Role of fault zone poro-plasticity in governing the transition from aseismic to seismic rupture

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and many other collaborators

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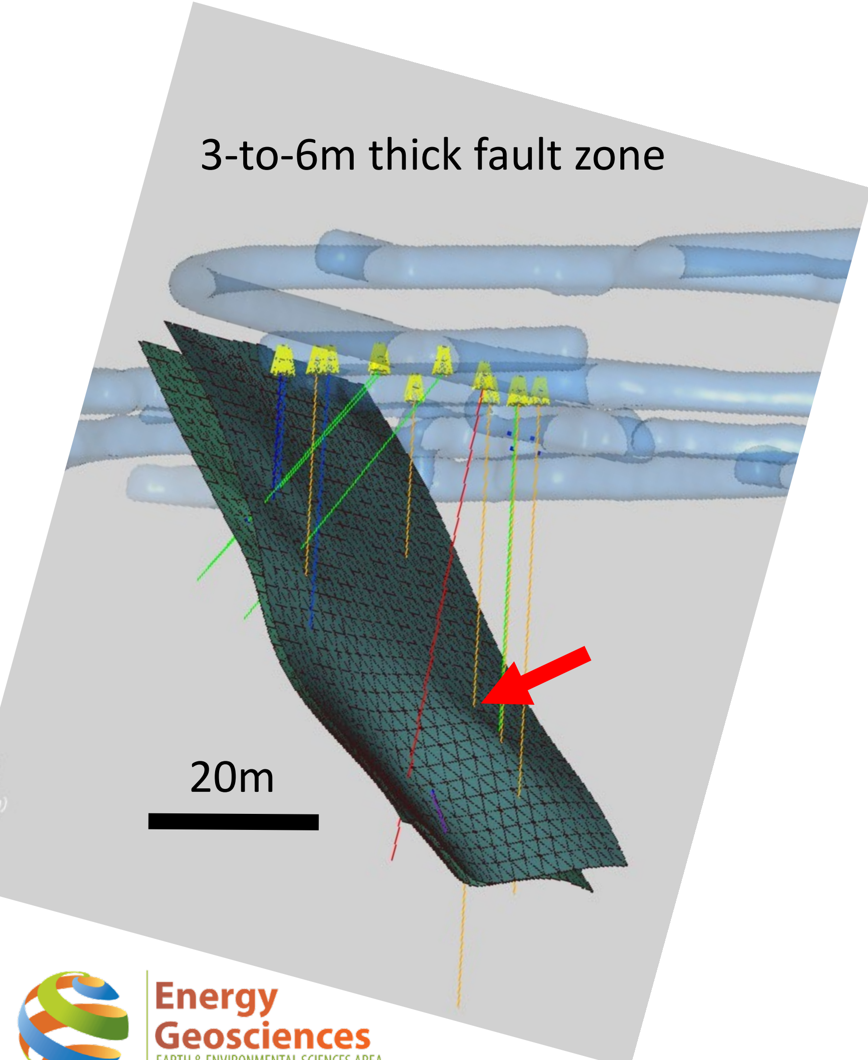
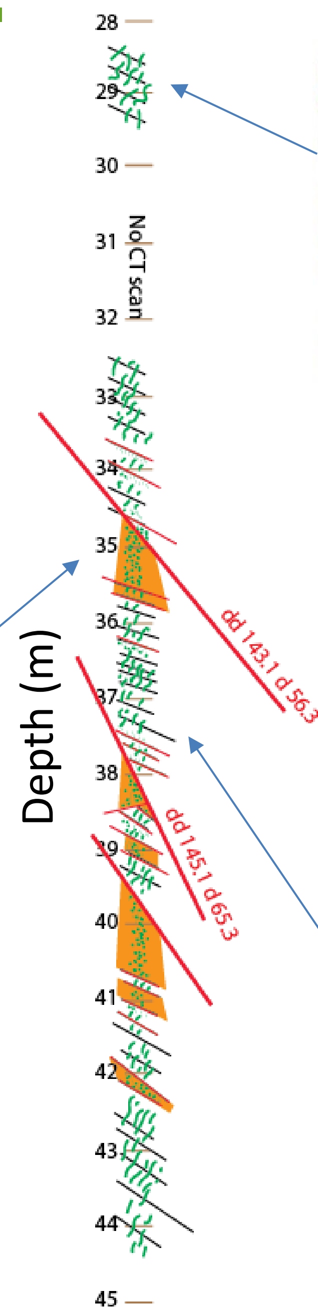
Field Scale Fault Zone Activation Experiments

Several field experiments conducted over the past decade on faults zones affecting clay rocks, carbonates and crystalline rocks.



Scaly clay fabric

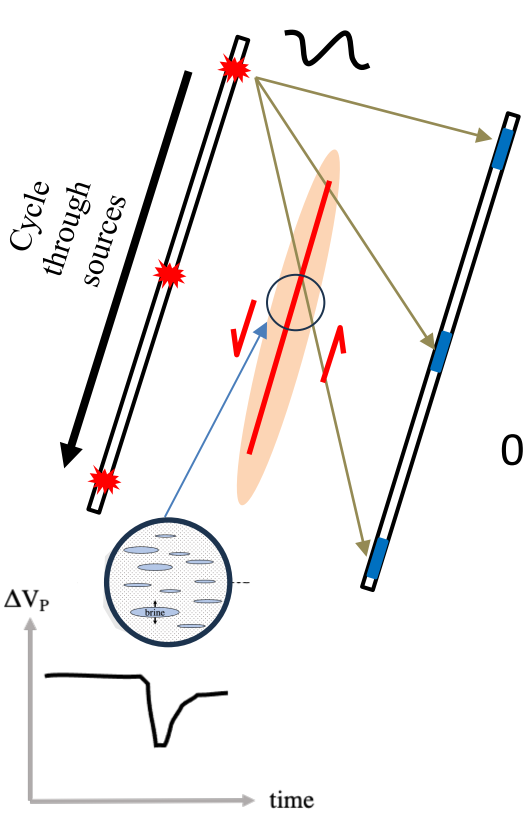


Intact rock

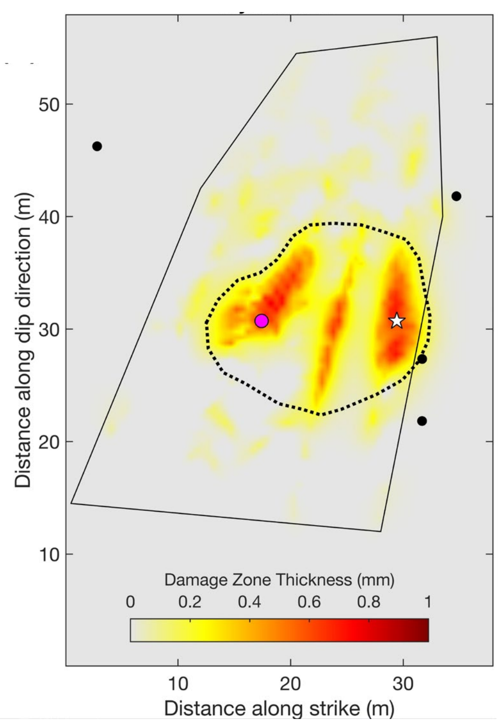
Fractured Damaged Rock

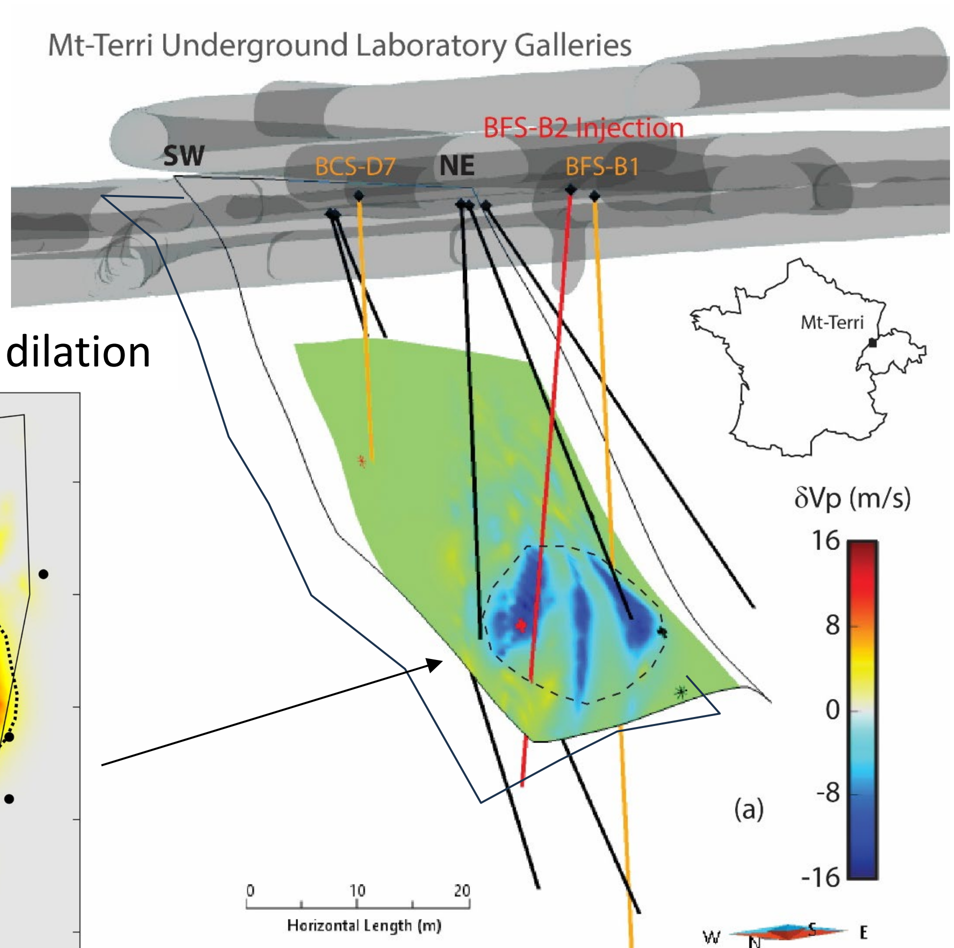
A dense monitoring in place

Active seismic imaging shows a large heterogeneous fault zone dilation



0.2 to 1 mm fault zone dilation



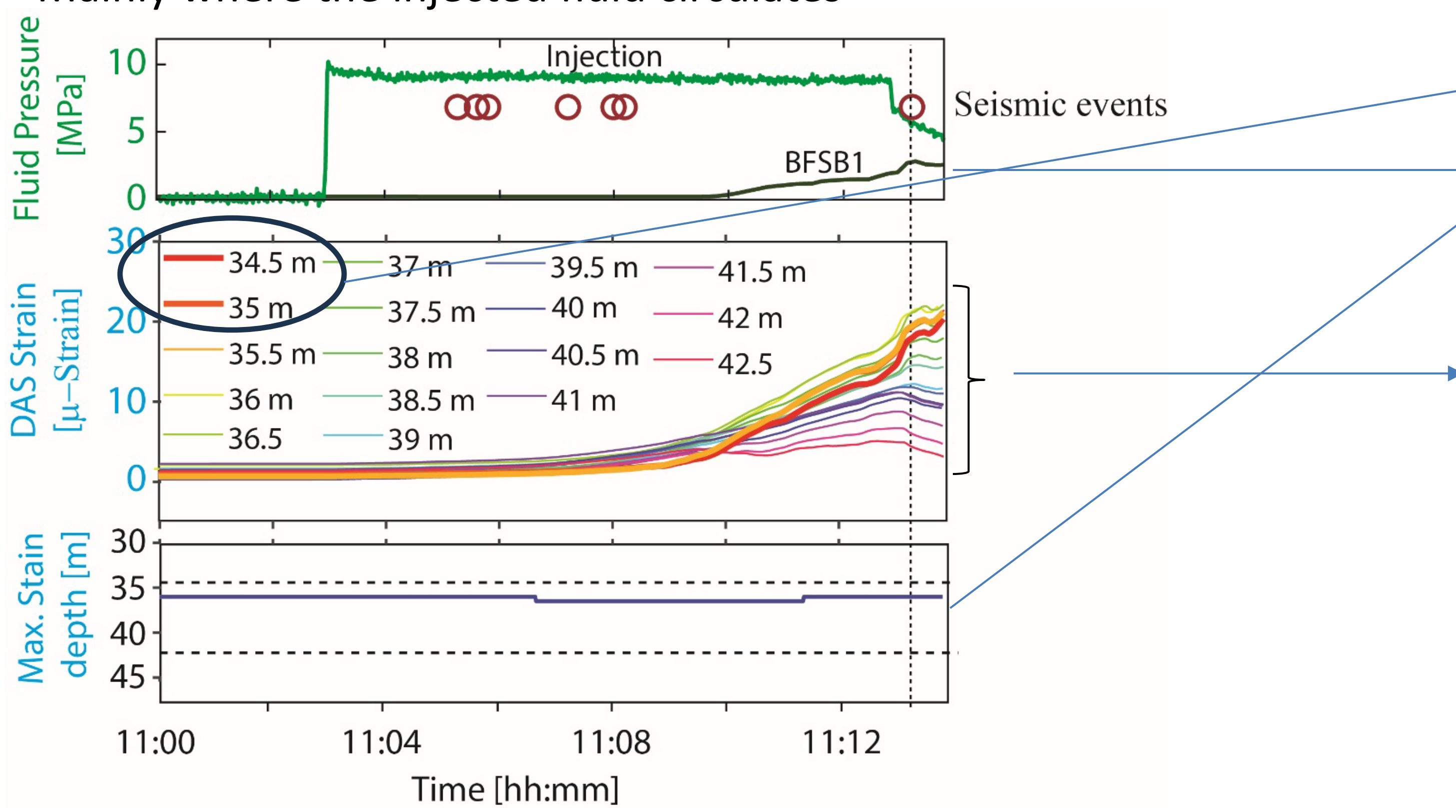


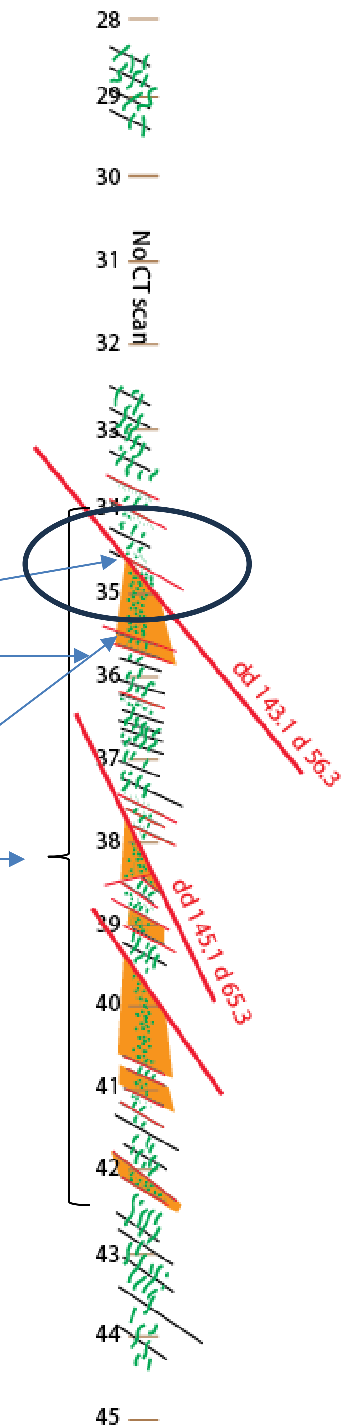
A dense monitoring in place

DAS fibers show a heterogeneous strain and strain-rate distribution in the fault zone

- Extensional Strain distributed in a complex way across the entire fault zone thickness
- Higher strain rate across the Top Main Shear Zone
- Maximum strain at the high-deformable scaly clay lens

Mainly where the injected fluid circulates





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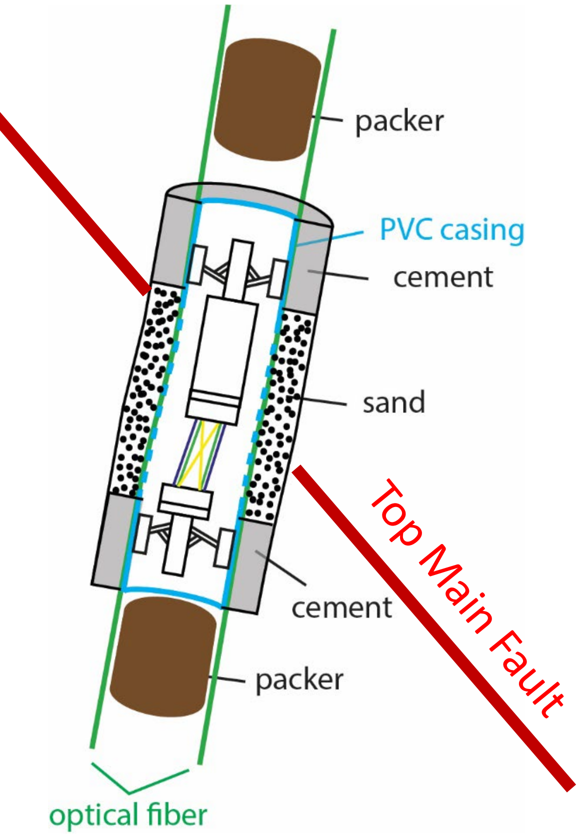
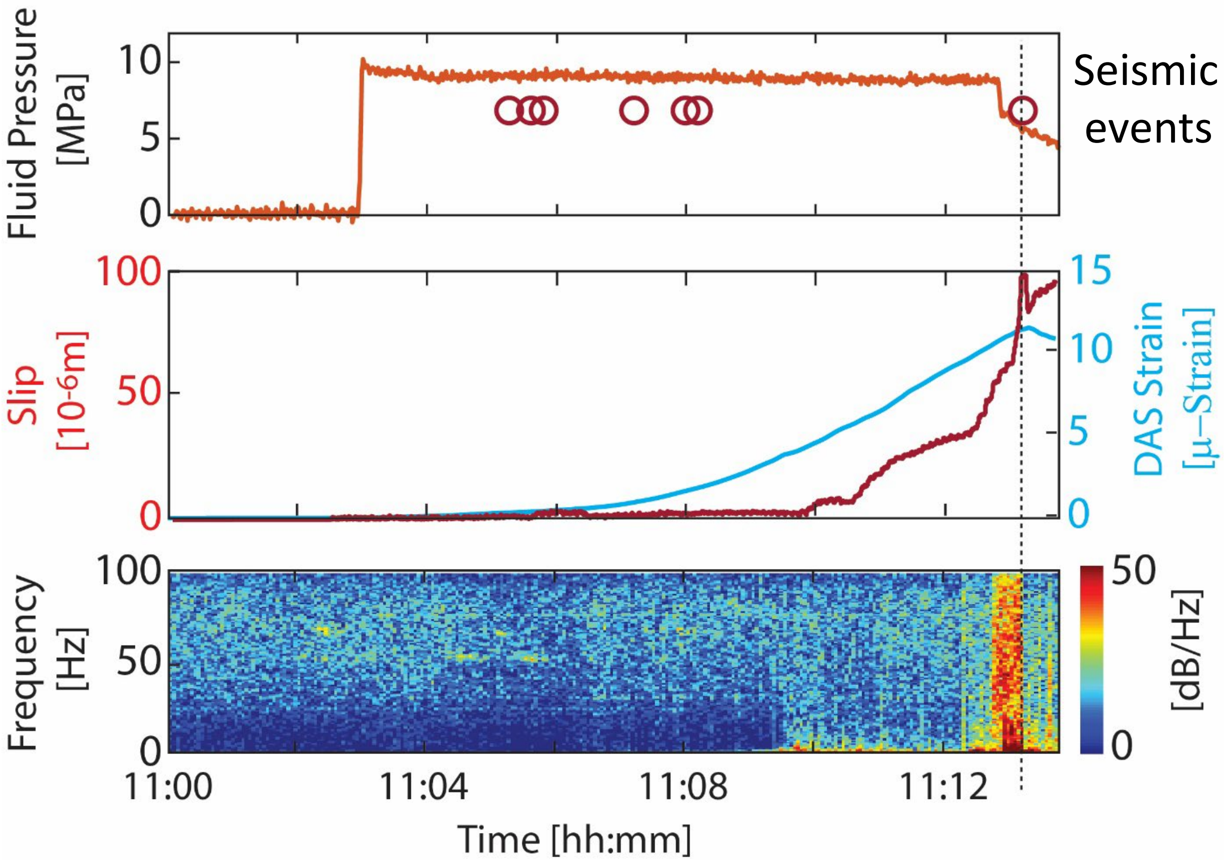
A dense monitoring in place

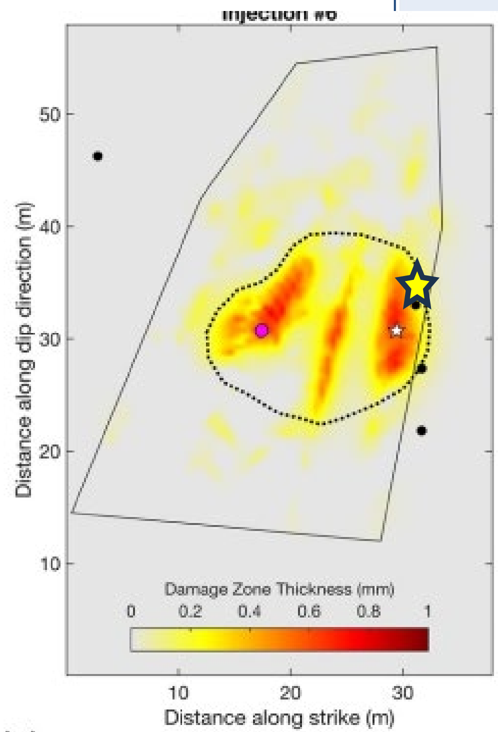
Fault zone extension (DAS) precedes slip acceleration on the Principal Shear Zone

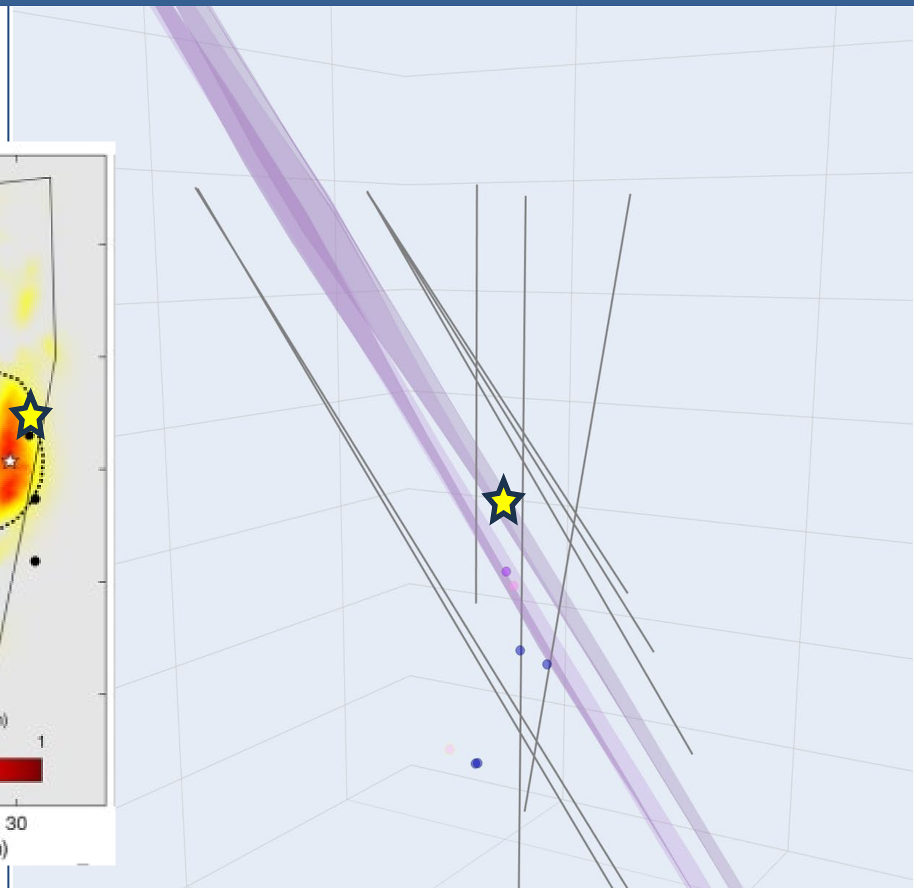


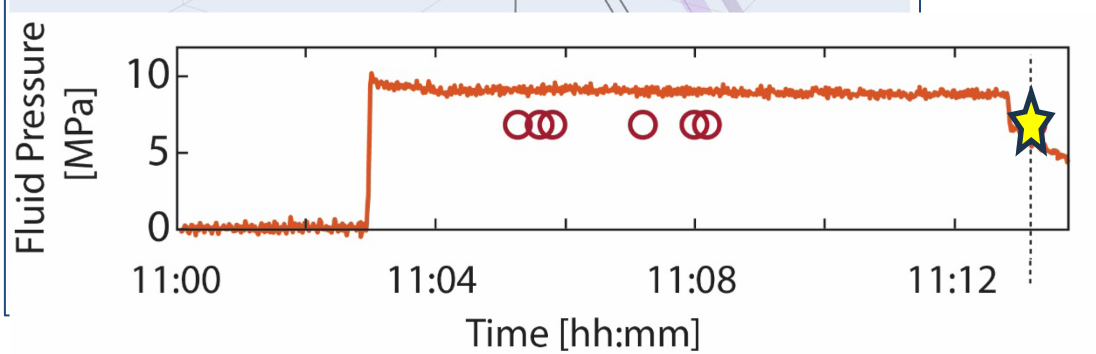


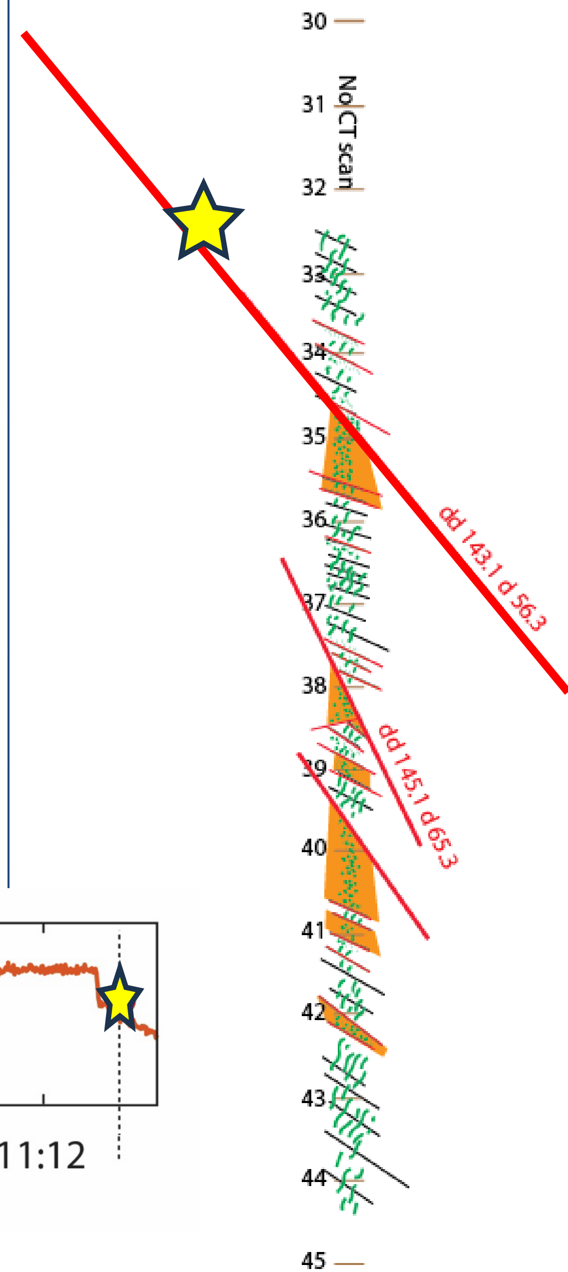
A dense monitoring in place

Seismic event localized on the principal shear zone









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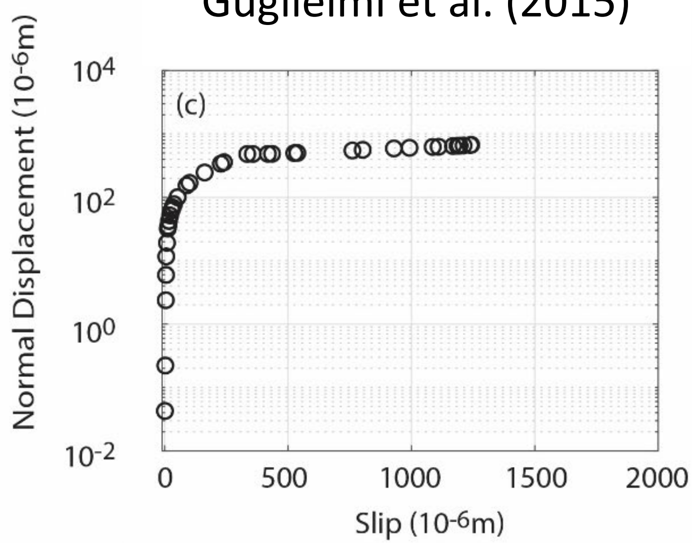
Same observations in other fault activation experiments involving other types of rocks

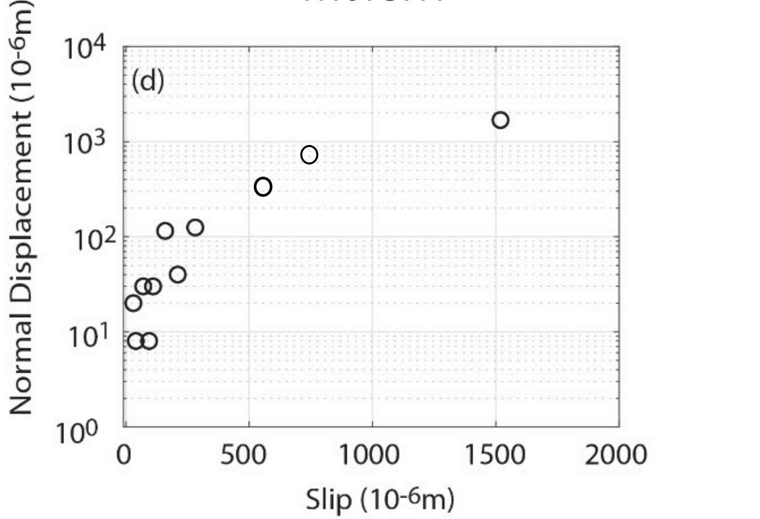
Most of the fault zone bulk dilation during activation occurs at small cumulative slip

When slip becomes dominant, eventually some induced seismic events

Carbonates
Guglielmi et al. (2015)



Argillites
MtTerri



Towards a Physics That considers Fault Zone Bulk Plasticity

These experiments show more than “only” frictional weakening

There is a large dilation of the entire fault zone that is not only related to slip on the fault principal surface.

Additionally, seismicity is observed, although dilatancy is suspected to promote stability.

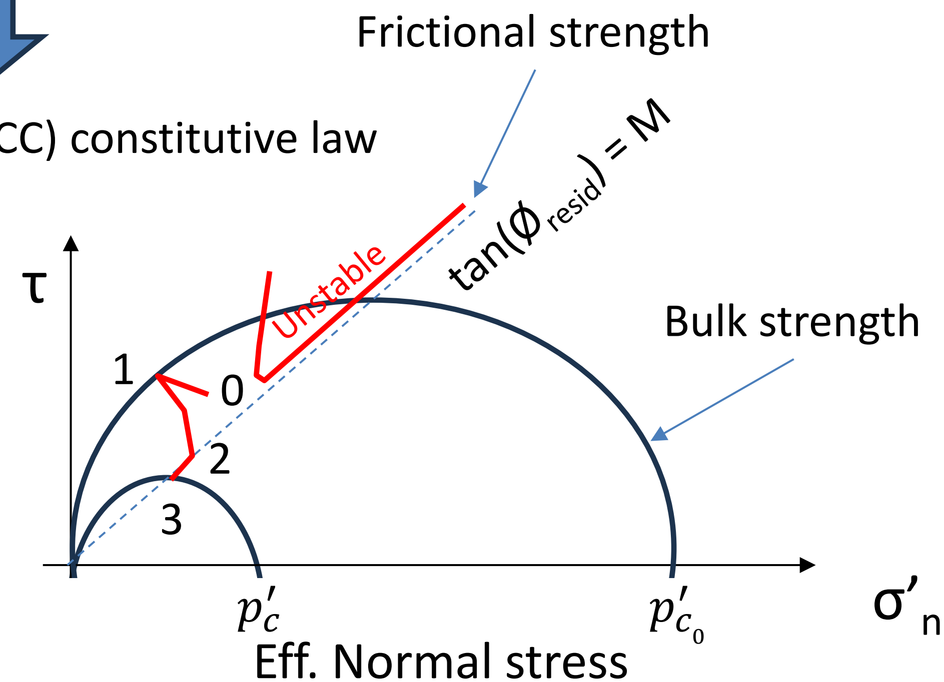
Modified Cam Clay (mCC) constitutive law

Fault rupture envelop equation

$$f(\sigma'_n, \tau, p'_c) = \sigma'^2_n + \sigma'_n p'_c + \frac{3}{M^2}\tau^2$$

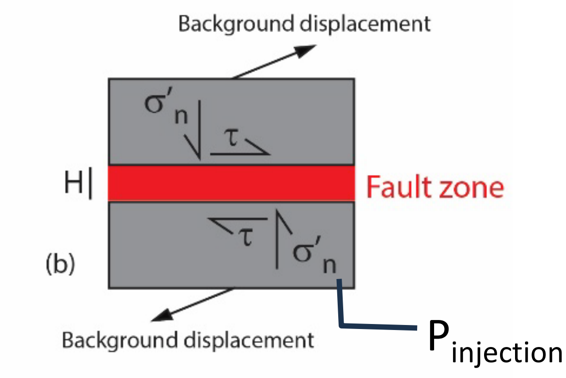
Fault bulk compressive strength varies with the normal displacement

$$p'_c = p'_0 e^{-\alpha \Delta u_{n/2}}$$



Matching the mCC parameters on Field Experiment datasets

We adapted the formulation from Piau et al. (2023)
to a fluid injection case
in an initially inactive fault zone



Pore pressure variation is calculated with

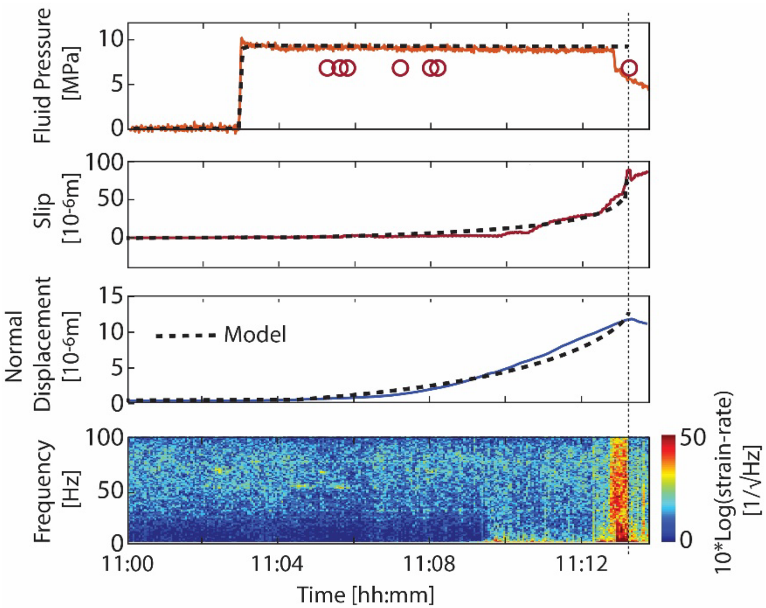
$$\Delta P_f = -S\Delta u_n + R(P_{injection} - P_{initial})$$

Where S = $1/(H\phi C_{fl})$ is equivalent to a global fault Skempton coefficient
And R is equivalent to a permeability

At failure, normal and tangential displacement velocities vary with the plastic multiplier K

$$\dot{u_n} = \dot{K}(2\sigma'_n + p'_c)$$

$$\dot{u_s} = \dot{K}\frac{6}{M^2}\tau$$



Model is reproducing reasonably well
the slip acceleration
and the bulk plastic dilation
observed at Mt-Terri

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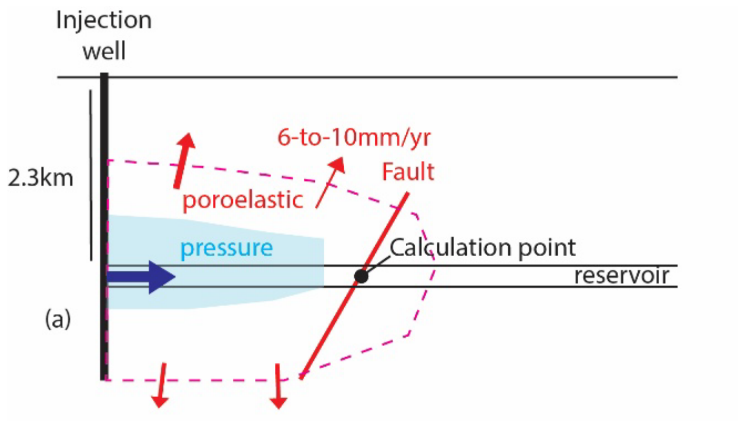
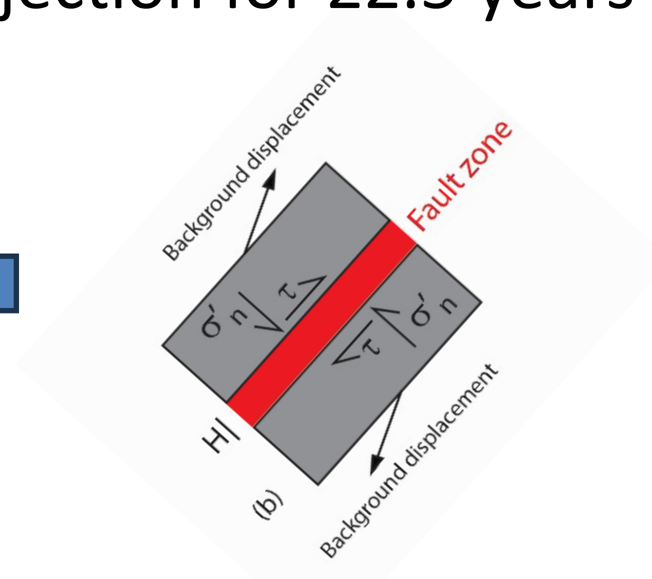
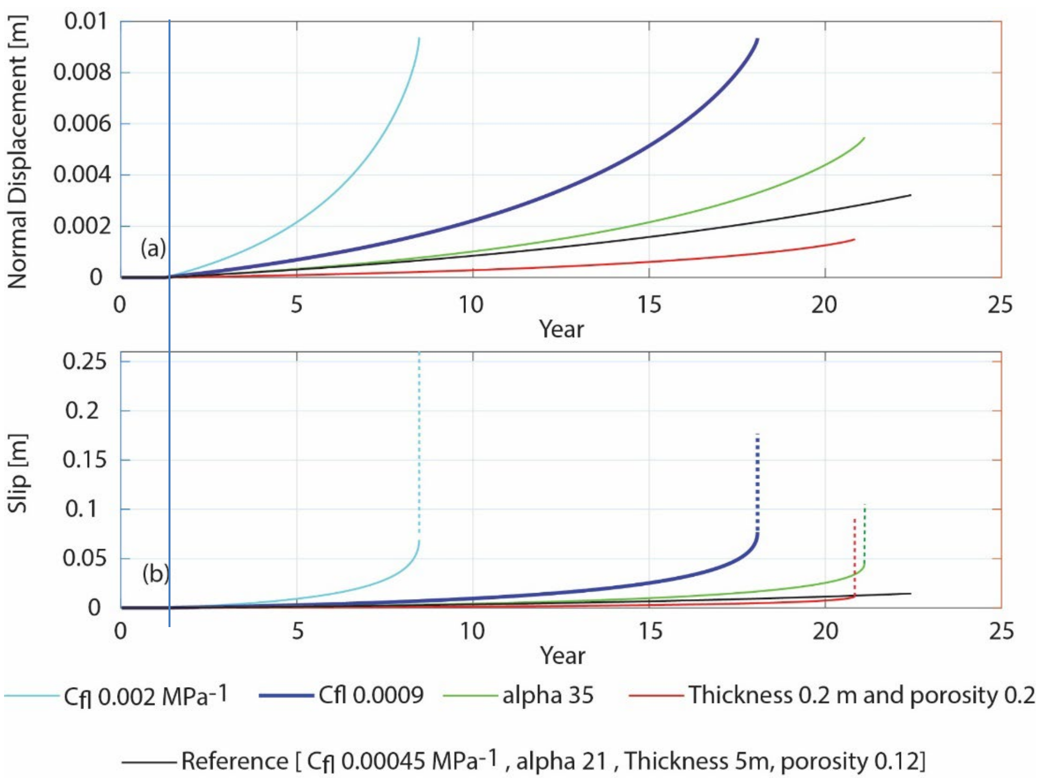
Parameters' Sensitivity and Consequences for larger scales…

Simulating a constant pressure injection for 22.5 years





Rupture Initiation



Slip acceleration is highly sensitive to

- The evolution of bulk compressive strength

$$p_c' = p_0' e^{-\alpha \Delta u_{n/2}}$$

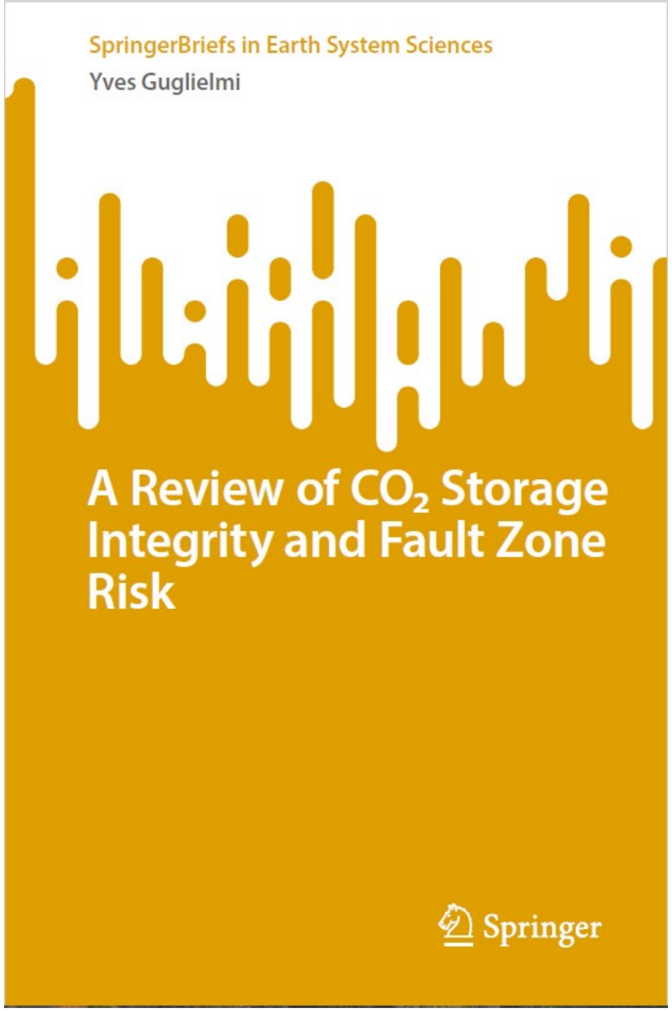
- Fault zone thickness and porosity
- Fluid compressibility in the Fault zone

Conclusion - Considering Fault Zone Bulk Poro-Plasticity…

Cam-Clay theory proves to be more general than a frictional-physics theory based on Coulomb failure and Rate-and-State formalism

(1) Important to consider faults as Zones
(2) Not only frictional mechanisms in the fault zones
(3) How the couplings between porosity and fluid properties evolve in these zones under shear is key

(4) More details in here →



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Thank You !