of the hydraulic diffusivity

Hydraulic Diffusivity Changes

Fluid Injection –> Pore Pressure Increase –> Reduction of Effective Stress –> Slip Accumulation



Diffusivity and Effective Stress



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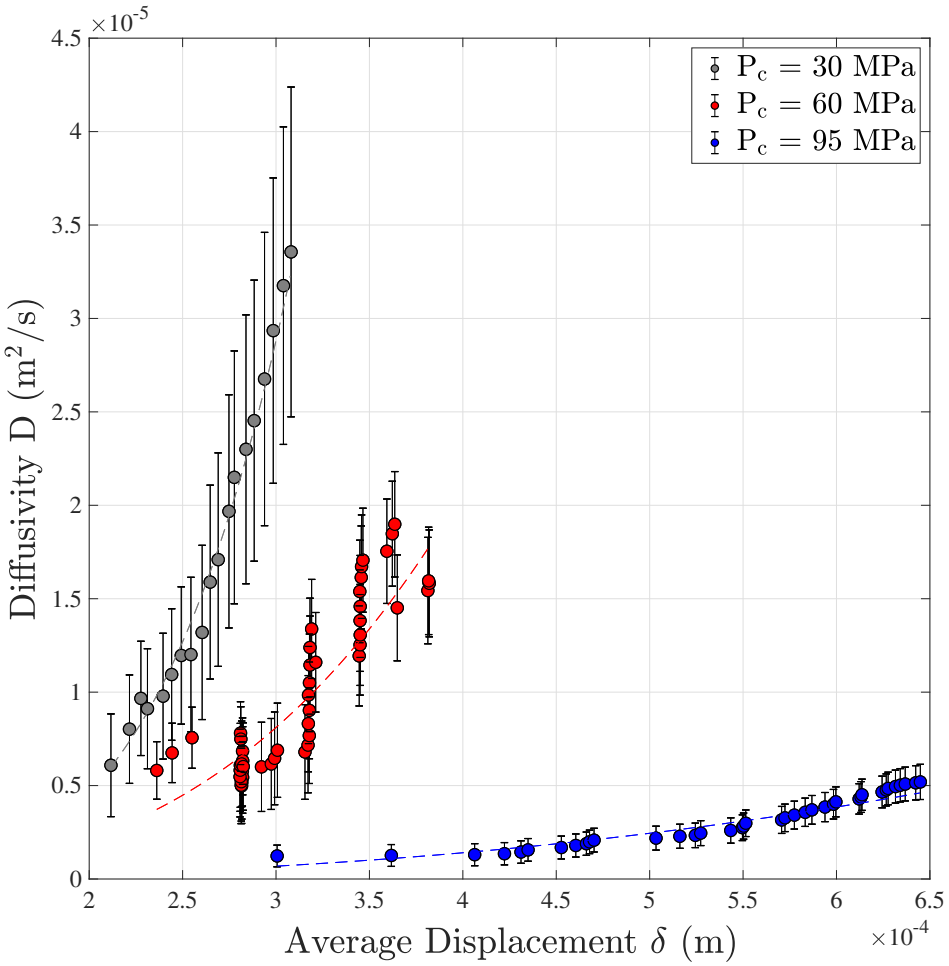
HIGHLIGHTS

- **A clear dependence between the variation of the hydraulic diffusivity and changes in effective stress.**
- Nonetheless, a different slope is observed at 60 MPa (experiment presenting a different slip behavior).
- Is there an **EFFECT** of the **Shear Displacement** on the diffusivity changes?

Diffusivity and Shear Slip Accumulation



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- Hydraulic diffusivity increases with shear displacement.
- This investigation remains however limited, as we only have one measurement of slip along the fault plane.
- We expect heterogeneous hydraulic diffusivity changes with respect to localized slip events along the fault plane. This remains to be investigated in future studies.

Conclusions & Perspectives

Numerical Approach

- Our numerical inversion approach proved to be quite effective.
- Very easily implemented.
- Can be extended to consider multiple input/output pressure boreholes, so to map a spatially heterogeneous hydraulic diffusivity.

Fluid Induced Fault Reactivation

- Hydraulic diffusivity strongly depend on the reduction of the effective stress.
- A relation with shear displacement is observed as well, but remains to be further investigated considering a spatially heterogeneous diffusivity.

Perspectives: Fully-coupled Hydro-mechanical modeling

- Investigate how hydraulic diffusivity changes could affect induced fault reactivation.

Thank you for your attention.

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