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Lessons Learned from a Controlled-Injection Fault Reactivation Experiment at Mont Terri, Switzerland: Can Fault Leakage Occur, When, and For How Long?

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Understanding fault reactivation as a result of subsurface fluid injection is critical in geologic CO2 sequestration (and other geo-energy applications such as wastewater injection) because it may result in enhanced fault permeability, potentially inducing CO2 leakage from the injection zone through the overlying caprock. Faults display a complex architecture characterized by a low permeability fault core surrounded by a 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, one of the key questions about fault reactivation in a seal layer concerns the potential for enhanced fluid displacement through a previously low-permeability aseismic formation.

Here we describe a controlled field stimulation experiment conducted in 2015 in a fault located in a clay formation in the Mont Terri Underground Research Laboratory (Switzerland). This fault, a perfect analogue to a minor fault that would hardly be detectable from surface seismic surveys during the initial design of a CO2 sequestration site, is characterized by a few meters 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 10-13 m/s). To estimate the potential of a dynamic permeability variation of the fault upon reactivation, we actively conducted four fluid injections in three packed-off sections of one borehole intersecting the fault while monitoring at high temporal resolution the displacement of the fault, the pore pressure, and the injection flowrate. We measured pore pressure changes and fault displacement in a second borehole several meters away along the fault plane. A third borehole was used to monitor induced seismicity with two three components accelerometers respectively set in the hanging wall and in the footwall of the fault, and three more boreholes were used to monitor the pore pressures in the intact hanging wall close to the fault zone.

This presentation discusses the main phenomenological lessons learned from the analysis and modeling of the injection experiments, with particular focus on the impact of aseismic and seismic fault slip on permeability increases and leakage potential along the fault. Fully coupled hydromechanical simulations represented the complex fault zone architecture as a continuum anisotropic layer (using the TOUGH- FLACD3D© simulator) and as a discontinuum fractured network (using 3DEC©). We show that the observed dispersion of the measured displacements in the fault core is related to activation of subsidiary fractures in shear rather than to the injection-related variation in the stress tensor. Thus applying a Coulomb stress criterion is not sufficient to predict fault activation and creation of leakage pathways, and we suggest that a refined criterion including both stress and strain (or strain rate) should be considered. In addition, complex hydraulic diffusivity variations with strain rate dominate the fault stability during the seismic nucleation.

References

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