Seismic and aseismic slip induced by hydraulic stimulation of a fault zone

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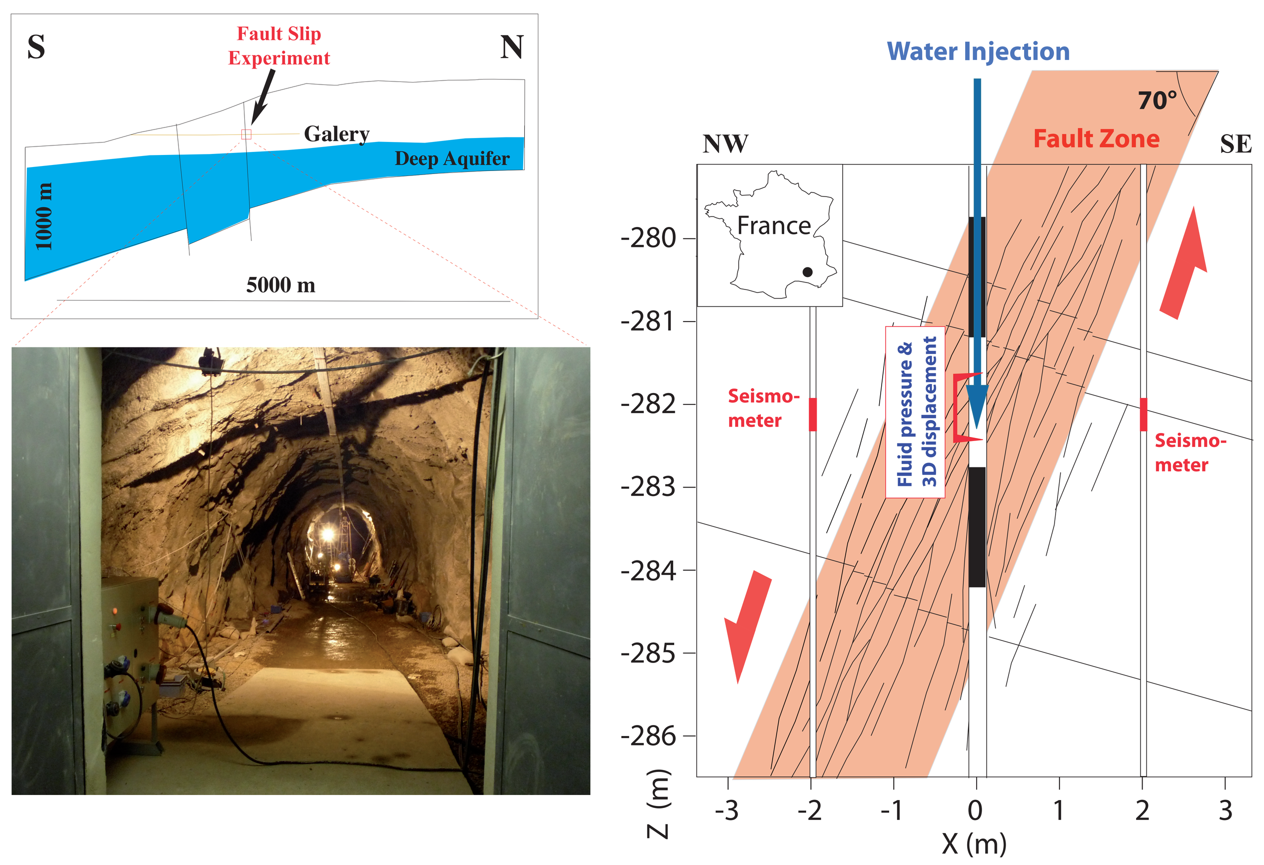
ABSTRACT

The role of fluids during the phase of slow slip preceding an earthquake is a central question in geophysics because fluid pressures are suspected to strongly condition the magnitude and energy of the acceleration to dynamic rupture. Yet to date few data are available to constrain these fluid-mechanical coupled effects on earthquake nucleation in fault zones, at appropriate scales. Here we present unique measurements of induced rupture on a natural fault under monitored mechanical and hydraulic conditions. We report continuous measurements of strain, seismicity and fluid pressure during nucleated slow slip reactivation on a 10-m long segment of a normal fault. The episodicity of fault slip is related to dilatancy-strengthening revealed by transient pore-pressure drops. We calculate that the slip is initiated by the fault material frictional weakening, the pore pressure increase just being the trigger. Then, there is a competition between high pressure fluid diffusion in the fault zone and multiple slow ruptures that generate 80% of the seismic energy until the permeability/porosity increase progressively become the predominant control on slip of large fault segments. Detection of variations in these pressure transients and their correlation to seismicity allow capturing irreversible evolutions of fault friction that lead to the nucleation process. Such results are crucial in defining mechanisms of natural and induced earthquakes, their precursors and risk assessment.

GEOLOGICAL CONTEXT

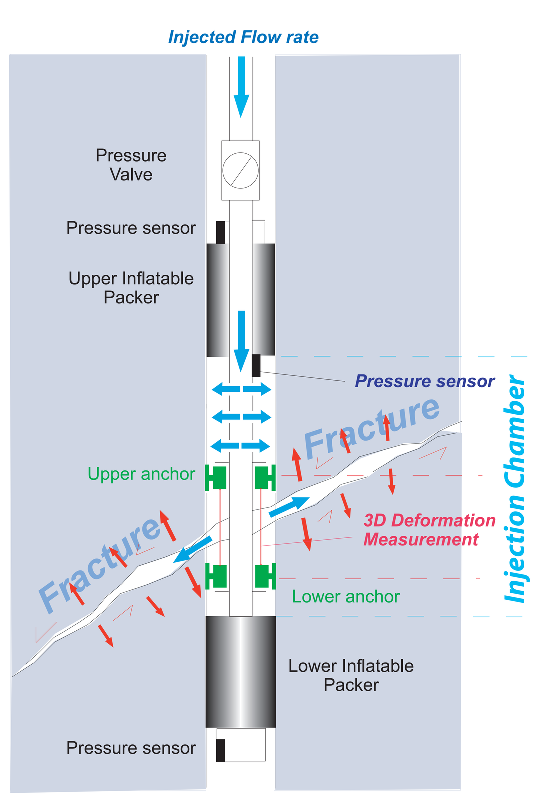


HYDROMECHANICAL MEASUREMENTS

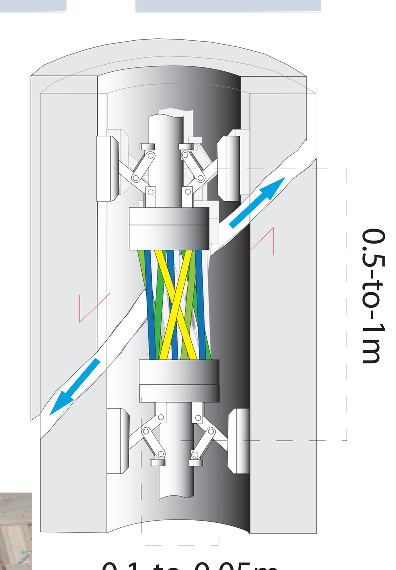
- **Probe dimensions**
Outside Diameter = 100 mm
Length = 5.3 m
3D fiber Bragg deformation [10^{-6} - 10^{-3}m]
and Temperature sensor [0 - 100°C]
Piezo-electric Pressure sensor [0 - 50bars]

- **Injection group** with flowmeters
[1 - 100 l/mn]

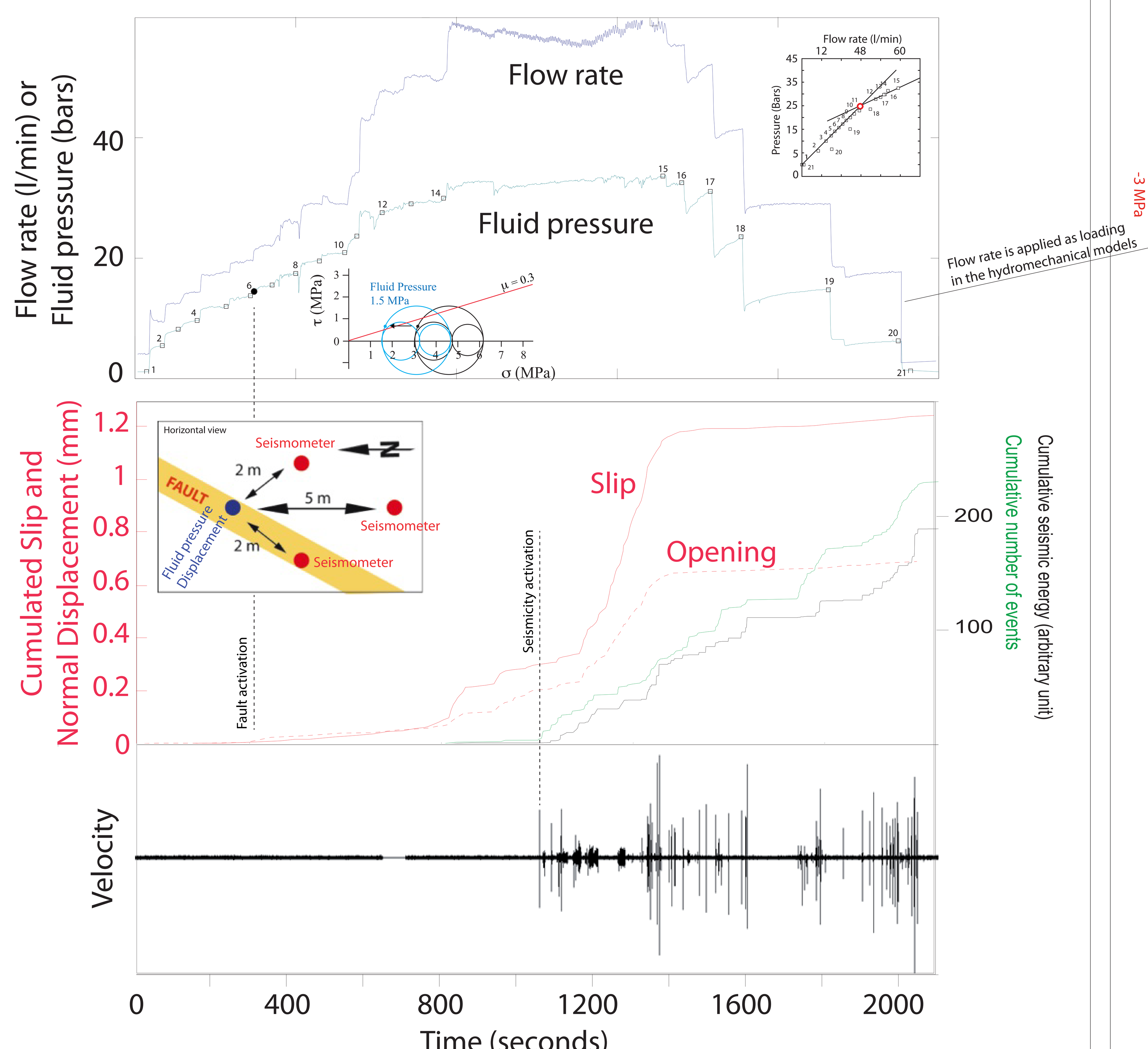
- **Acquisition**
Multi-channels (5 to more)
Real time visualisation
1 Hz and 500 Hz sampling rates
Possibility to couple with seismic crosshole monitoring systems

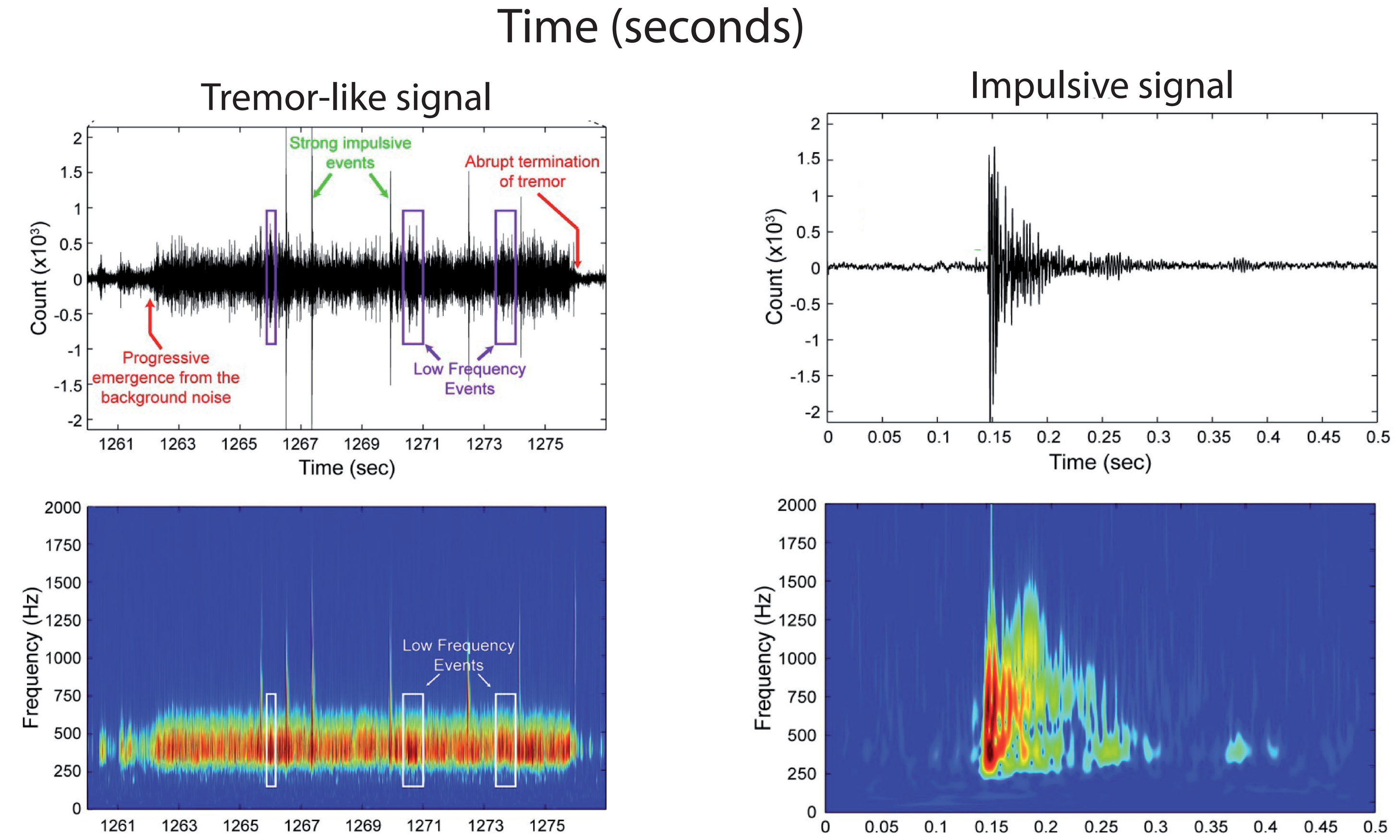


- **Complete package for manipulations at depths of 0 to 250-m**

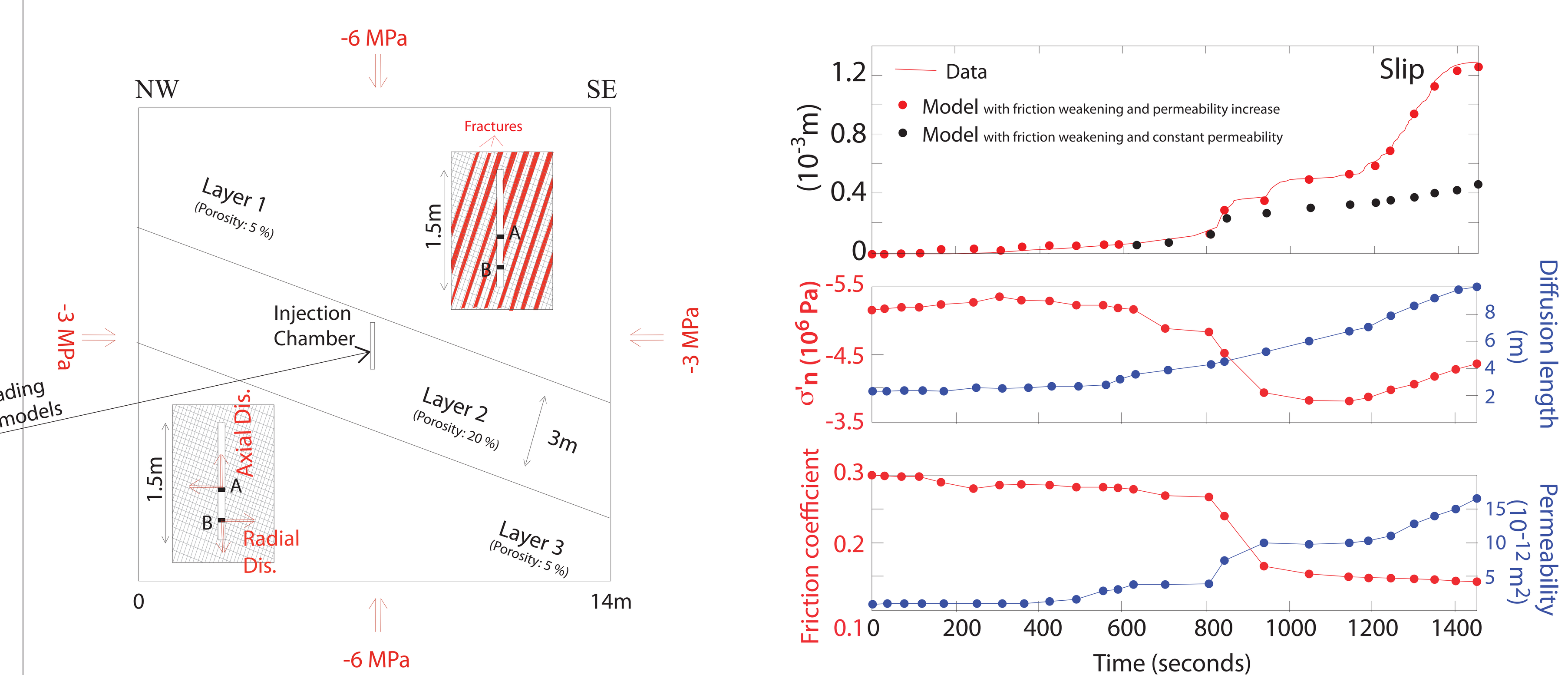


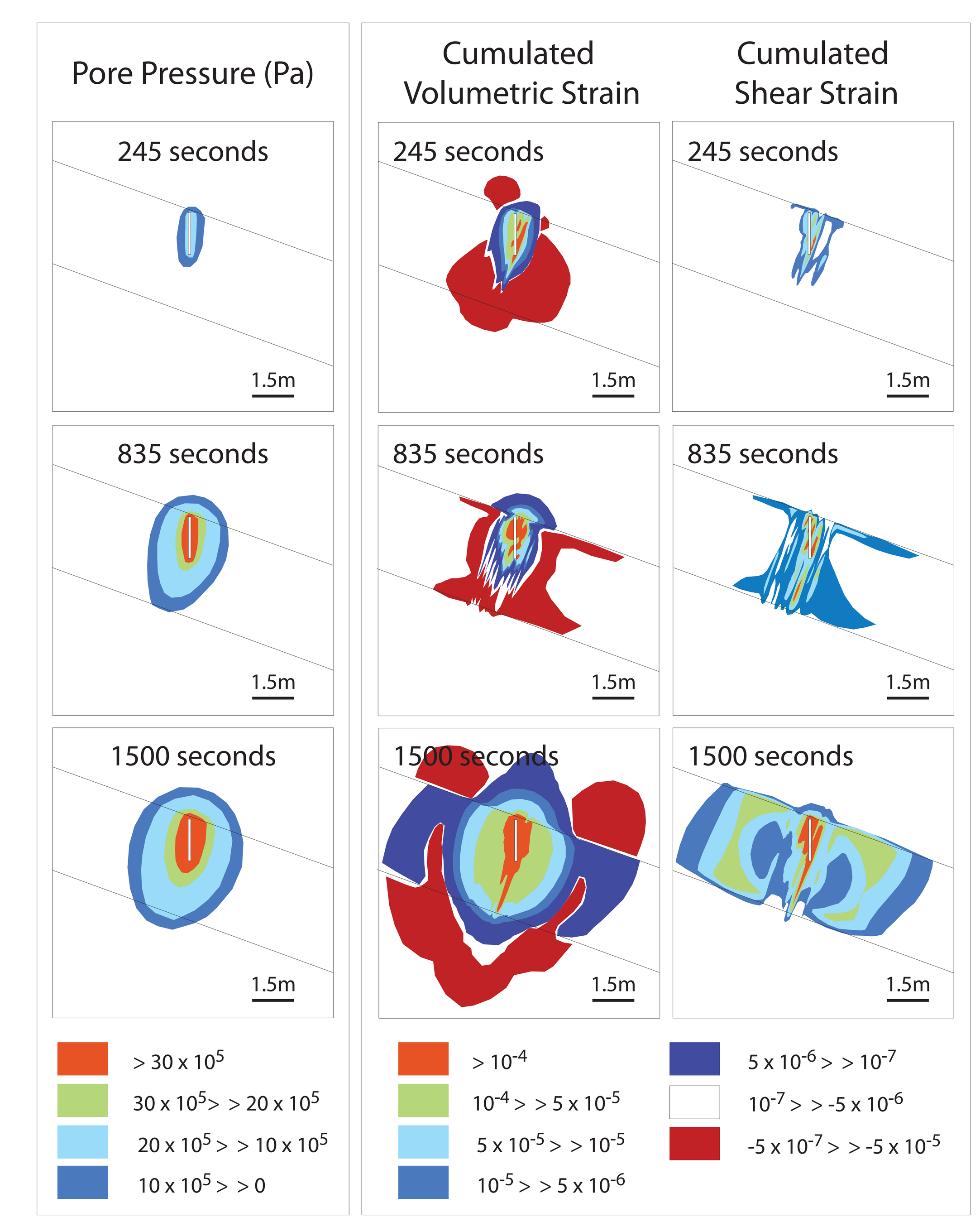
SYNCHRONOUS MONITORING OF FLUID PRESSURE, FAULT DISPLACEMENT AND SEISMICITY





HYDROMECHANICAL MODEL (Fluid diffusion, Effective stress, Mohr-Coulomb failure)





CONCLUSION

- Hydraulic stimulation experiments at meter-scale demonstrate the possible coupling between fluids and faulting
- To the best of our knowledge, first direct evidence that fluids can induce aseismic and seismic slip thanks to our simultaneous monitoring.
- Fluids can initiate fault slip and different associated seismic signatures (Impulsive and Tremor-like signals).
- Fluids can affect the permeability and friction in a highly non-linear way.
- Fluid diffusion, properties changes and off-fault deformation control fault slip.