Seismic and aseismic fault slip in response to fluid injection observed during field experiments at meter scale

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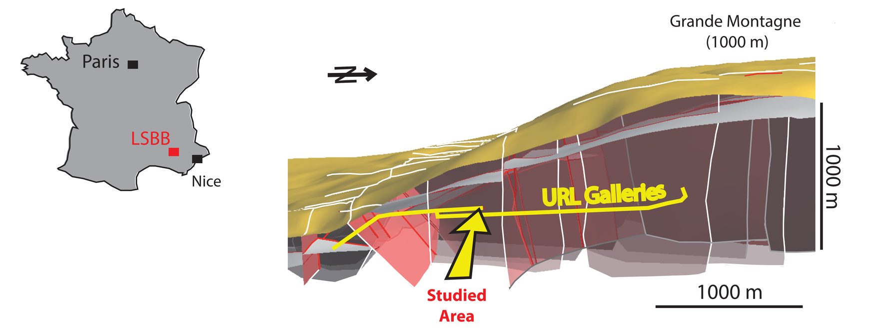
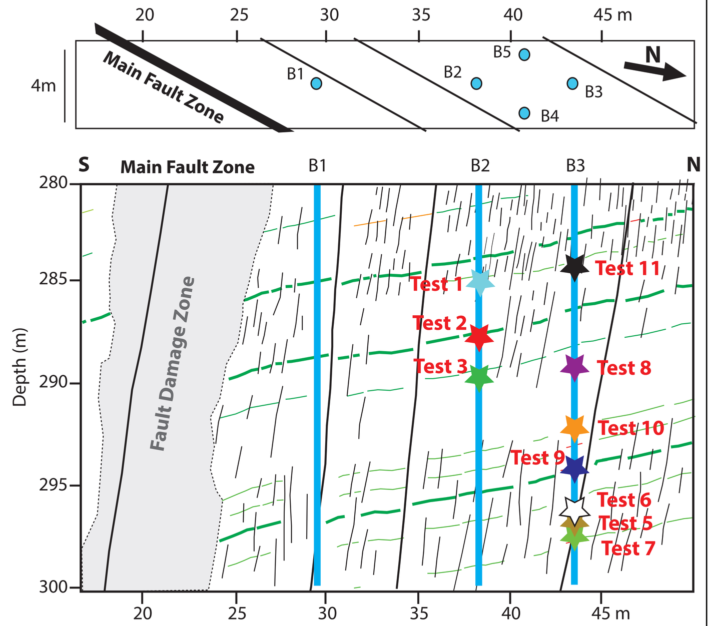
Abstract

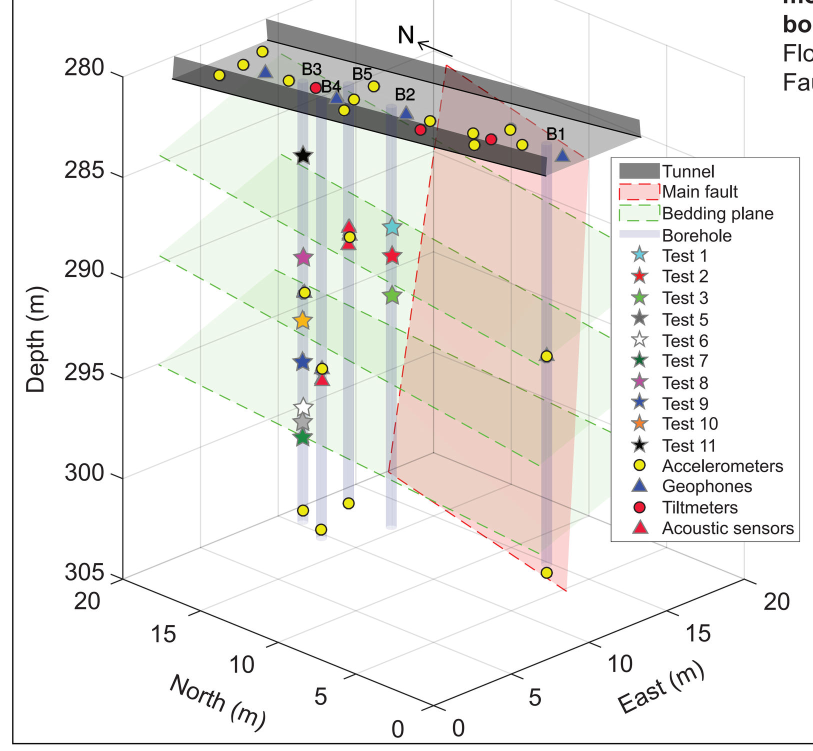
During fluid injection, the observations of an enlarging cloud of seismicity are generally explained by a direct response to the pore pressure diffusion in a permeable fractured rock. However, fluid injection can also induce large aseismic deformations which provide an alternative mechanism for triggering and driving seismicity (Guglielmi et al., 2015). Despite the importance of these two mechanisms during fluid injection, there are few studies on the effects of fluid pressure on the partitioning between seismic and aseismic motions under controlled field experiments. Here, we describe in-situ meter-scale experiments measuring synchronously the fluid pressure, the fault motions and the seismicity directly in a fault zone stimulated by controlled fluid injection at 280 m depth in carbonate rocks. The experiments were conducted in a gallery of an underground laboratory in south of France (LSBB, http://lsbb.eu). Thanks to the proximal monitoring at high-frequency, our data show that the fluid overpressure mainly induces a dilatant aseismic slip (several tens of microns up to a millimeter) at the injection. A sparse seismicity (-4.2 < Mw < -3.14) is observed several meters away from the injection, in a part of the fault zone where the fluid overpressure may be null or very low (Duboeuf et al, 2017). Using hydromechanical modeling with friction laws, we simulated an experiment and investigated the relative contribution of the fluid pressure diffusion and stress transfer on the seismic and aseismic fault behavior. The model reproduces the hydromechanical data measured at injection, and show that the aseismic slip induced by fluid injection propagates outside the pressurized zone where accumulated shear stress develops, and potentially triggers seismicity. Our models also show that the permeability enhancement and friction evolution are essential to explain the fault slip behavior. Our experimental results are consistent with large-scale observations of fault motions at geothermal sites (Wei et al., 2015; Cornet, 2016), and suggest that controlled field experiments at meter-scale are important for better assessing the role of fluid pressure in natural and human-induced earthquakes.

Experimental conditions

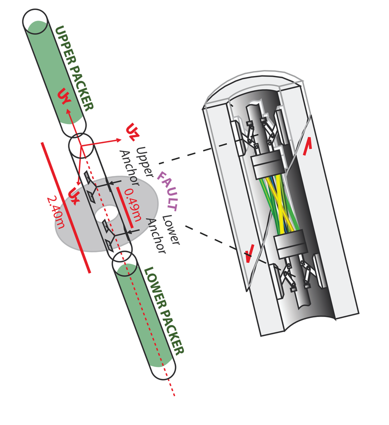
Fault reactivation by fluid injection at 280 m depth in an underground laboratory (LSBB, France).
The fault zone (20 m thick) is located in fractured limestone. Five vertical boreholes (20 m long) from the gallery ground allow to access to a variety of geological structures (fault planes, fractures, bedding planes). Thanks to these boreholes, 11 injection tests were performed with proximal hydromechanical and seismological measurements over a broad frequency range.







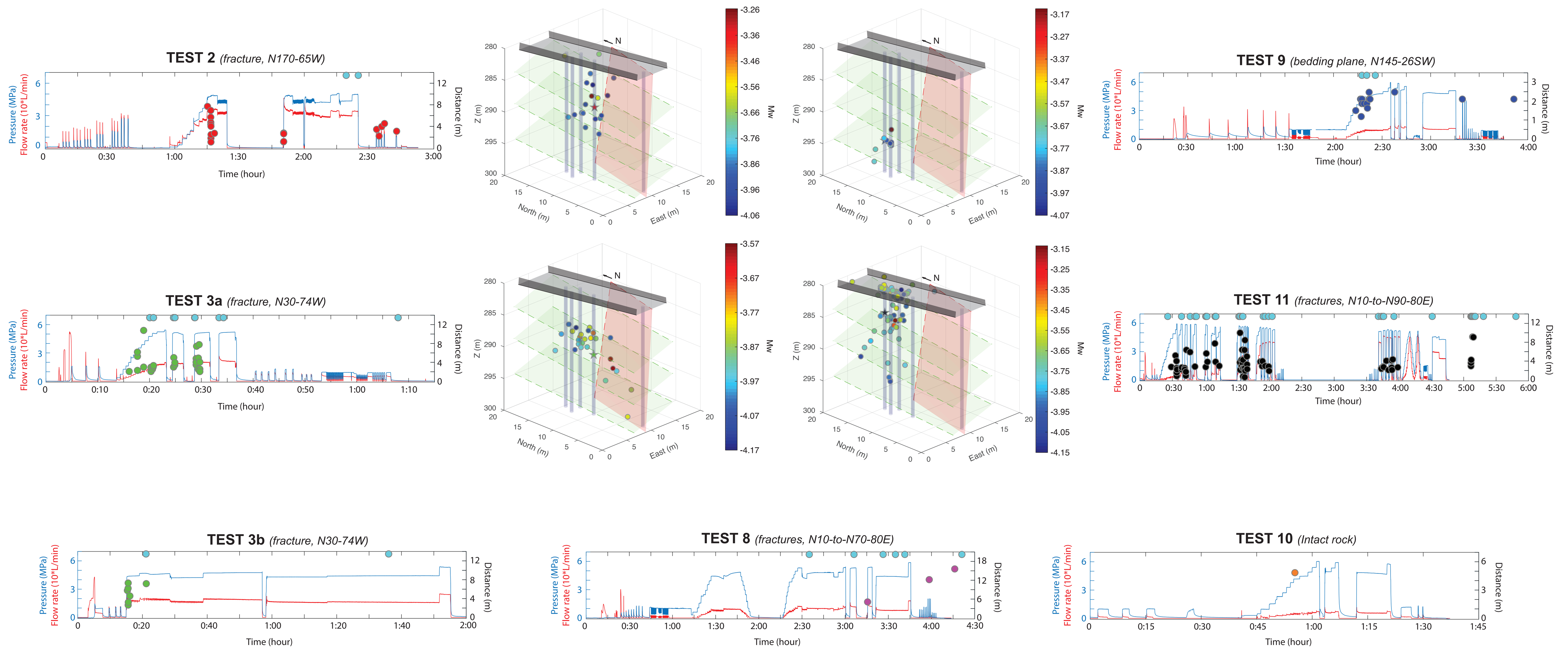
High-frequency (1 kHz) hydromechanical monitoring at the injection using a fiber-optic borehole probe (SIMFIP, Guglielmi et al., 2013):
Flow rate (+/- 0.1 l/min), Fluid pressure (+/- 1 kPa), Fault motions (+/- 1 micron)



Proximal geophysical monitoring (3 - 35 m) at high-frequency (10 kHz) near the injection (38 sensors) (Duboeuf et al, 2017):
22 accelerometers (10 Hz - 5 kHz)
9 geophones (10 Hz - 0.5 kHz)
4 acoustic sensors (1 Hz - 10 kHz)
3 tiltmeters (0.1 Hz - 0.5 kHz)

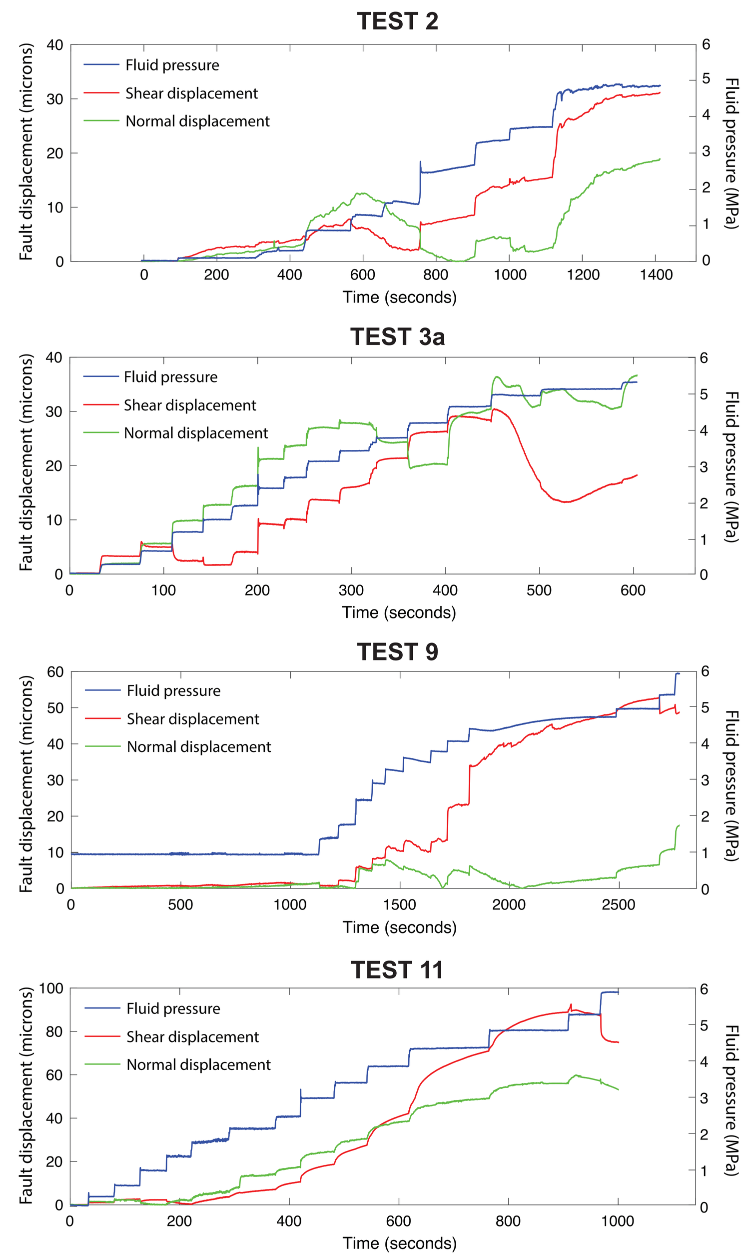
Fluid pressure and seismicity

Although pressures at a level comparable with the initial state of stress were injected and that different fractures and faults were reactivated, only a sparse seismicity (215 events) was recorded. The seismicity is unequally distributed among tests. Some of them do not show seismicity (Tests 6 and 7) or only few seismic events are detected (9 and 1 events for Tests 8 and 10, respectively). Other ones present a moderate seismicity (about 20 events) as Tests 2 and 9. Tests 3 and 11 have generated the most intense seismic activity of the experiments, with 48 and 117 seismic events, respectively. We determine that the moment magnitudes vary between -4.2 and -3.14. Most of them (63%) are between -3.5 and -3.9. Among the entire series of detected seismic events, 137 events have been absolutely or relatively located with a mean accuracy of 1.5 m. 85% of the seismic events occurred at distance greater than 2 m from the injection. Even considering an error of 1.5 m in the location, they cannot be located on the injection chamber. Therefore, a significant lack of seismic events is observed in the vicinity of the injection (Duboeuf et al., 2017).



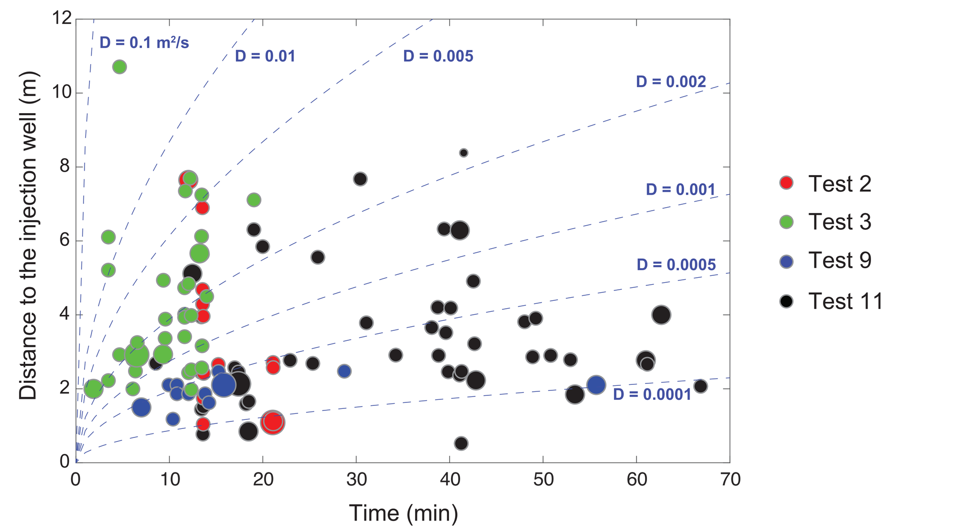
Fault hydromechanical response at the injection

Hydromechanical measurements at the injection show that fault deforms inelastically. The increase in fluid pressure induces highly dilatant and slow slip. The observation that the fault opens during the injection implies that permeability varies in close relation to the evolution of fluid pressure.

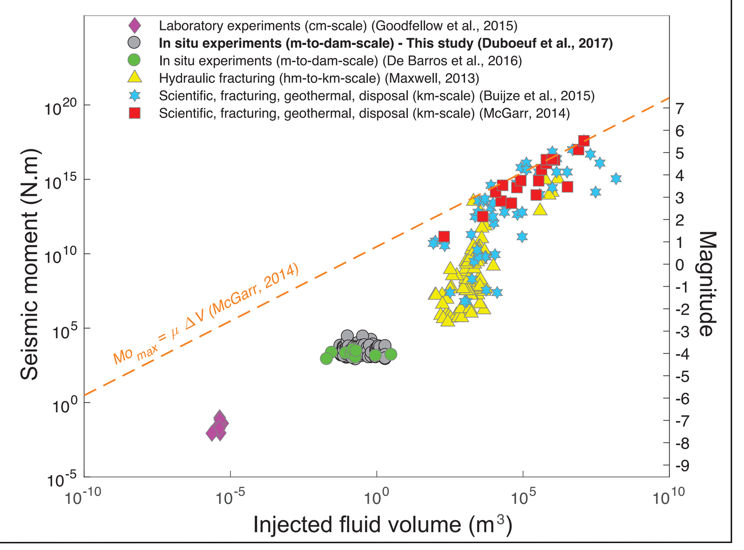


Driving mechanisms for seismicity

Seismic events recorded during Tests 9 and 11 seem to follow a fluid diffusion law. Our analysis shows that the diffusivity coefficient varies of 1 order of magnitude during tests. However, the hypocentral distribution for Tests 2 and 3 does not follow a diffusion law as events are clustered in time, but they are rather scattered in space. This suggests that the controlled mechanism of this seismicity might not be directly associated with a fluid diffusion but rather with a mechanism of stress perturbation through failure in the medium.

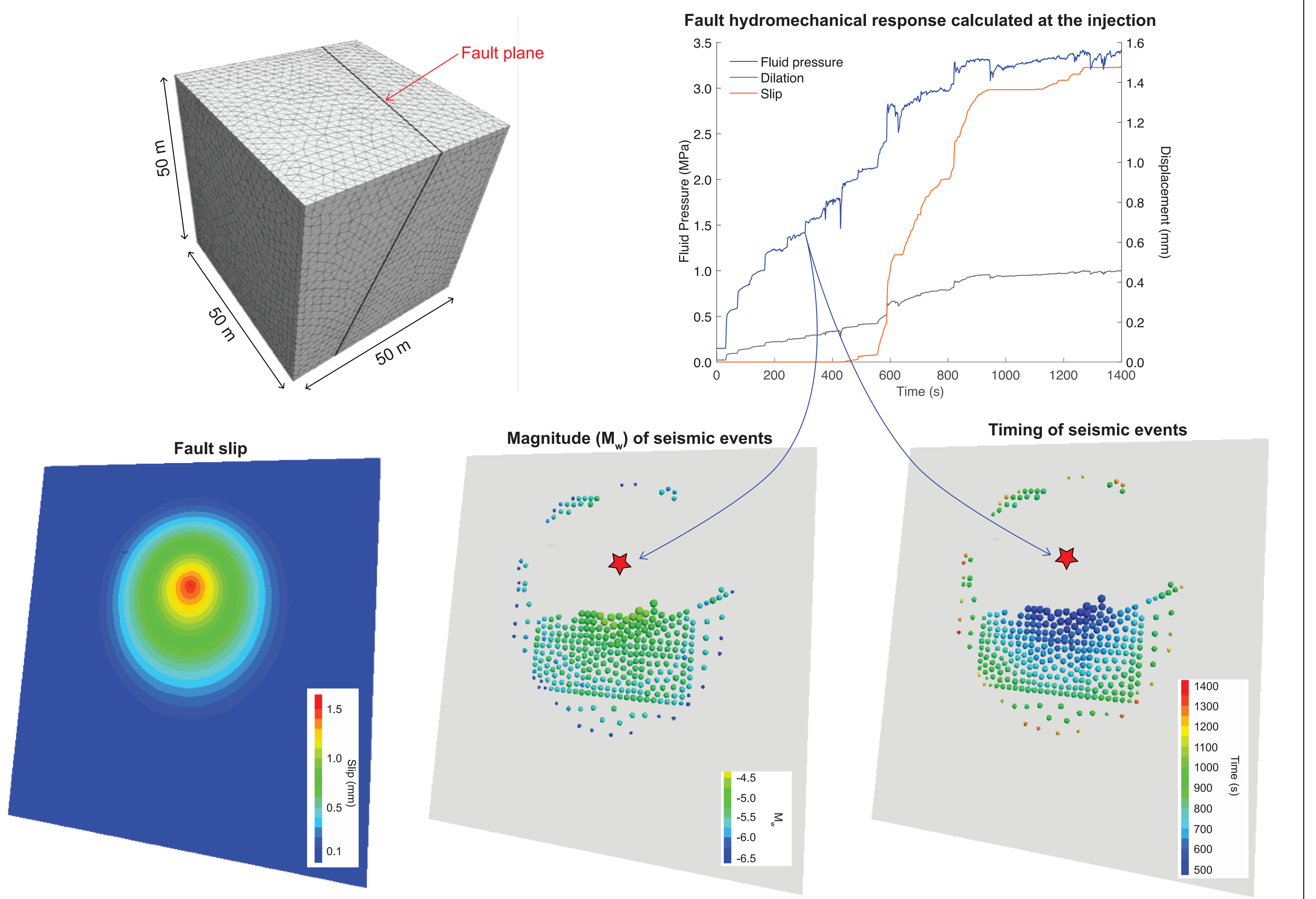


Our experiments indicate that a significant part of deformation is aseismic. According to the relationship of McGarr (2014), the maximum seismic moment should be about 41 GN.m, which is far above the value of 27 kN.m that we observed here. As this relationship is based on the assumption that all the deformation is seismic, this confirms that a strong part of the deformation is aseismic in our experiment.



Hydromechanical modeling of fault slip

We have developed a hydromechanical model of fault slip by fluid injection based on experimental data collected in 2010 in the same fault (Guglielmi et al., 2015) that we have stimulated in the present study. Model includes two-way coupling (fluid-to-solid, and solid-to-fluid), fluid flow along the fault, strain-dependent permeability, and friction laws. Based on the experimental data, we simulated a local fluid injection into a rate-and-state and permeable fault embedded in a 3D elastic and impervious medium. The geometry, initial stresses and physical parameters are inferred from laboratory and in-situ testing. The remote normal and shear stress resolved on the fault plane are constant. The initial value of stress (σ_{no} = 4.25 MPa, τ_o = 1.65 MPa) and fluid pressure (p_o = 0) into the fault represents the conditions of the in-situ experiment (Guglielmi et al., 2015). Our numerical results show that the fault undergoes opening and slip. As the result of fluid injection, the pressure perturbation diffuses within the permeable fault and triggers aseismic slip, which may, at least, help to trigger seismicity nearby, but at distance, during fluid injection.



Conclusion

- We have presented a comprehensive in situ investigation of the seismogenic and hydromechanical behavior of a fractured zone in a carbonate reservoir.
- The experiments show that fluid injections mainly induce aseismic motions (99% of the observed deformation) that drive a sparse seismicity far from the injection point.
- The experiments are used to assess the role of fluid pressure diffusion and stress perturbation through failure as driving mechanisms for seismicity.
- Our numerical model reproduces the general hydromechanical and slip behavior observed at the injection point. Model shows that slip is aseismic at the injection point, and seismicity develops at the front of the aseismic slip.
- In summary, our study shows that injection-induced aseismic motions play a crucial role for both the fluid pressure diffusion and the distribution of seismicity. Thus, aseismic motions should be accurately measured during fluid injections and considered with great care in the analyses of induced and triggered seismicity.
- Future directions:
  - Continue to investigate what conditions, physical parameters and mechanisms promote aseismic and seismic fault slip during fluid injection.
  - Use scaling laws for comparing the seismicity observed during these meter-scale experiments with ones observed at kilometer scale both at sites of fluid injection-induced seismicity and on seismogenic faults.

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