Can fault leakage occur before or without reactivation?
Results from an in situ fault reactivation experiment at Mont Terri

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Abstract

In reservoir/seal systems, fault reactivation is classically described by Amonton’s law which governs stability or failure of a fault from the ratio of shear stress to normal stress. Understanding fault reactivation is critical in geologic CO₂ sequestration because it may result in enhanced fault permeability, potentially inducing CO₂ leakage from the injection zone through overlying caprock and eventually triggering shallow seismic events. Faults display a complex architecture characterized by a relatively low permeability fault core surrounded fractured damage zone. Fault models associating low permeability cores with high permeability damage zones are thus widely accepted. However, it is also known that the evolution of active fault zone properties results from concurrent processes that create and destroy porosity and permeability. Constitutive laws relating permeability with fault structure, stress, and strain remain poorly constrained. Thus, the key questions about fault reactivation in a seal layer concern the potential enhanced fluid displacement through a previously low-permeability aseismic formation.

This paper discusses a controlled field stimulation experiment (FS experiment dedicated to the In-situ clay faults slip hydro-mechanical characterization) conducted in a fault located in a clay formation in the Mont Terri Underground Research Laboratory (Switzerland). This fault is an analogue to a minor fault that would hardly be detectable from surface seismic surveys during the initial design of a sequestration site. It is a steepened thrust fault affecting the Opalinus clay formation oriented N140° and dipping 50-to-60°SE. It is characterized by a 2.8-to-4.2m thick core surrounded by a fractured damage zone. Under the present stress state, the static permeability of the fault zone is very low (in the order of 10E-13m/s). To estimate the potential of a dynamic permeability variation of the fault, we used six vertical boreholes 1.8-to-20m spaced, three of them intersecting the entire fault zone (figure 1). We actively conducted 3 fluids injections in 3 packed-off sections of one borehole while passively monitoring in one packed-off section set across the main fault plane in a second borehole 3.8m spaced (this hole was also used to estimate the stress state close to the main fault plane). While pressurizing the different borehole intervals at maximum injection pressures of 5-to-6.3 MPa set across the fault zone, we monitored the displacement tensor’s variations, the pore pressure and the injected flowrate in the two boreholes. The third borehole was used to monitor the induced seismicity with two three components accelerometers respectively set in the hanging wall and in the footwall of the fault. The three remaining boreholes were used to monitor the pore pressures in the intact hanging wall close to the fault zone. All the data are synchronized.

Two different hydromechanical fault responses were observed: no permeability variation occurred in the highly deformed fault core compared to a large non-linear factor-of-10-to-1000 permeability
increase in the fractured damage zones of the fault. Such high transient permeability locally occurred in the fault zone under conditions when most (63-to-93%) of the displacements induced on the tested discontinuities remained reversible, small (micro-to-millimeter scale) and mostly aseismic. Permeability recovery time can be very fast after the fault stimulation, occurring in a few tens of seconds. Interestingly, when there is such a poroelastic pressurization in the damage zone, a 0.1-to-0.7 millimeter slip occurred on the main fault plane located at the boundary between the low permeable fault core and the damage zone. In one case, slip is mainly associated to the pore pressure increase in the main fault plane because there is a hydraulic connection between the injection source located in the fault damage zone with the main fault plane. In the other case, slip is clearly not associated to such a pore pressure increase. No hydraulic connection was evidenced, showing that slip can be produced on the main fault plane while a poroelastic pressurization occurs off the plane in the fault damage zone.

We present preliminary analyses of the experimental data using fully coupled hydromechanical simulations figuring the fault zone architecture as a continuum anisotropic layer (using TOUGH-FLACD3D® simulator) and as a discontinuum fractured network (using 3DEC®). Simulations allow to explore the possibility that fluid migration along fault zones may be decoupled from slip when the fault is not favorably oriented for shear activation considering the Coulomb stress state, and to discuss under which conditions fault leakage may occur before or without a Coulomb failure reactivation.

Figure 1: Mt Terri fault activation experiment setting. A – Three-dimensional view of the Mt Terri main fault plane with the location of the experiment. B – Detailed map of the boreholes setting. C – Simplified cross section of the Main Fault with the locations of the packed-off sections. Borehole BFS1 is the hydromechanical monitoring hole (section at 37.65m depth) and the stress measurement hole (section at 47.2m). Borehole BFS2 is the injection hole at three packed-off sections 38, 40.6 and 44.65m. Borehole BFS3 is the seismic monitoring hole at 35.9 and 44.8m depths. Boreholes BFS6, 4 and 5 monitored the pore pressures at 29.8, 38 and 45m depths.