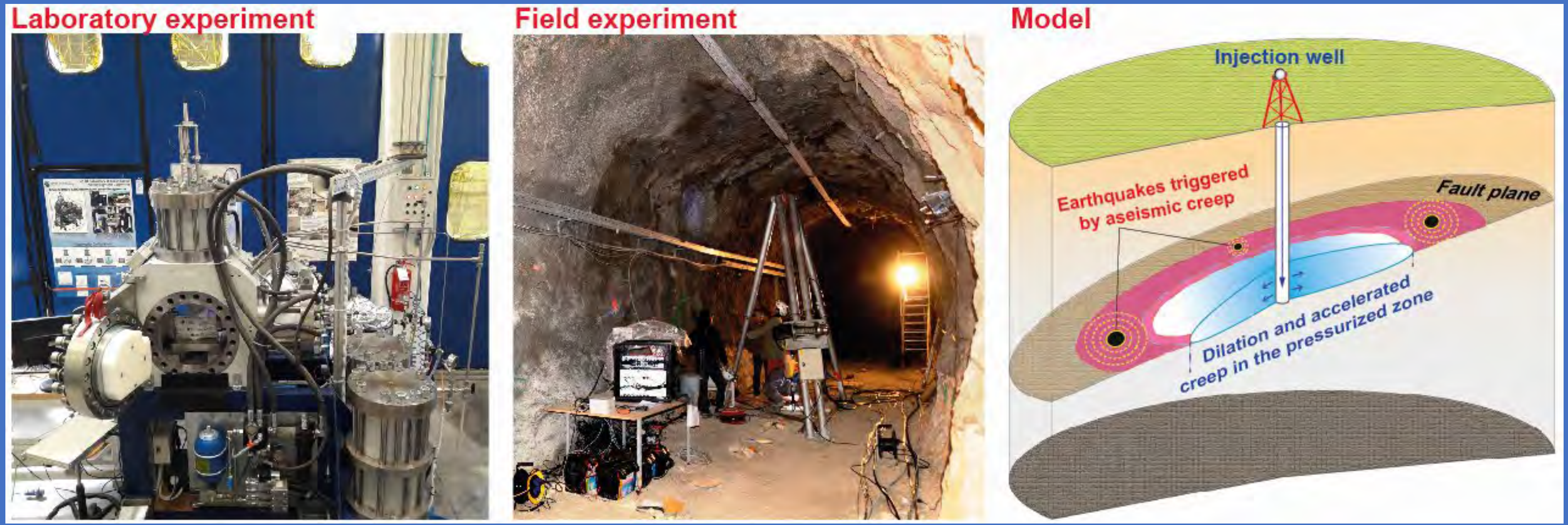
3rd Induced Seismicity Workshop, Davos, 5-8 March, 2019

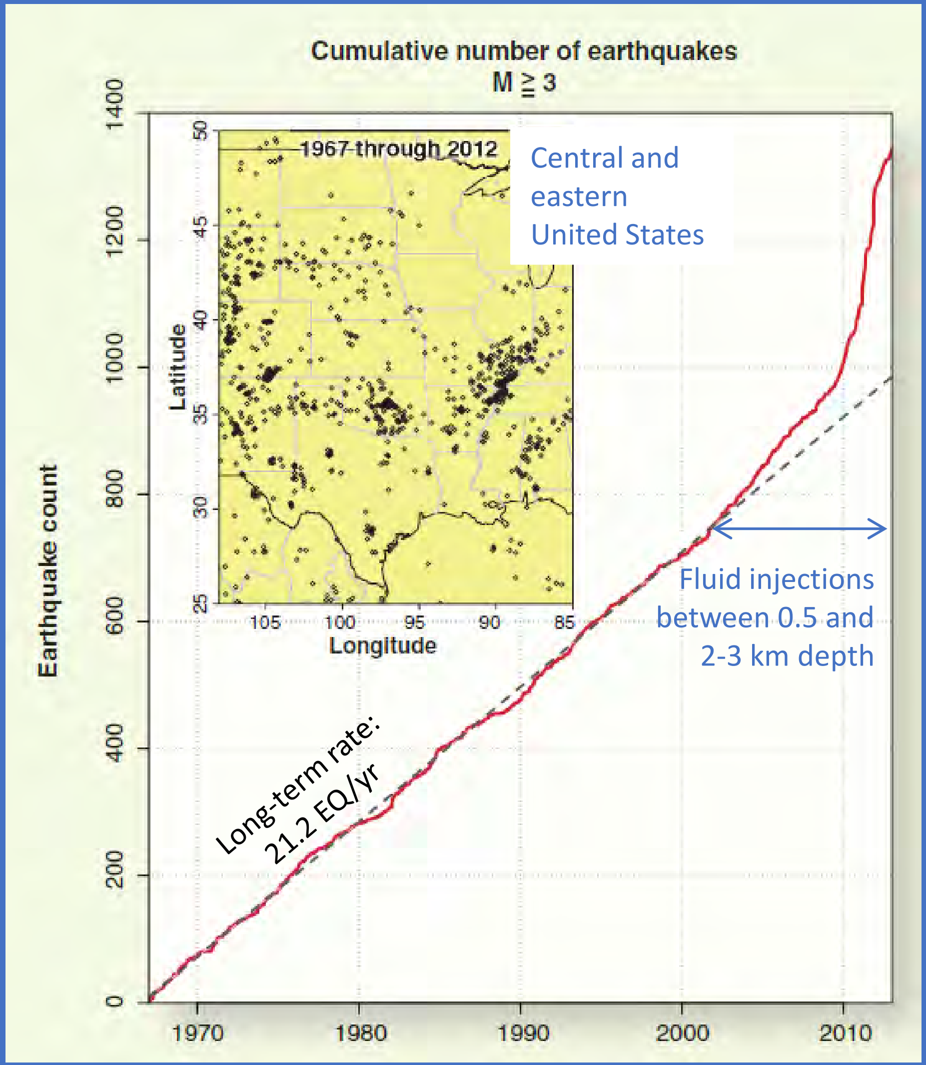
Injection-Induced Seismicity and Aseismic Fault Slip in Laboratory and In-Situ Experiments and Hydromechanical Models

Frédéric Cappa, Marco Maria Scuderi, Cristiano Collettini,
Yves Guglielmi and Jean-Philippe Avouac



Motivation

Evidence that fluid injections can trigger earthquakes



Injection-induced earthquakes

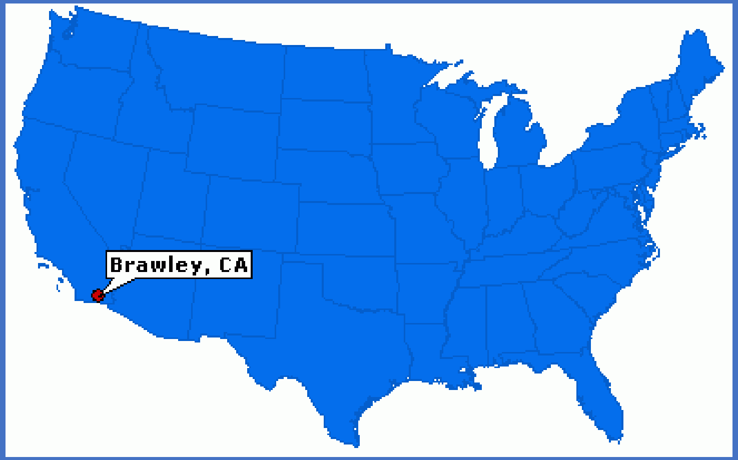
Ellsworth, Science, 2013

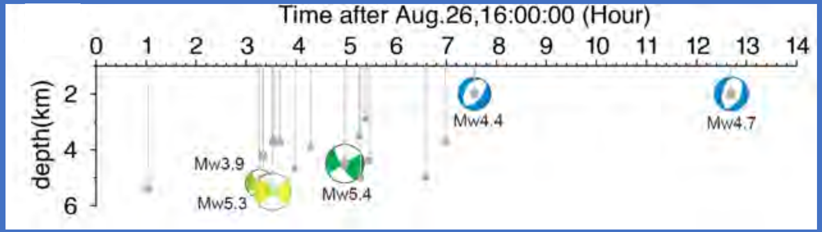
Motivation

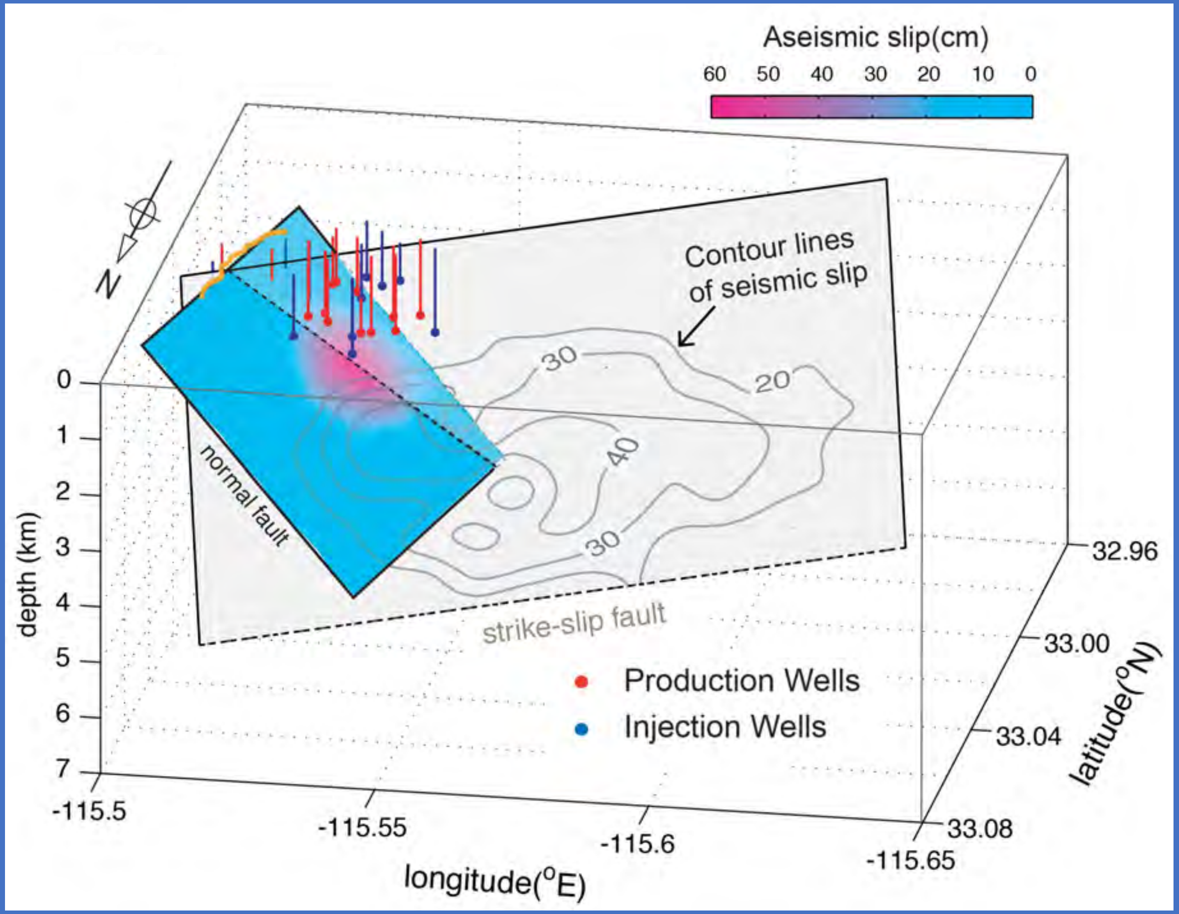
Evidence that fluid injections can induce aseismic slip, which then triggers earthquakes

The 2012 Brawley swarm triggered by injection-induced aseismic slip

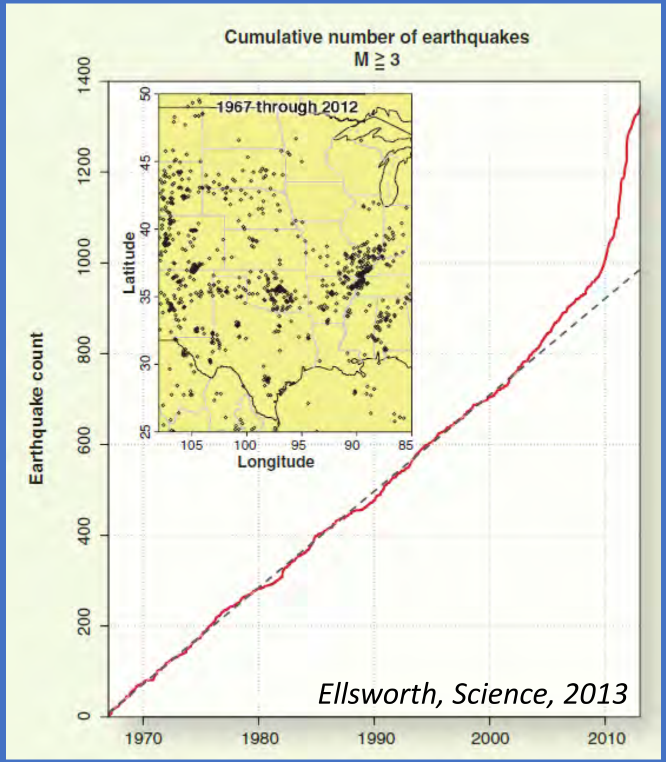
Wei et al, EPSL, 2015



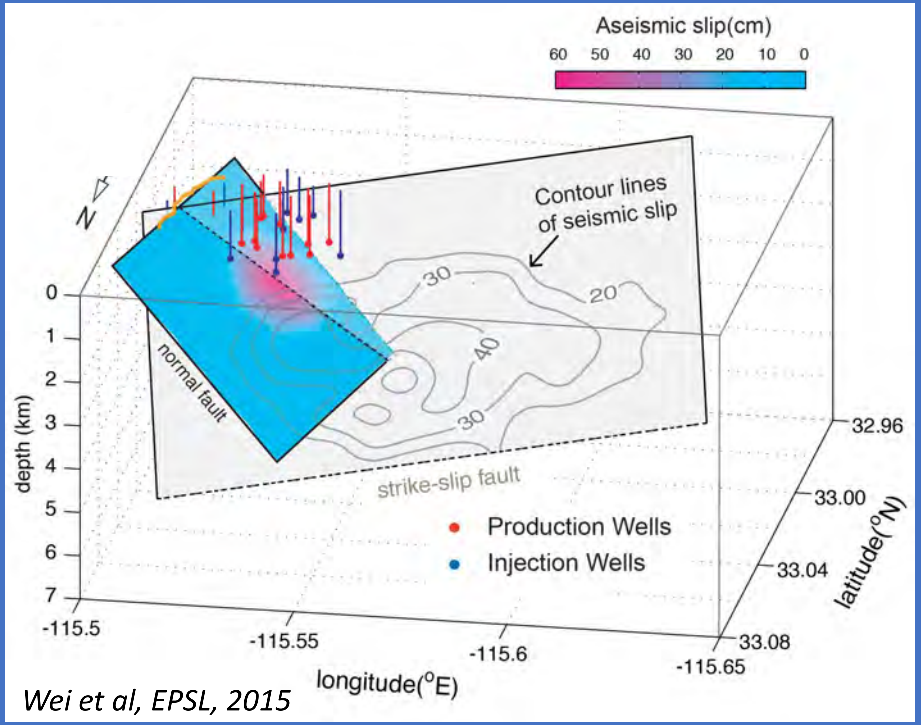




Earthquakes and Fluid Pressure



Fluid Pressure and Aseismic Slip



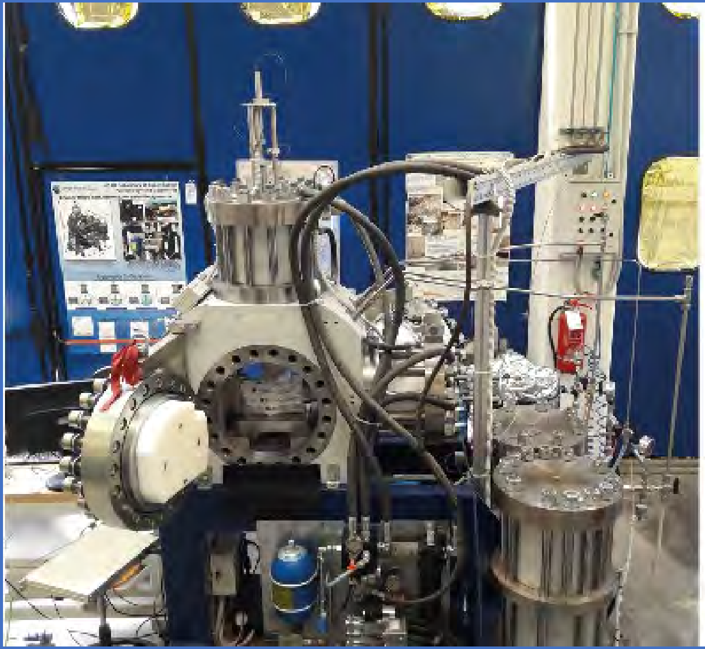
How fluids affect the mode of fault slip (seismic vs. aseismic) is an open question

Need to measure simultaneously fluid pressure, deformation and seismicity directly within fault zones under controlled conditions

BRAVA, Italy:
- Biaxial Apparatus in a Double Direct Shear configuration within a Pressure Vessel
- Sample: 5 cm x 5 cm of fault gouge

Collettini et al., 2014;
Scuderi and Collettini, 2016

Laboratory



In-situ

LSBB, France:
- 280 m depth
- Direct access to fault zone within a limestone reservoir

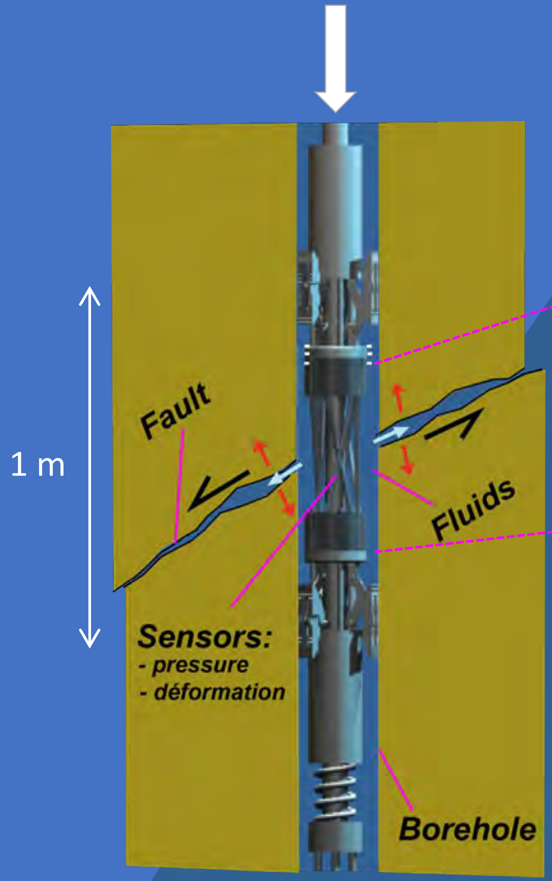
Fault sample

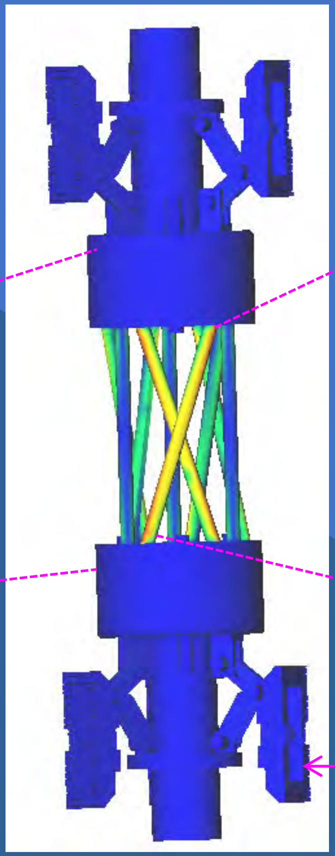
cm Same physical processes ? **m**

Bridge the gap between scales,
as well as lab and natural conditions

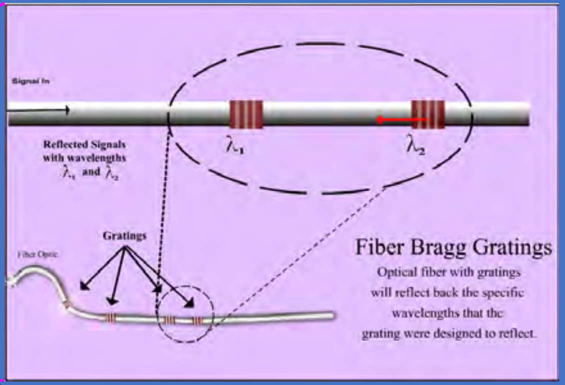
A new tool to activate fault in-situ from hydraulic injection

Water injection in the fault





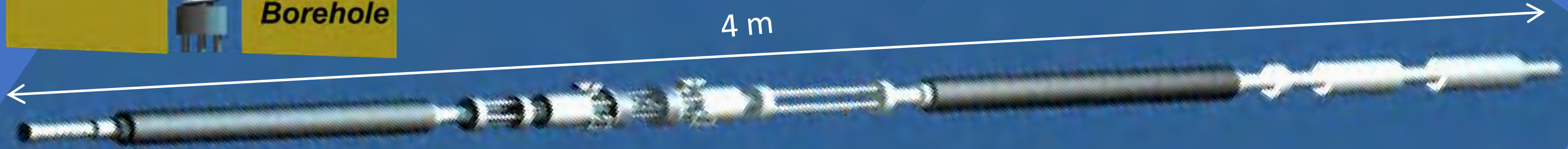
Fiber optic pressure and deformation sensors



Anchor

Accuracy:
1 µm for displacement
1 kPa for fluid pressure

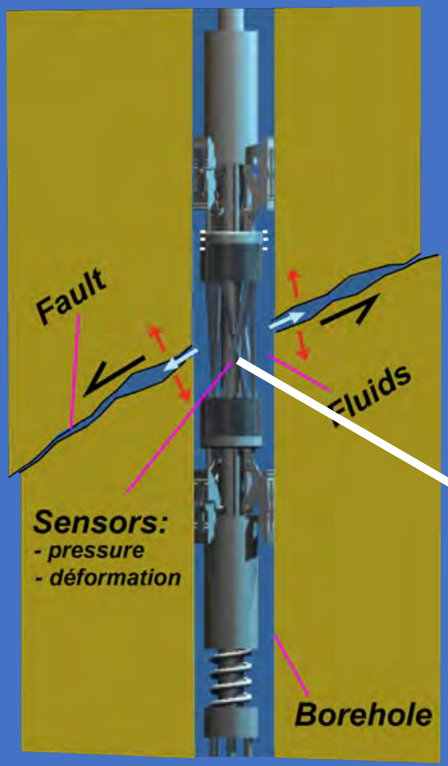
Sampling rate:
1000 Hz

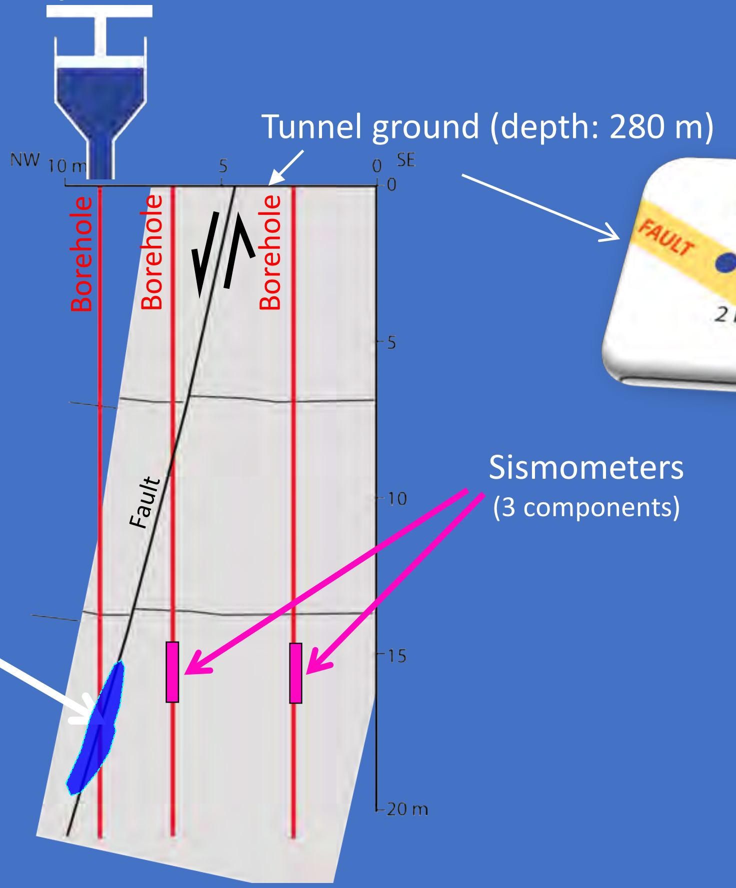


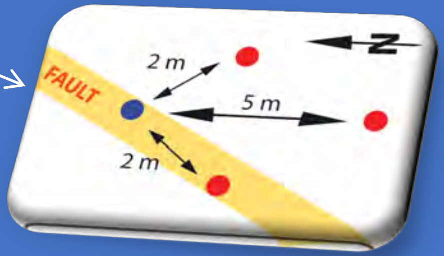
SIMFIP probe: Guglielmi et al., 2014

Experimental conditions in the field

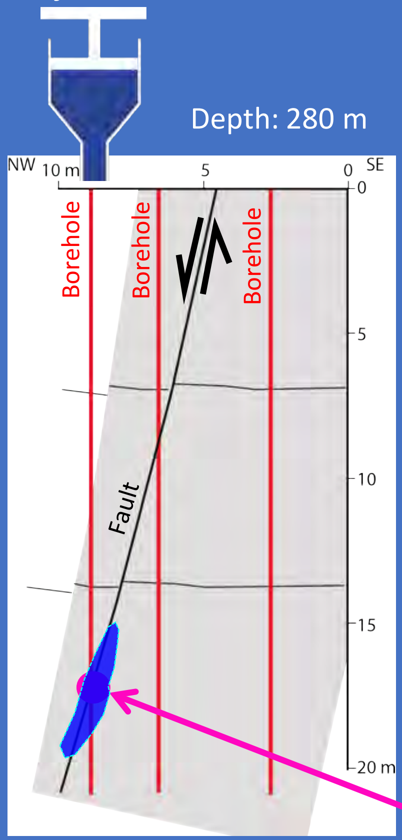
(LSBB, France)

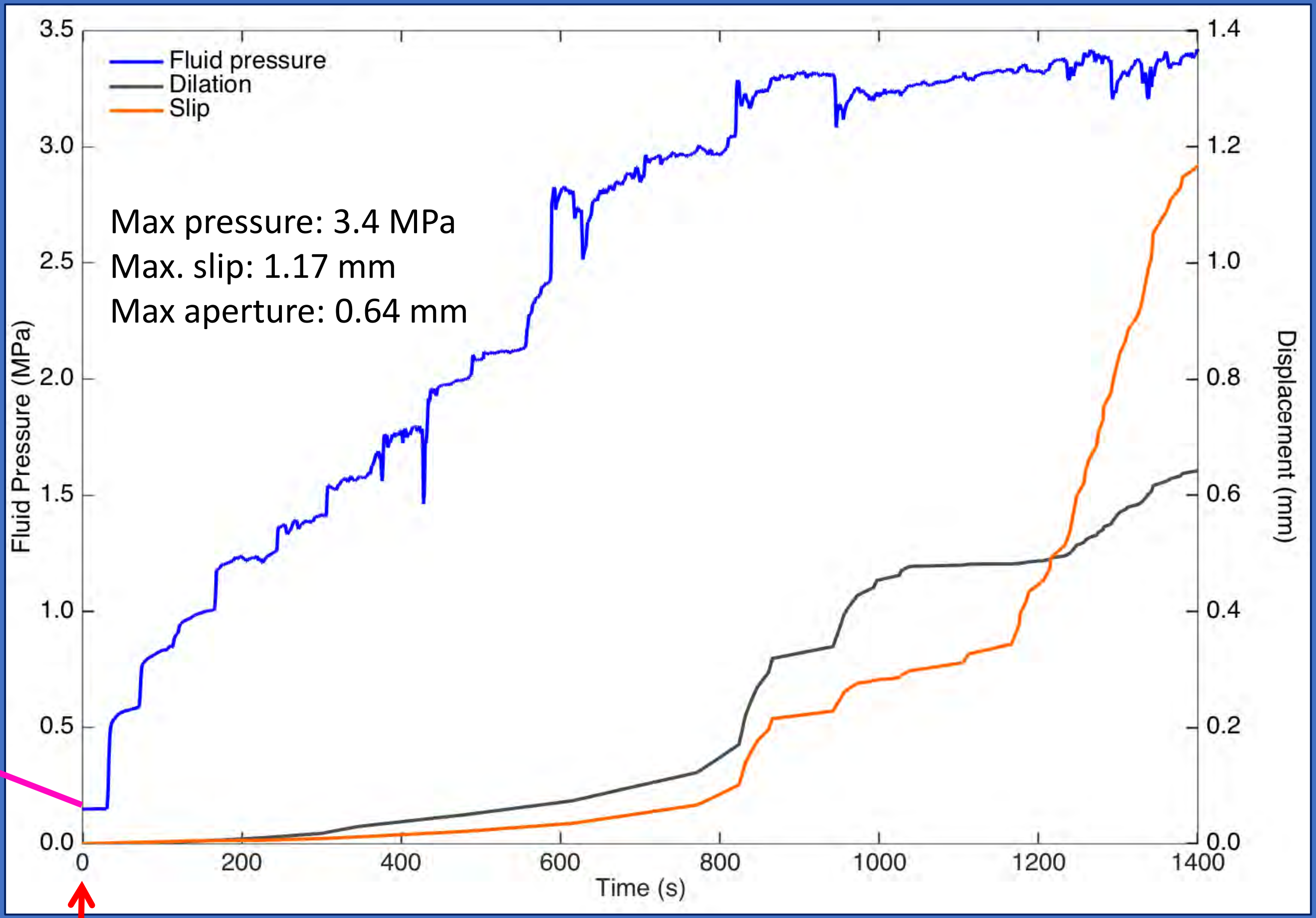






The fluid injection induces a pressure increase which produces fault opening and slip

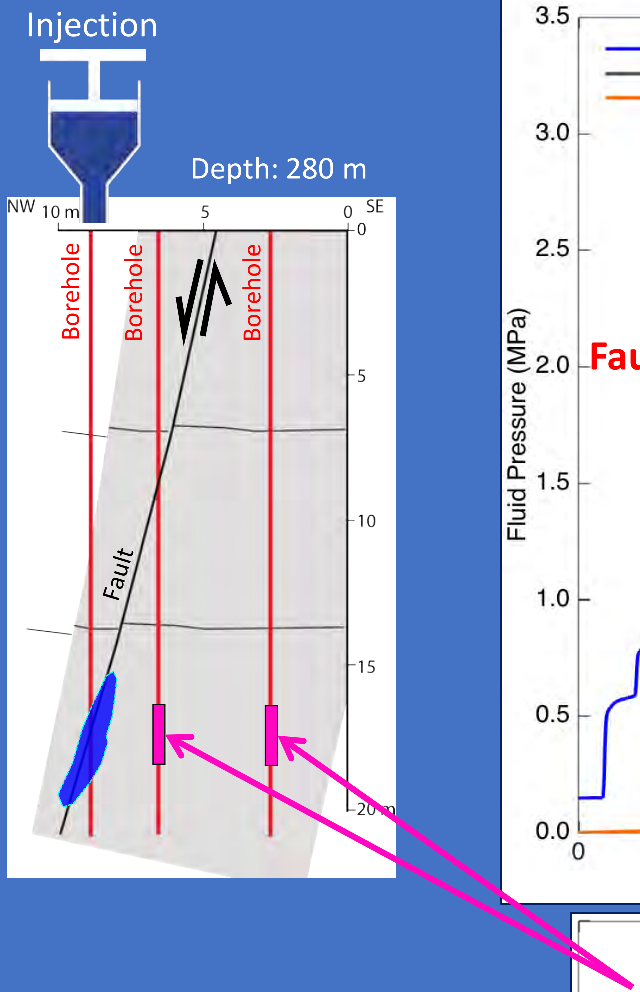


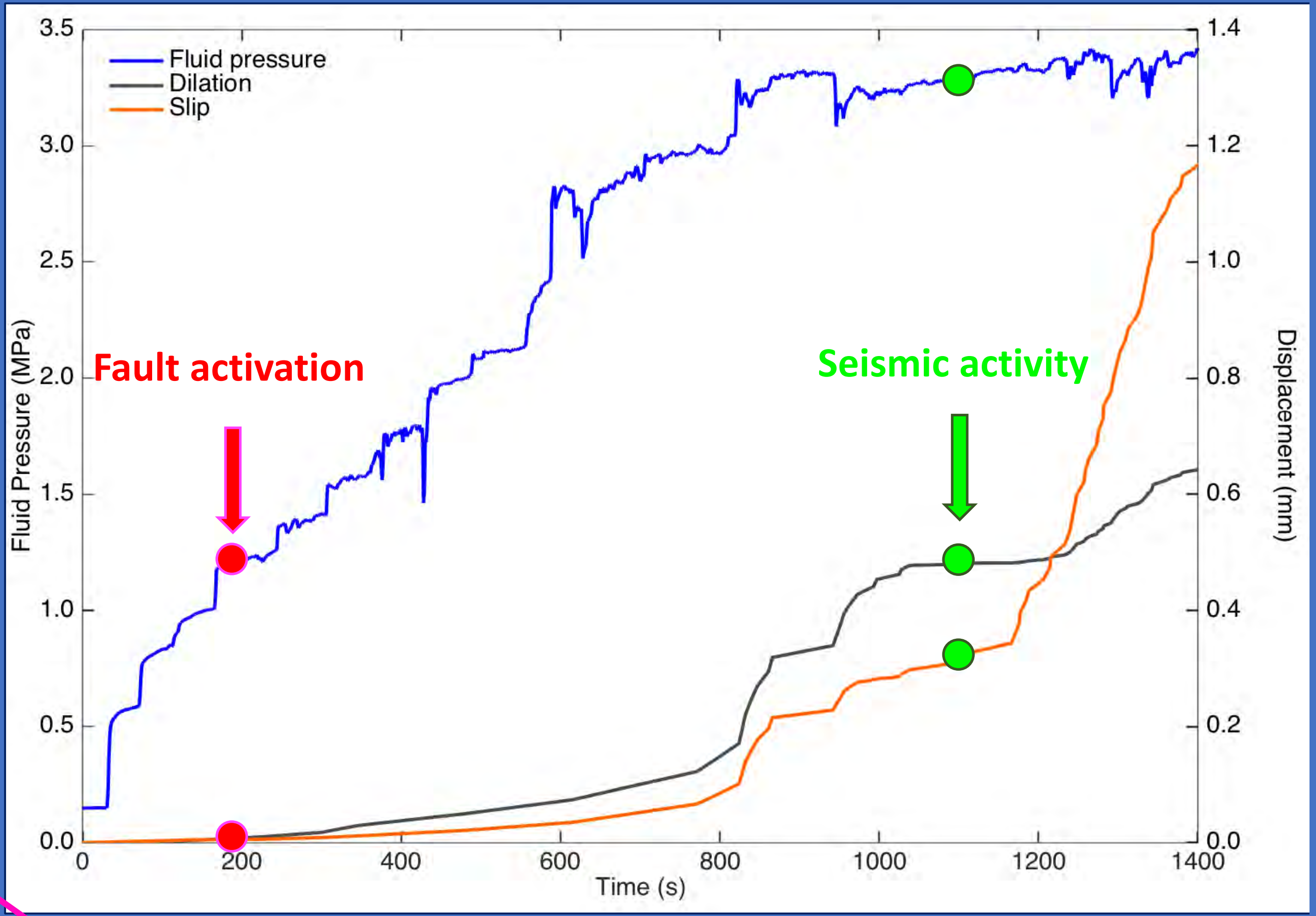


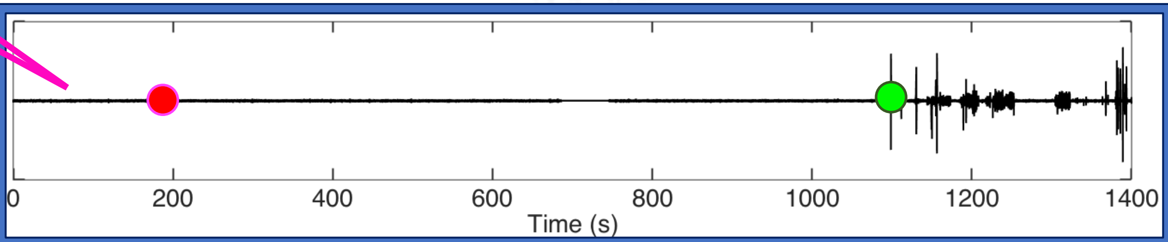
Injection starts

Guglielmi, Cappa et al., Science, 2015

Aseismic slip before the seismicity starts







Guglielmi, Cappa et al., Science, 2015

What we have learned
from this in-situ experiment

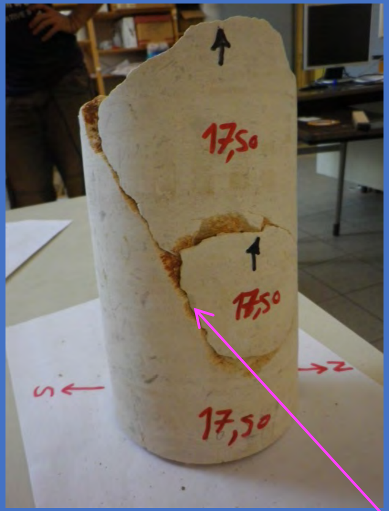
- Fluid pressure mainly induces fault opening and aseismic slip at injection.

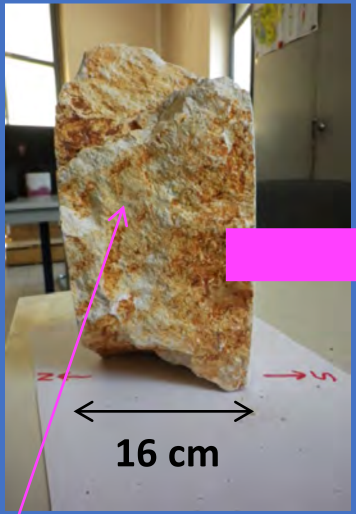
- Seismicity starts at the onset of significant fault slip.

↳ Other experiments into the same fault zone showed that the seismicity is located far from the injection between 1 m and 12 m
(Duboeuf et al., JGR, 2017; De Barros et al, Sci. Rep, in press).

Reproducing the fluid injection in the lab and characterizing the frictional behavior with increasing fluid pressure

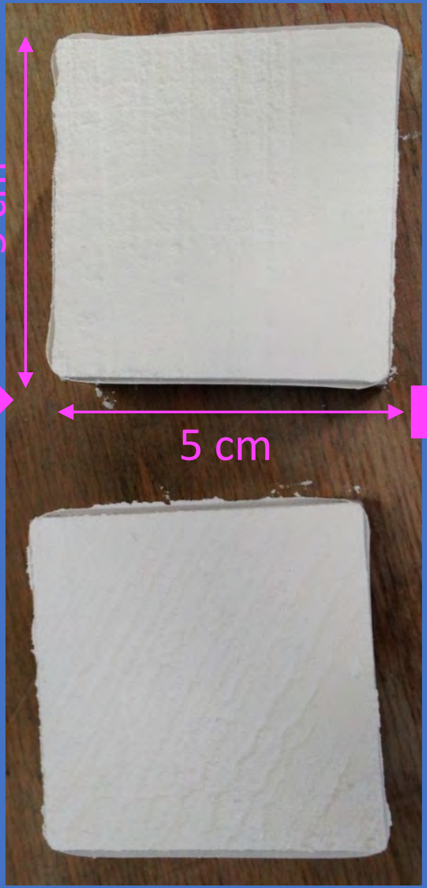
Rock samples (limestone) from boreholes





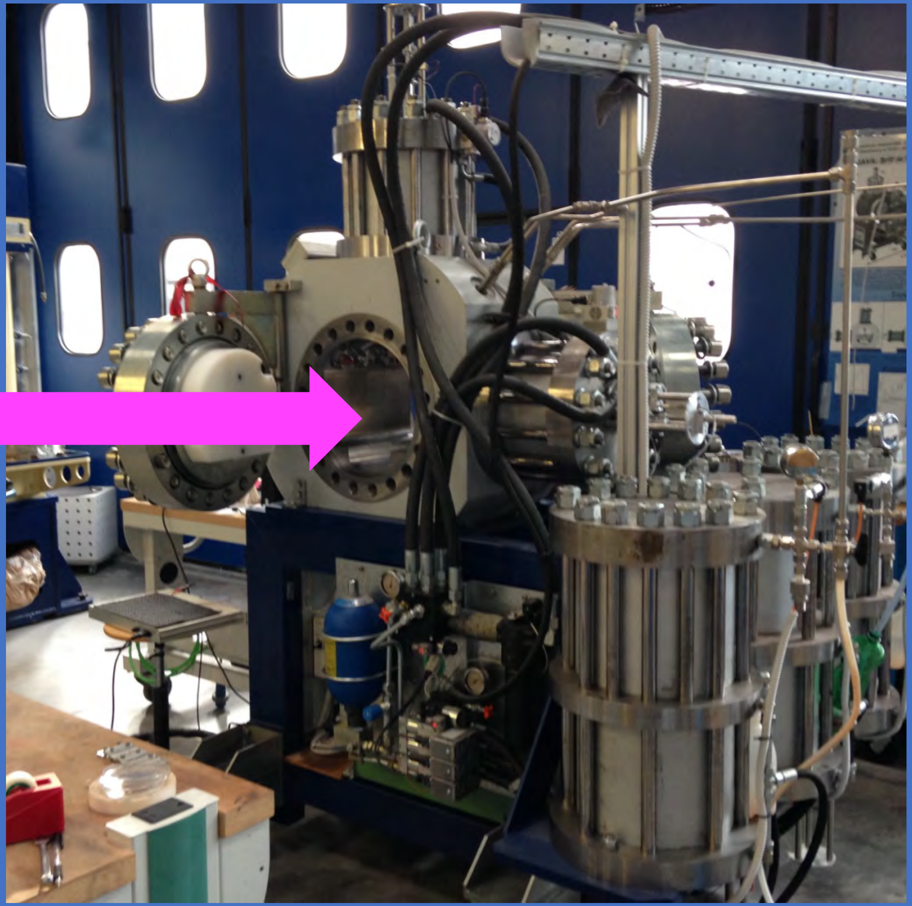
Fault plane

Powder (Ø<125 μm) from fault wall rock



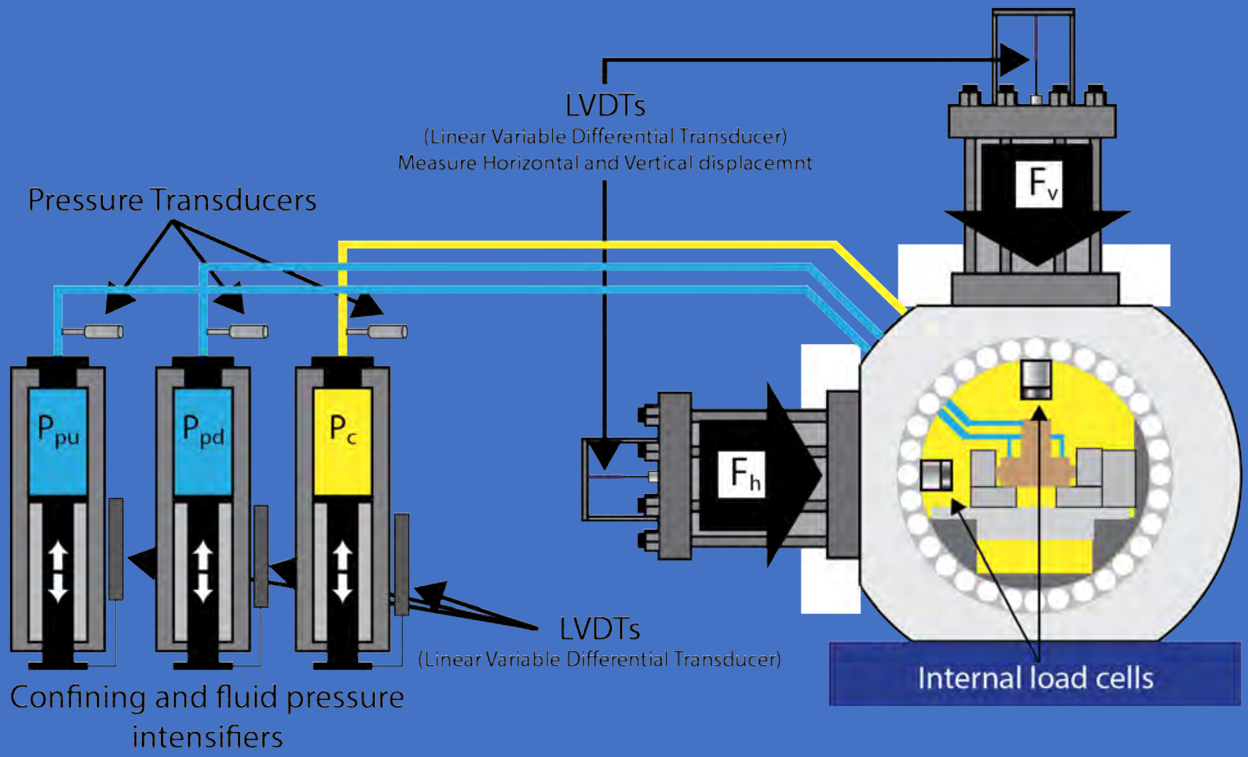
BRAVA apparatus

(Collettini et al., IJRM, 2014)



Experimental conditions in the laboratory

(BRAVA, Italy)



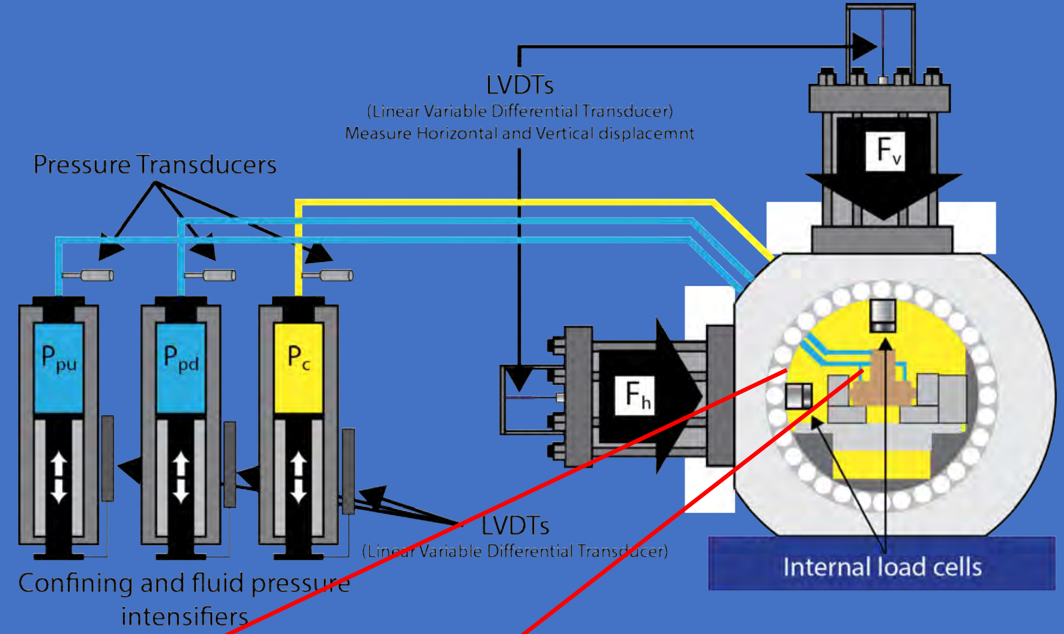
Fluid pressure (+/- 7kPa), fault slip and opening (+/- 0.1 µm) are monitored at a sampling rate of 1000 Hz.

Biaxial Apparatus
in a Double Direct Shear configuration
within a Pressure Vessel

Collettini et al., IJRM, 2014; Scuderi and Collettini, Scientific Reports, 2016

Experimental conditions in the laboratory

(BRAVA, Italy)



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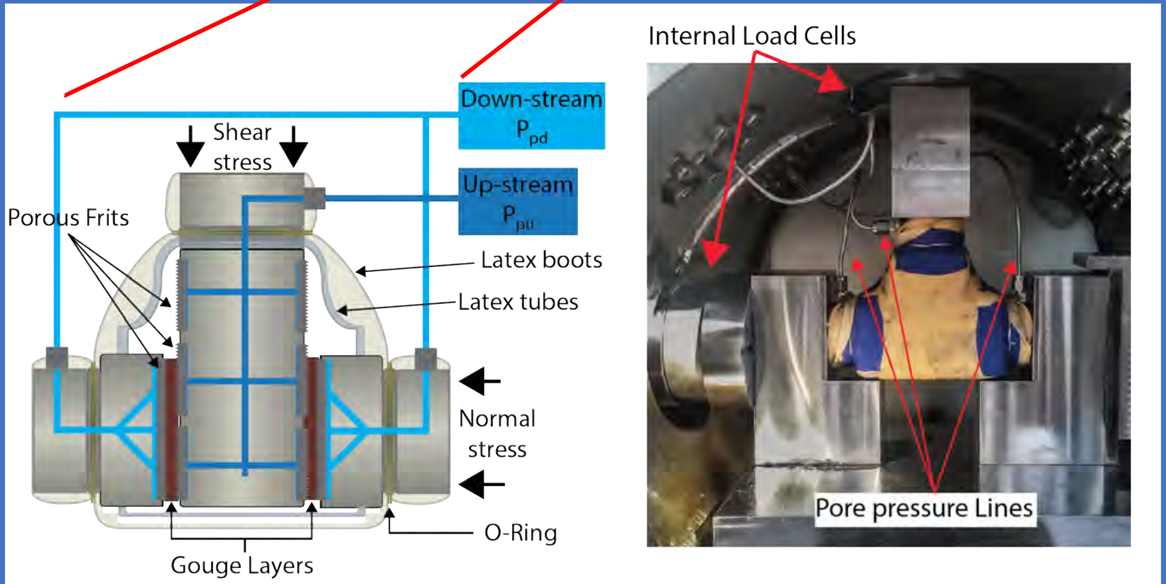
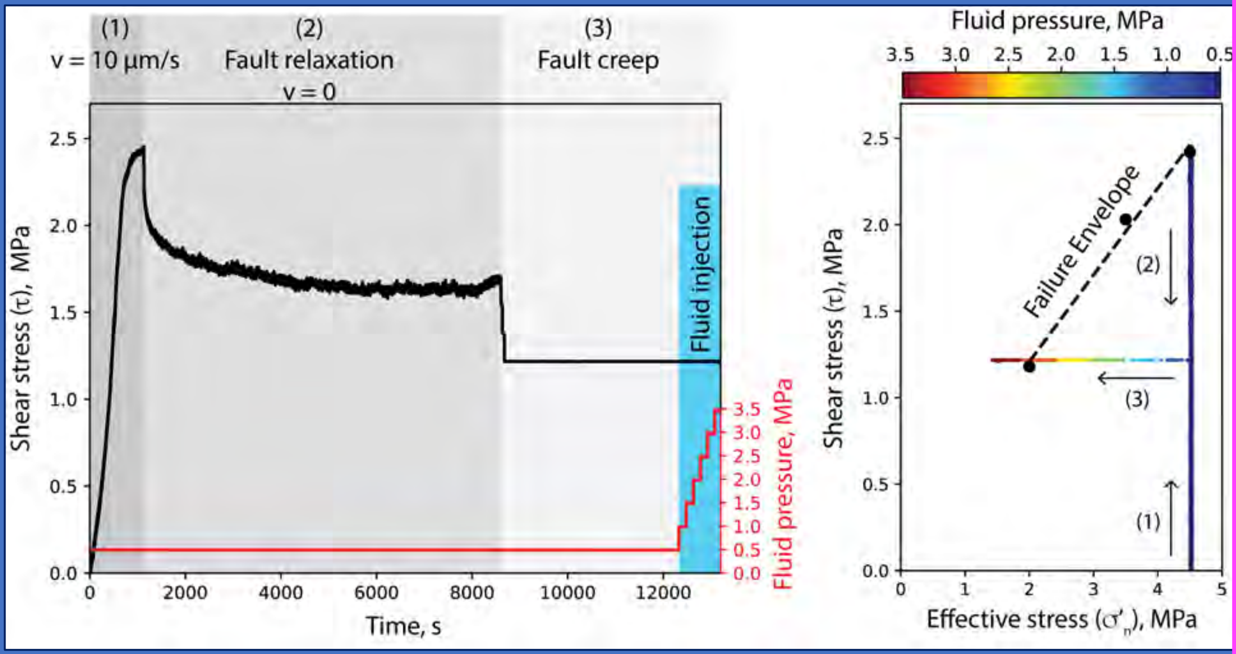


Experimental protocol

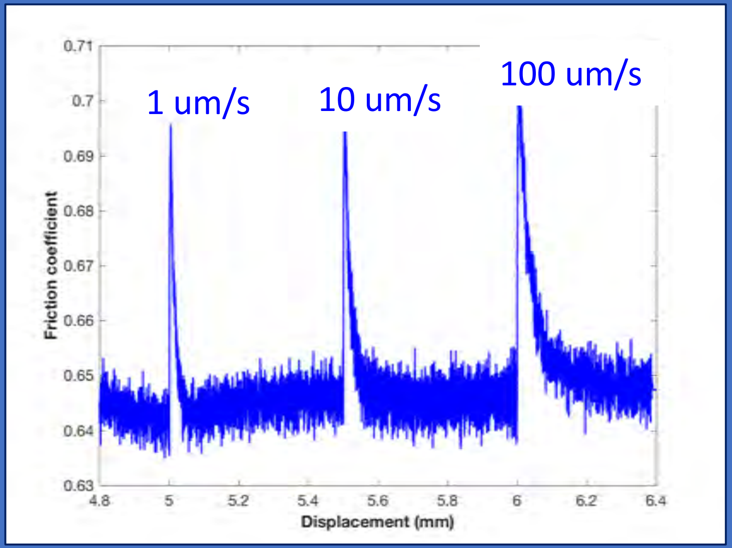
Fluid injection with increasing fluid pressure (step-by-step: 0 to 3.5 MPa) at stress levels similar to the in-situ experiments

- Initial normal (4.5 MPa) and shear (1.2 MPa) stress before injection

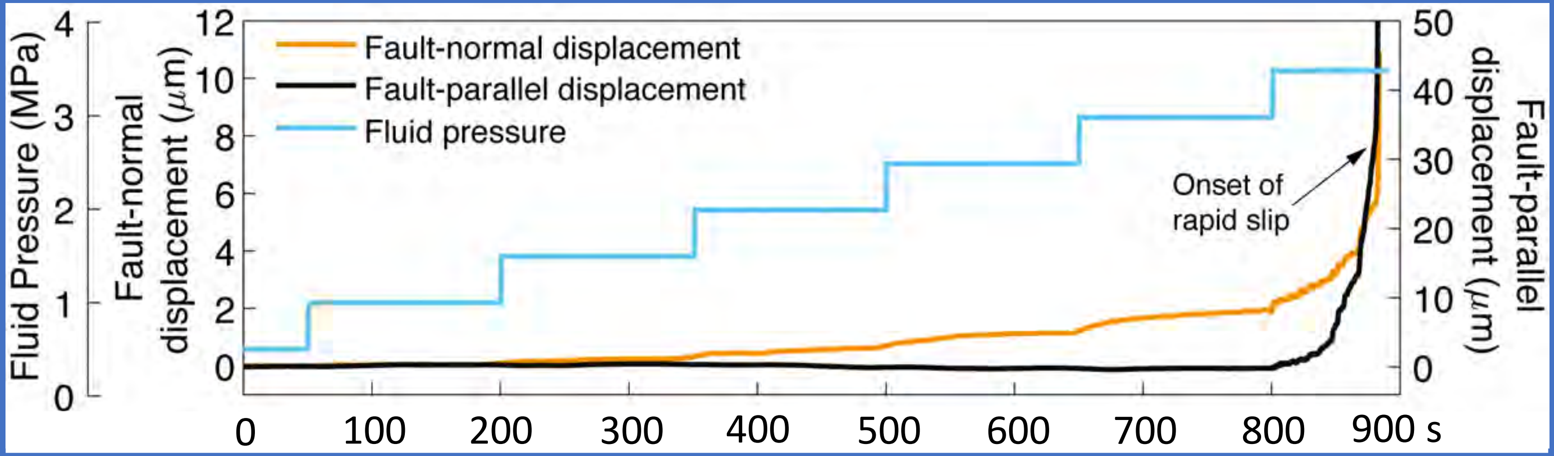


Determination of the rate-and-state frictional properties at different levels of effective stress and slip velocity

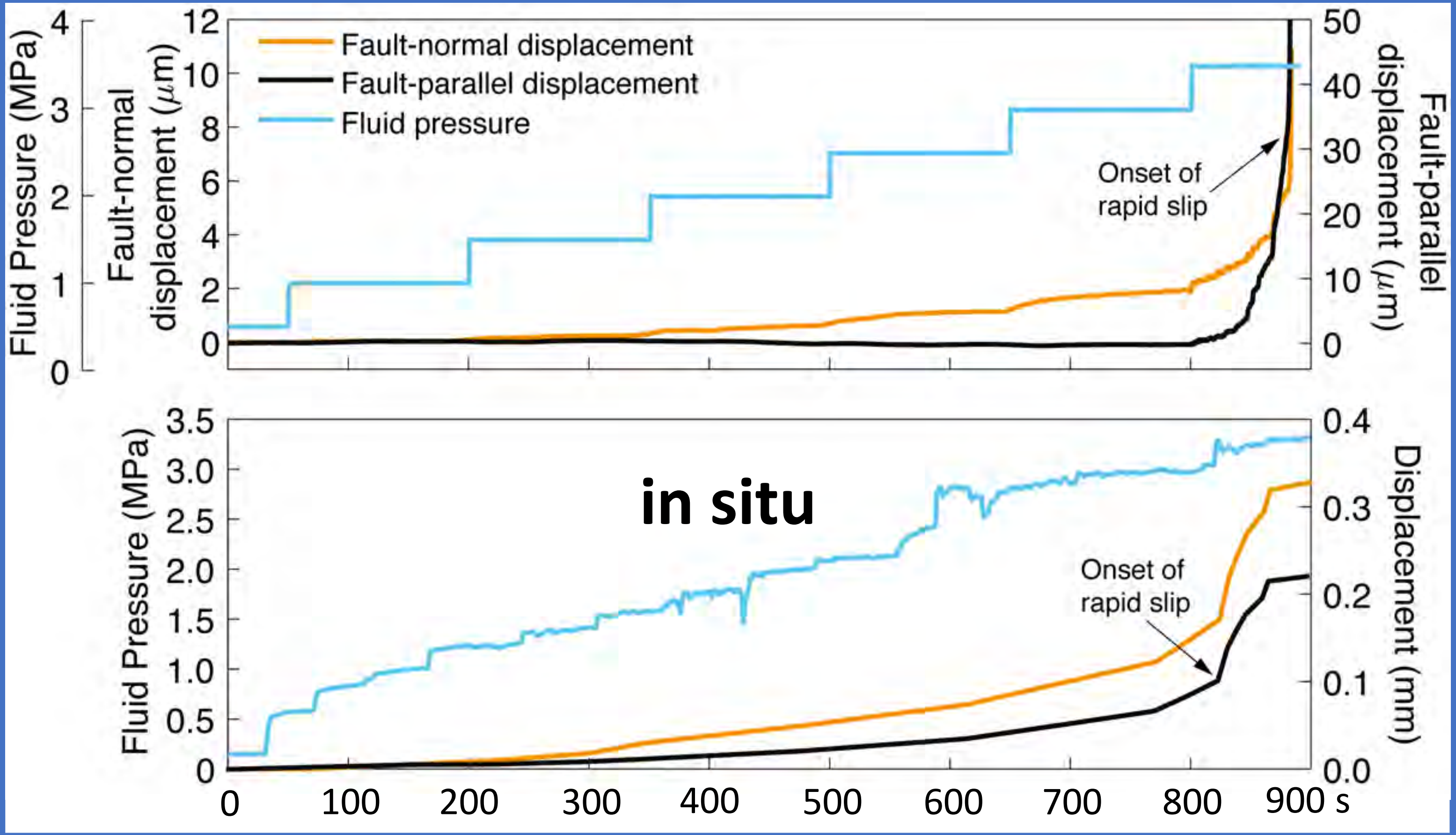
- Velocity step (0.1 to 100 microns/second)
- Fluid pressure (0, 1.5, 3 MPa), Effective stress (2 to 5 MPa)



Fault deformation during fluid injection

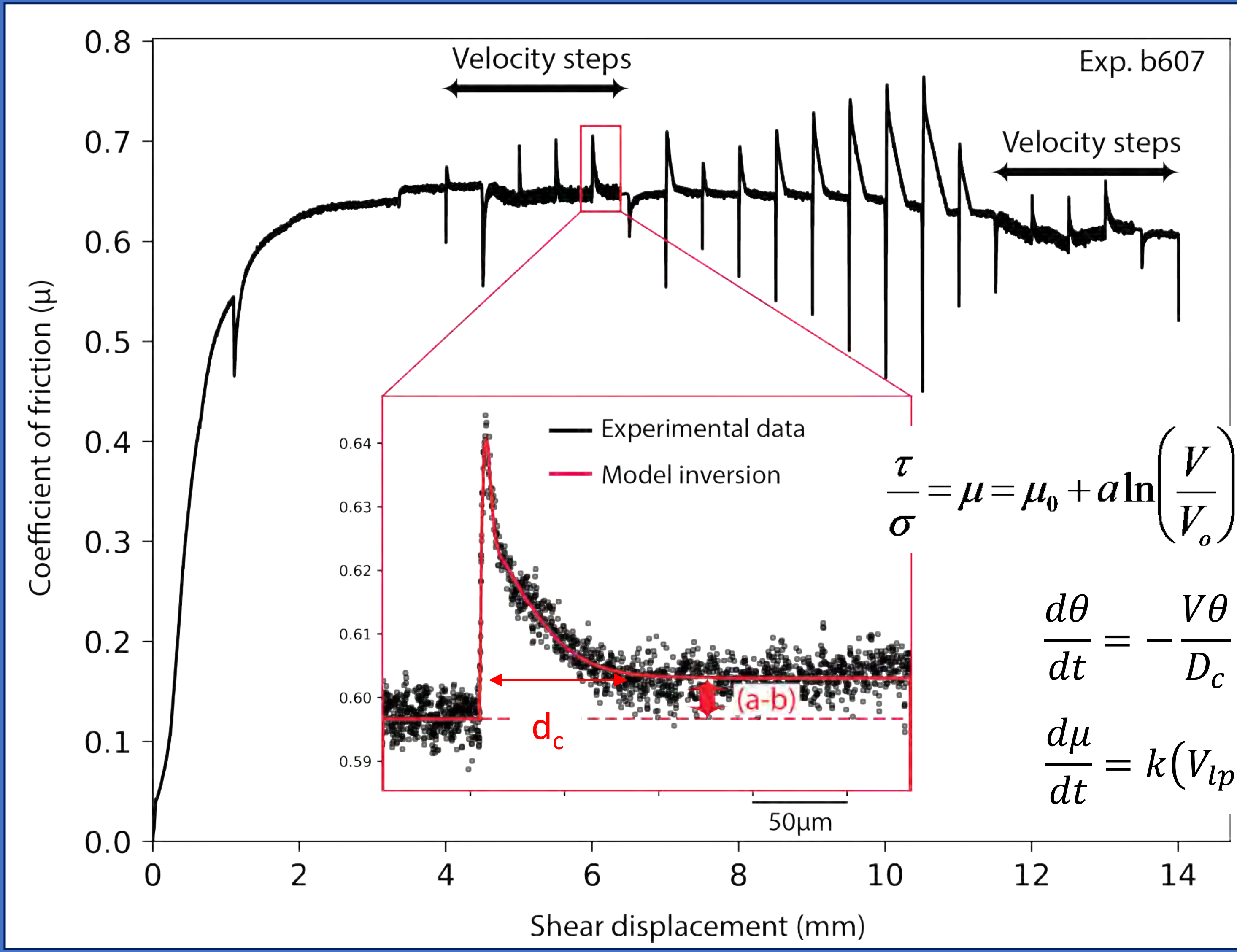


Fault deformation during fluid injection



Fluid injection experiments on laboratory and natural faults reveal a similar phase of fault opening and accelerating slip

Frictional behavior evolution with increasing fluid pressure
(dry, 0, 1.5, 3 MPa)



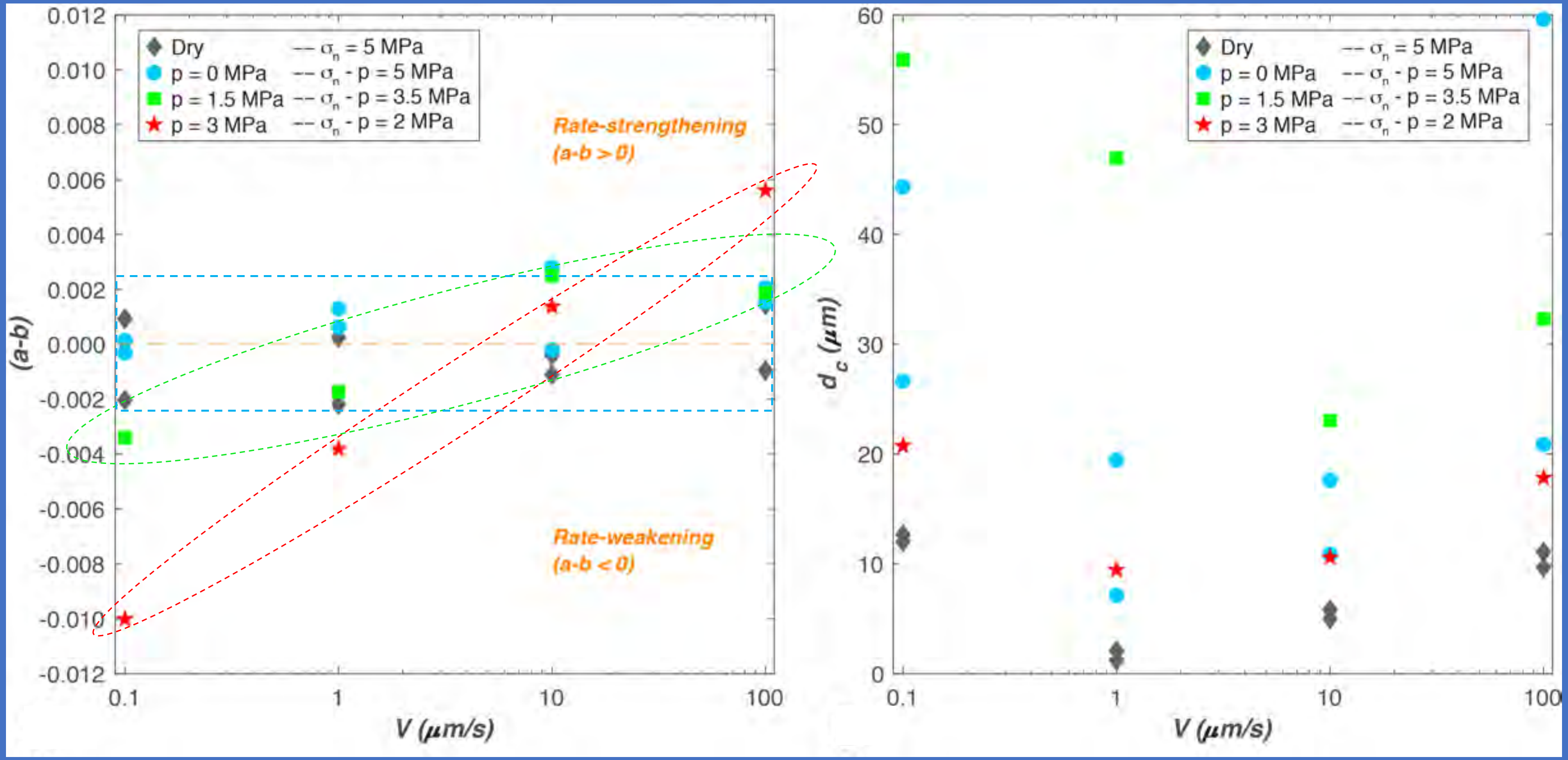
$$\frac{\tau}{\sigma} = \mu = \mu_0 + a\ln\left(\frac{V}{V_o}\right) + b\ln\left(\frac{V\theta}{D_c}\right)$$

$$\frac{d\theta}{dt} = -\frac{V\theta}{D_c}\ln\left(\frac{V\theta}{D_c}\right)$$

$$\frac{d\mu}{dt} = k\left(V_{lp} - V\right)$$

Frictional behavior evolution with increasing fluid pressure (dry, 0, 1.5, 3 MPa)

Rate-and-state parameter *(a-b)*   **Critical slip distance *(d_c)***



The frictional properties vary with increasing fluid pressure and slip velocity.

(a-b) evolves from rate-weakening to rate-strengthening and d_c increases with increasing fluid pressure.

The transition makes the fault more prone to generate aseismic slip in the pressurized zone.

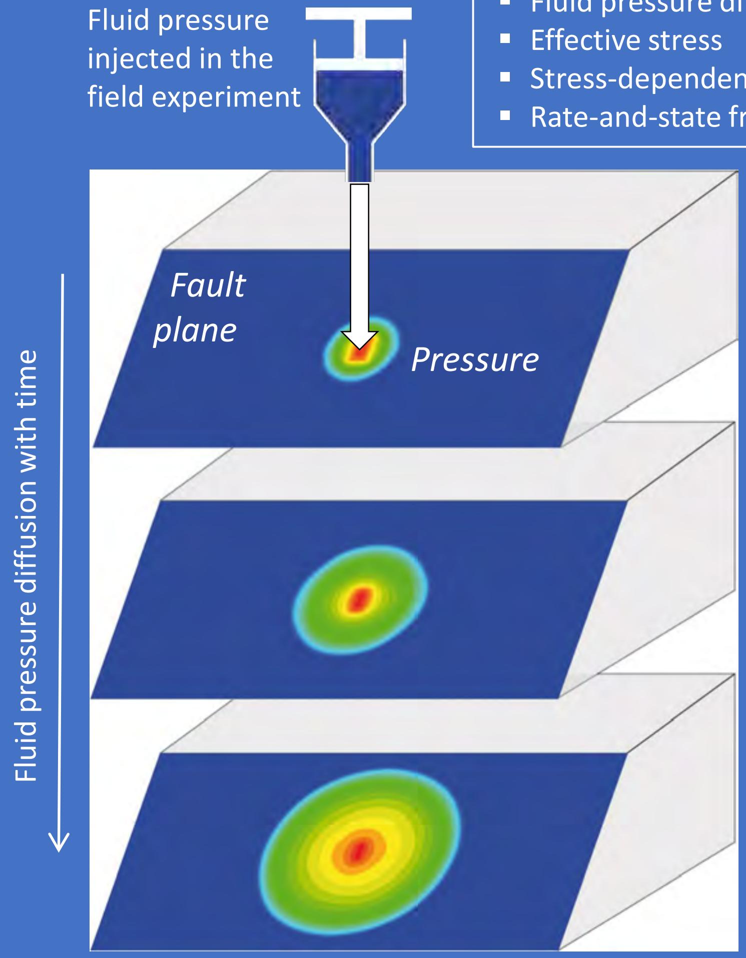
Hydromechanical model of fluid injection and fault slip

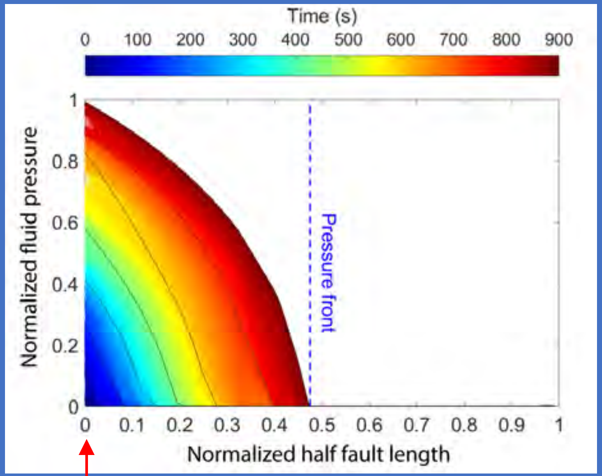
We have used the results from laboratory experiments to inform a three-dimensional hydromechanical model to test if these properties are consistent with the in-situ observations

The model includes:

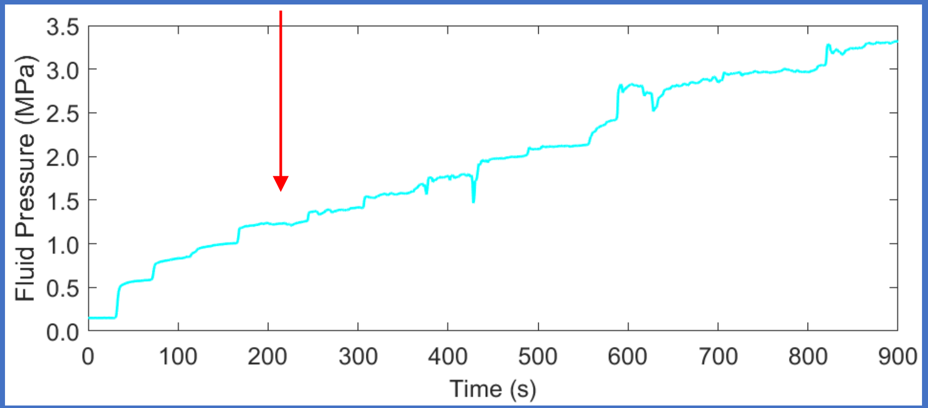
- Fluid pressure diffusion
- Effective stress
- Stress-dependent permeability
- Rate-and-state friction

Fluid pressure injected in the field experiment

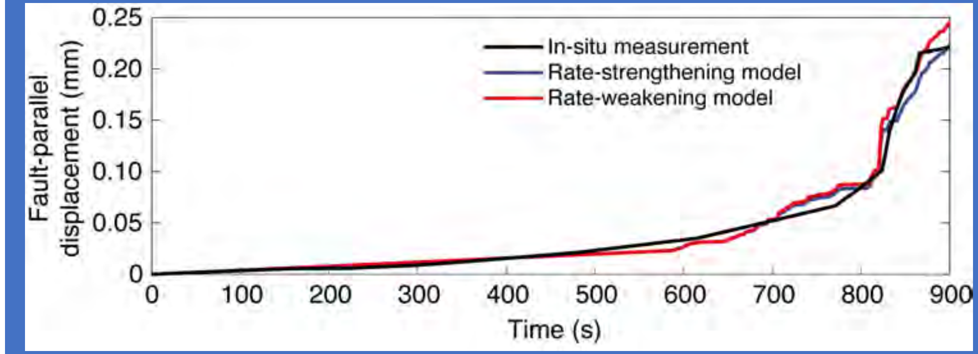




Fluid injection



Calculated fault slip



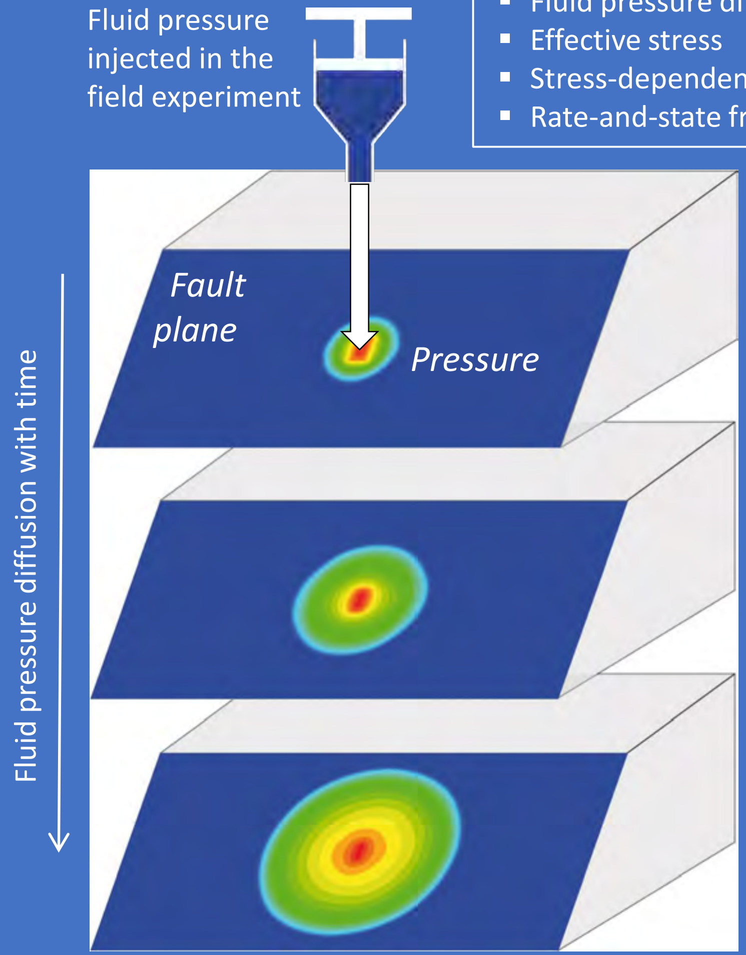
The model predictions are consistent with observed fault slip at field scale

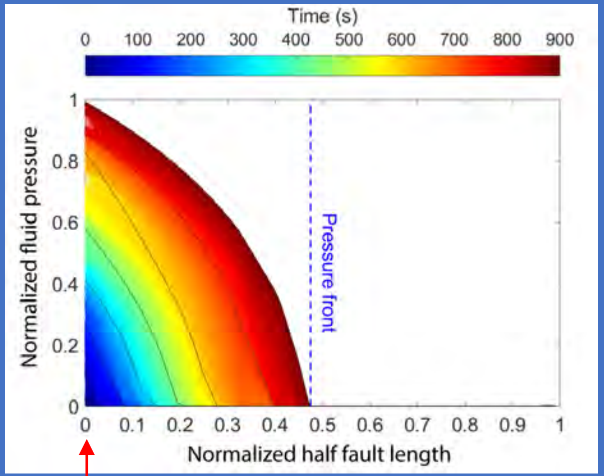
Hydromechanical model of fluid injection and fault slip

We have used the results from laboratory experiments to inform a three-dimensional hydromechanical model to test if these properties are consistent with the in-situ observations

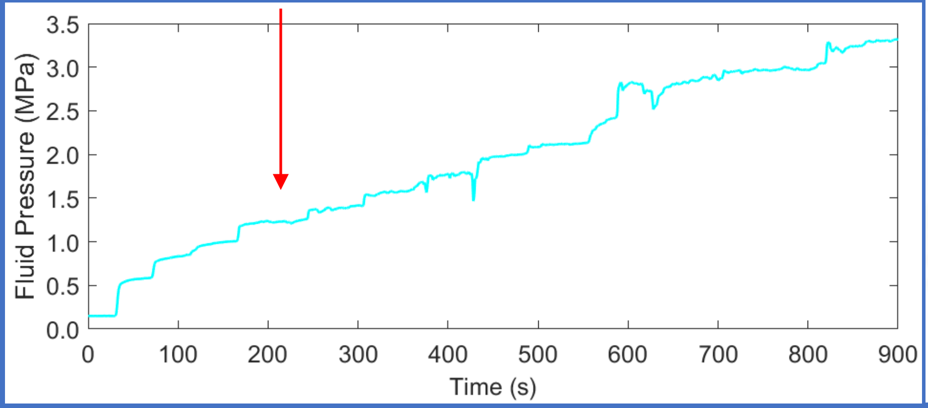
The model includes:

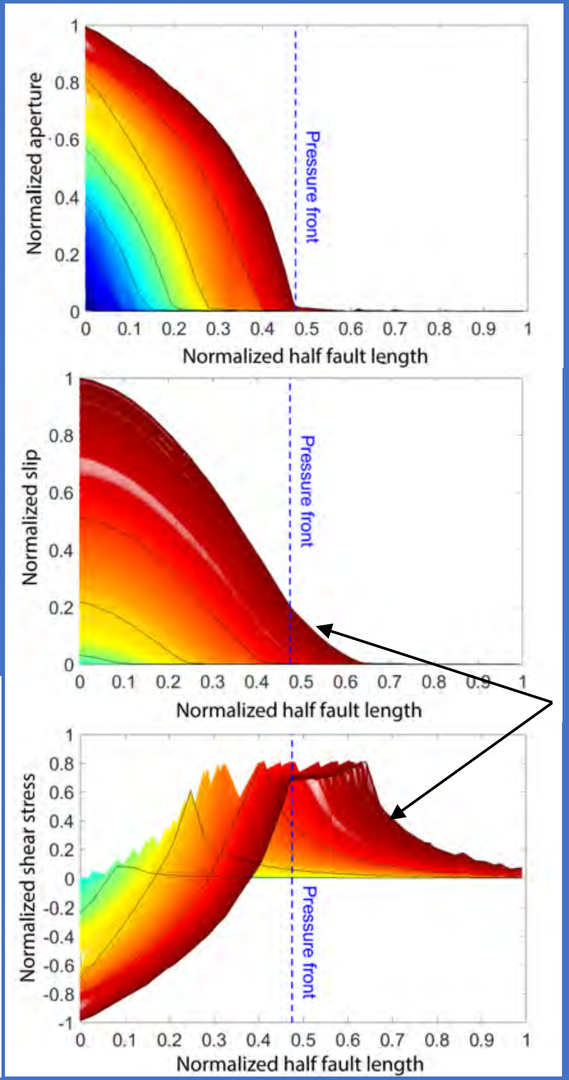
- Fluid pressure diffusion
- Effective stress
- Stress-dependent permeability
- Rate-and-state friction





Fluid injection



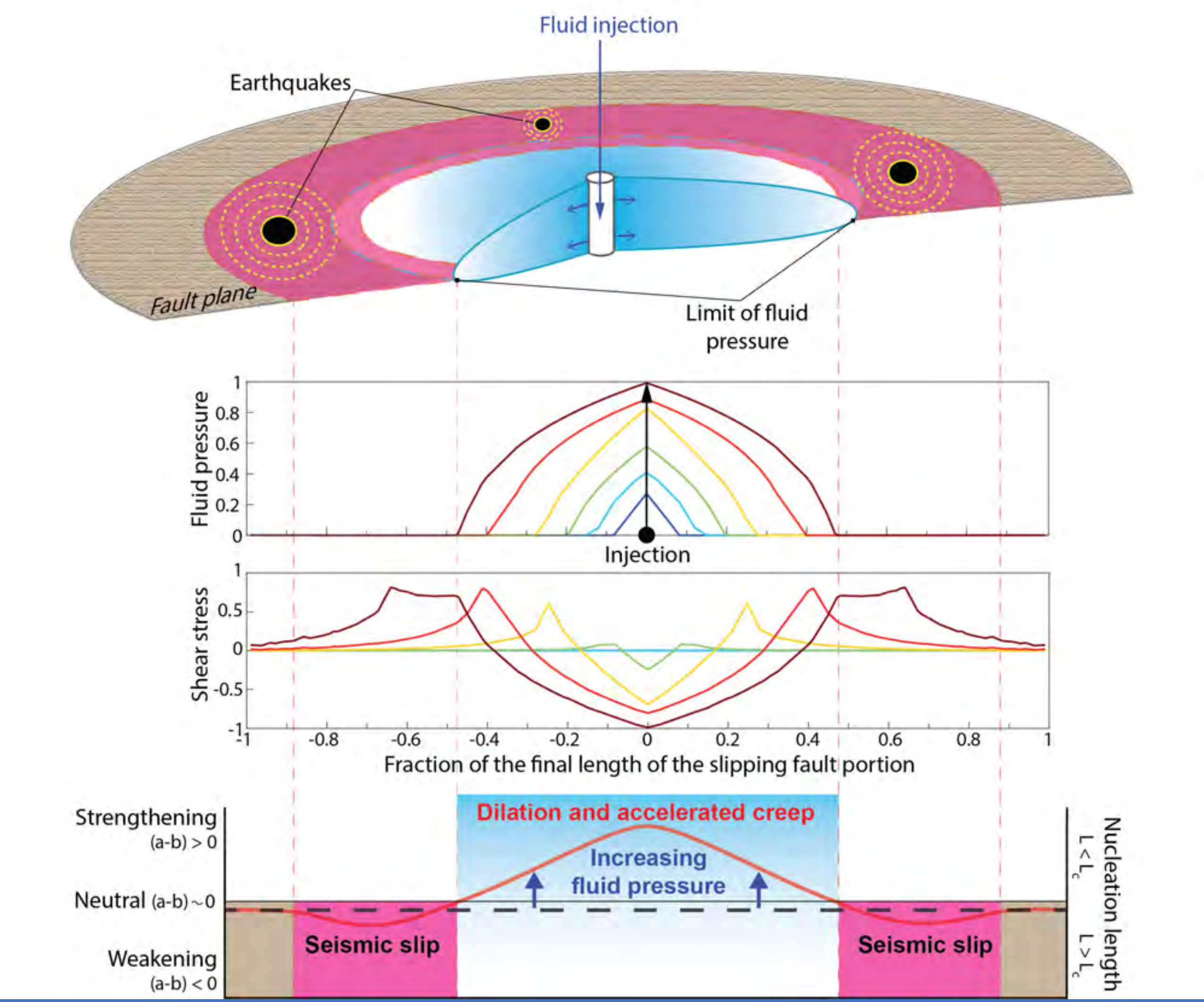


Slip and stress increase beyond the fluid-pressurized region

What we have learned from the comparision between laboratory and in-situ experiments, and hydromechanical models

- Fluid injection on laboratory and natural faults reveal a similar phase of fault opening and accelerating creep up to the main instability, suggesting a common underlying mechanism that is scale-independent.

- Seismicity can be triggered indirectly by the injection due to loading of nonpressurized fault patches by aseismic slip.

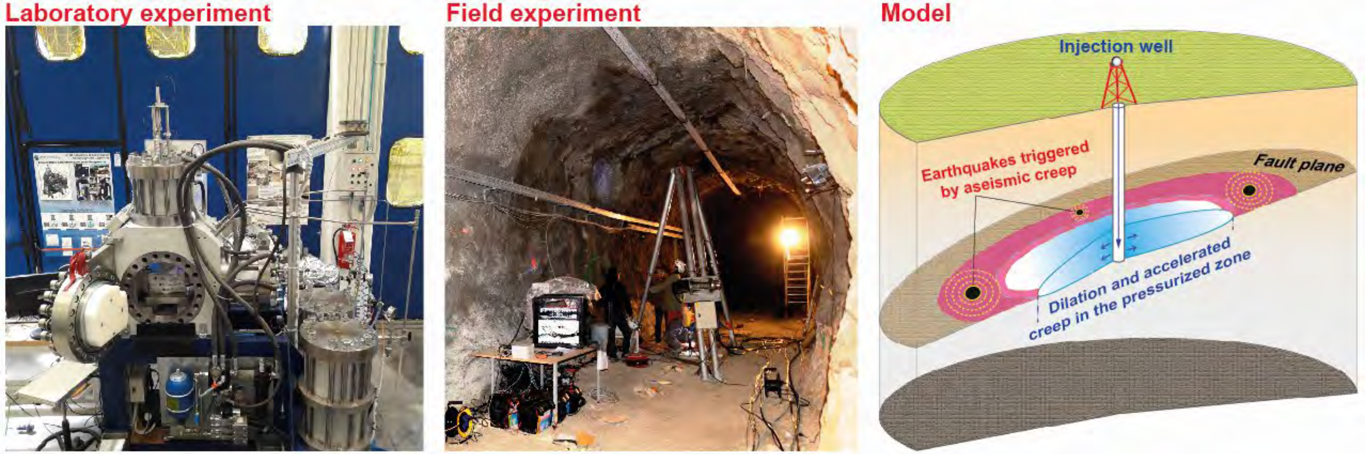


Cappa , Scuderi et al., Science Advances, 2019

Conclusion

- We demonstrate that fault slip induced by fluid injection in a natural fault at the decametric scale is quantitatively consistent with fault slip and frictional properties measured in the laboratory at the centimetric scale.
- The increase in fluid pressure first induces accelerating aseismic slip and fault opening (i.e. permeability enhancement) together with rate-weakening behavior. As the fluid pressure increases further, friction mainly becomes rate-strengthening favoring aseismic slip.
- Seismicity is most probably triggered indirectly by the fluid injection due to propagating aseismic slip that can increase shear stress to failure beyond the pressure front.
- Considering this interaction, physics-based models that employ new friction laws including the effects of fluid pressure and its rate of change on friction parameters may help to anticipate fault response to injection.

More detail in *Science Advances* : *"Stabilization of fault slip by fluid injection in the laboratory and in-situ"* by Cappa F., Scuderi M.M., Collettini M., Guglielmi Y. and Avouac J.P. *Online in open-access on March, 13, 2019*



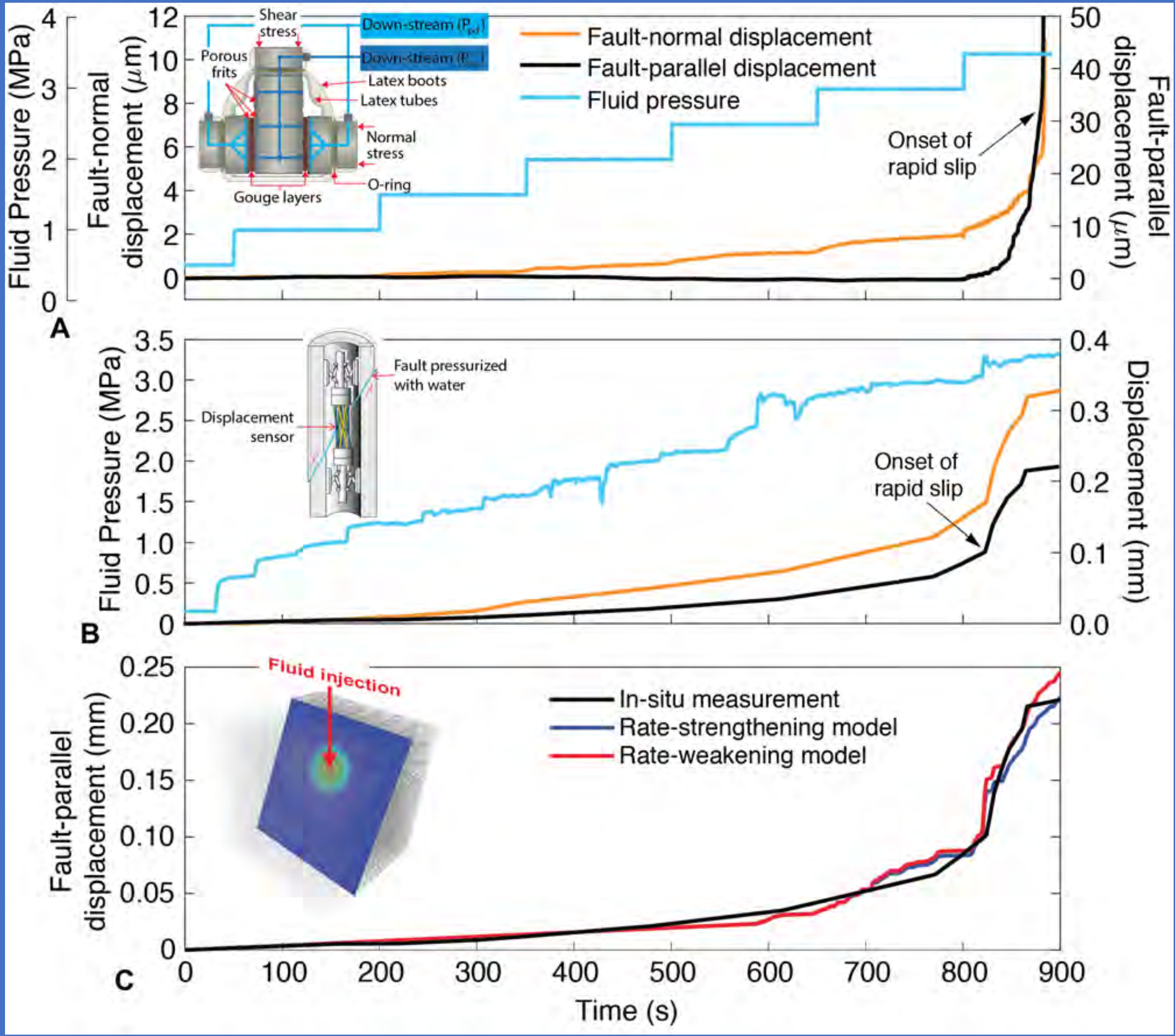
Supplementary materials

Comparison between experiments and models

Laboratory

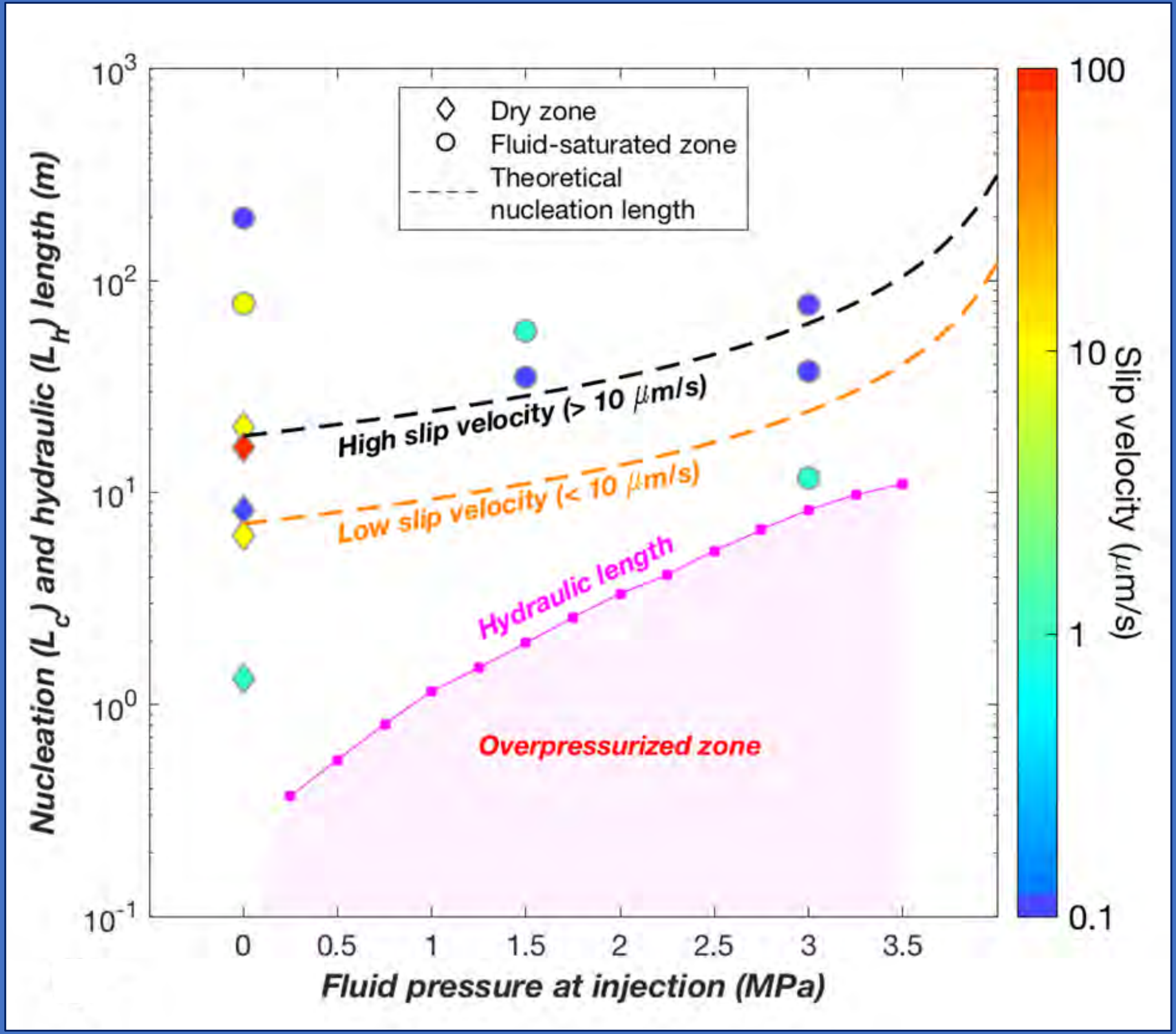
In-situ

Hydromechanical model



Cappa, Scuderi et al., Science Advances, 2019

Slip remains stable, although friction may be rate weakening as the fluid pressure is increased because the pressurized zone of forced slip does not exceed the critical size for unstable slip



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