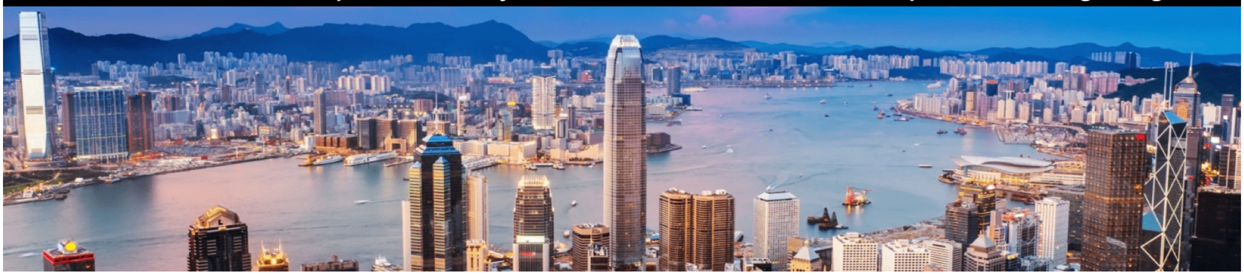

Rock faulting and injection-induced fault reactivation in the laboratory: Micro-seismicity as a (nearly!) real-time imaging tool.

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Introduction

During injection of fluids in underground reservoir formations (e.g., hydraulic fracturing fluids or CO_2 for long-term storage), the in situ pore pressure can increase. This will impact the mechanical stability and hydraulic conductivity of pre-existing faults and fractures. The mechanical stability of a rock formation can be monitored through its micro-seismic response. Relating the micro-seismic response of the rock to its physical and mechanical properties under well-controlled laboratory conditions is key to the interpretation of field micro-seismic data, and to ultimately predicting the potential occurrence of larger magnitude earthquakes ($M > 3$-4). In addition, beyond the direct seismic risk, the reactivation of pre-existing faults can also lead to new pathways for the injected fluids to escape toward shallower aquifers or to the atmosphere. It is therefore important to characterize and predict not only the occurrence of fault reactivation, but also its consequences in term of modifications of the pre-existing fault system, and therefore of the natural fluid pathways (fate of the injected fluids). This paper describes laboratory triaxial deformation experiments replicating typical field injection scenarios in naturally faulted reservoirs. Micro-seismicity imaging is used to decipher the evolution of the fault system generated by triaxially loading the rock to failure, then injecting a fluid in order to reactivate this fault system. The fluid used for the injection-induced reactivation phase is either a brine to simulate wastewater injection operations in the field, or liquid CO_2 to simulate CO_2 geo-sequestration operations.

Material and methods

We developed a specific laboratory workflow to assess the potential for and consequences of fault reactivation at realistic subsurface conditions. An array of 16 ultrasonic transducers is attached to a cylindrical rock specimen ($D = 38$ mm, $L = 80$ mm, see Figure 1), which is then subjected to an injection-induced fault reactivation experiment in a dedicated triaxial stress vessel. These transducers allow us to record and locate in space and time the micro-seismic activity (also called acoustic emissions) induced by the reactivation process. In other words, we use micro-seismicity monitoring in the laboratory as a (nearly!) real-time tool for imaging the structural changes undergone by the faulted rock during the fluid-driven reactivation. A typical reservoir analogue, namely the Berea sandstone, was selected to represent natural siliciclastic reservoirs at depth. First, the porosity and gas permeability were measured on several samples originating from the same block of Berea sandstone available for this project ($\phi_{avg} \sim 19\%$, $k_{avg}(N_2) \sim 116$ mD). Second, a series of conventional (axisymmetric) triaxial tests were conducted to characterise the rupture envelope and the brittle/ductile deformation regimes of the Berea sandstone. After this preliminary characterisation of multiple samples, two similar ones were selected to conduct injection-induced fault reactivation tests using the new laboratory workflow: one with brine and the other with CO_2. In these experiments we simulate a typical reservoir at 2000 m depth (pore pressure = 24 MPa, overburden stress = 46 MPa, horizontal stress = 30 MPa), well within the domain of brittle deformation for the Berea sandstone. At these conditions, CO_2 is typically in a liquid state. Each specimen is first faulted by increasing the vertical stress beyond the peak value in a triaxial stress vessel. The faulted specimen is then stabilized by decreasing the vertical stress (return to the in-situ conditions). The freshly formed fault is subsequently reactivated by fluid injection (brine or liquid CO_2) and increase of the pore pressure until slip occurs again.

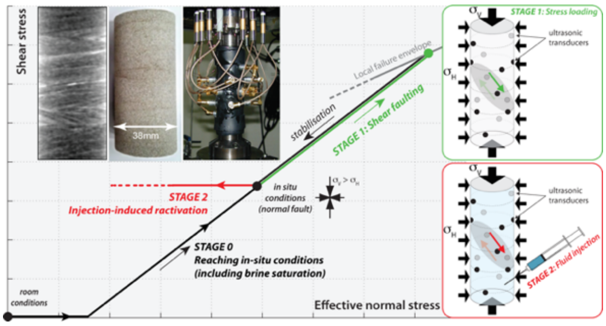

Figure 1. Schematic summary of the new laboratory workflow: Stage 0: reaching the in-situ conditions; Stage 1: triaxial stress loading and shear faulting; Stage 2: fluid injection (brine or liquid CO_2) and fault reactivation by pore pressure increase.

Results and conclusion

For the injection-induced reactivation stage (stage 2), Figure 2 illustrates the evolution with time of (a) the effective mean stress reflecting the vertical stress drop during slip, cumulative micro-seismic activity; (b) the axial and radial strains; and (c) the horizontal (plane) and sub-vertical (interplane) ultrasonic P-wave velocities, during the injection of brine (left) or liquid CO_2 (right). The velocity data are used to define the appropriate velocity structure of the rock in order to invert for the location of the micro-seismic events recorded during this stage of the experiment. Figure 2 also shows the results of this spatio-temporal location of the micro-seismic activity. Finally, this figure also reports the 3D rendering of the fault system as characterised after each experiment by X-ray CT imagery, segmentation and thresholding to outline the fractured zone. Qualitatively, there is no significant difference between injecting brine or CO_2 in the initially brine-saturated Berea sandstone, neither in terms of micro-seismic response, nor in terms of operational parameters such as the threshold reactivation pore pressure (3.8 MPa with brine and 5 MPa with liquid CO_2 above the natural formation water pressure of 24 MPa), or the vertical stress drop. In both cases injection results in a complex fracture network dominated by a major failure crossing the whole sample at 60 degrees of the axial load and the development of numerous sub-vertical fracture planes. The micro-seismic activity outlines the complex faulting pattern developed during fracturing and reactivation. It is confirmed by the X-ray CT images acquired independently after the experiment was completed. The scatter in the orientation of the different fractures/faults generated suggest that beyond the reactivation of pre-existing faults, fluid injection can lead to fractures/faults with different spatial orientations. In other words, in response to an underground pore pressure perturbation, not only pre-existing faults can rupture and slip (reactivate), but also new faults can nucleate and propagate in different directions (Figure 2). This mechanism is however not accounted for in geomechanical models, in which only pre-existing mapped faults allowed to reactivate. Extrapolation to the field scale suggests that injection-induced reactivation can lead to a spatial extension of the seismogenic zone, which could lead to inter-formation faulting, and as such promote inter-formation fluid migrations, or breach of reservoir containment in unexpected (unmonitored) locations.

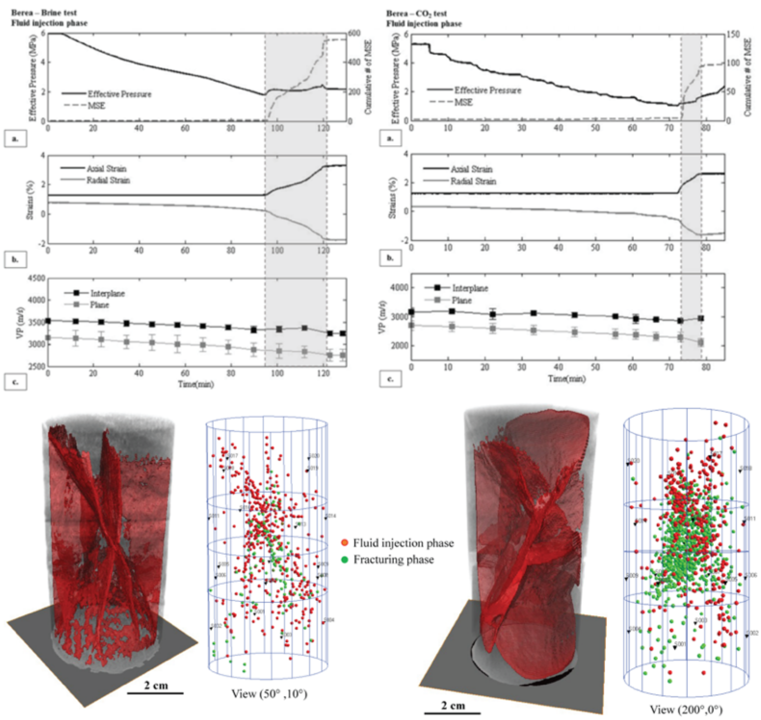

Figure 2. Top graphs: summary of the quantitative results obtained during the reactivation of the pre-faulted Berea sandstone by injection of brine (left) and liquid CO_2 (right): vertical stress drop, cumulative micro-seismic activity, axial/radial strains, horizontal (plane) and sub-vertical (interplane) ultrasonic P-wave velocities. Bottom X-ray CTs: 3D rendering of fracture/fault pattern. Bottom sample models: spatio-temporal locations of the micro-seismic activity obtained by injection of brine (left) and liquid CO_2 (right). The green events were recorded during triaxial pre-faulting (stage 1), and the red events were recorded during the injection-induced reactivation (stage 2).