Fault criticality and leakage below the Coulomb plastic limit: insights from hydraulic stimulations in the Opalinus Clay, Mont Terri rock laboratory, Switzerland

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We present results from a controlled fault-stimulation (FS) experiment conducted in 2015 in the Opalinus Clay in the Mont Terri rock laboratory (Switzerland). This in-situ experiment addressed questions: does reactivation of a fault in a clay formation creates a permeable flow path in previously low-permeability rock, and how does the permeability of this path evolve as repeated fault injections are conducted in sequence?

The Mont Terri rock laboratory is intersected by a fault zone, called the “Main Fault”, a perfect analog to a minor fault zone that would hardly be detectable from surface seismic surveys during the initial design of a CO_2-sequestration site or a radioactive waste repository. This second-order structure, interpreted as a shear fault-bend fold, is a few m thick and, under the ambient stress state, has a very low static hydraulic conductivity (on the order of 10^{-13} m/s). To estimate the potential of a dynamic hydraulic conductivity variation of the fault upon reactivation, we actively repeated high-pressure fluid injection cycles every 30 minutes intercalated with rest periods of the same duration. Stimulations were conducted between four packed-off sections of two vertical boreholes intersecting the fault at an overburden depth of 300 m and spaced 3 m apart (Fig.1). In each section, the three-component displacement of the fault, the pore pressure, and the injection flowrate were continuously monitored at 1 kHz sampling frequency. The three-component displacement sensor allowed us to measure sub-mm movements of selected discrete fault planes reactivated during a succession of step-rate pressure tests.

Using slip-tendency analysis and “3DEC” numerical software that together enable a fully coupled hydromechanical modelling, we estimated the variability of the stress tensor across the fault zone by fitting the measured 3D displacement vectors with the fault-plane geometry described by optical image logging and drillcore mapping. We found that faulting mechanisms are different across the fault zone (Guglielmi et al., 2016). One mechanism is pure fracture opening in the slightly deformed host rock that is characterized by bedding parallel fractures; another mechanism is a mixed mode with dominant dilatant shear that evolves towards the fault core composed of a complex pattern of interconnected fault planes.

Our key findings are:

1) Displacements measured during pressurisation are influenced by local stresses around the discontinuities and not by the far-field stress. Therefore, it is of prime importance to image and characterise in detail the structural complexity of a fault-zone architecture that appears to strongly condition its stability. Most of the activated discontinuities are almost perpendicular to principal maximum horizontal stress direction σ_H. Discontinuities are activated even when unfavourably oriented in respect to the stress field.

2) The observed and measured fault-opening pressure has low sensitivity relative to stress orientation, also at pressures below the Coulomb plastic limit (Jeanne et al., 2017)

3) Taking into account displacement measurements in the analyses, we estimate the orientation of the maximum horizontal stress in the injection intervals to be close to N310-N317 within an accuracy of ±10° (Guglielmi et al., submitted).

4) In the fault core, dispersion of the measured displacements is related to activation of at least three sets of differently-oriented fractures and not to variations in the stress tensor. The stress state does not seem to change in direction across the fault zone. Our results are in good agreement with the commonly accepted stress tensor for the Mont Terri rock laboratory (Martin & Lanyon, 2003). To completely define the stress tensor, we need to adapt the magnitudes to fit the measured displacements and fault hydraulic opening pressures.

5) Our observations show that flow channeling strongly controls leakage beyond and during fault rupture nucleation. This has several major implications in assessing the risk of potential fault leakage. Applying a Coulomb stress criterion to the average fault orientation is not sufficient to predict fault activation because fault slip is initiated by the accumulation of plastic strain caused by fluid diffusion at smaller scales on secondary heterogeneities within the fault zone. We suggest that a refined criterion including both stress and strain (or strain rate) should be considered to better understand and predict fault activation (Jeanne et al., 2018).

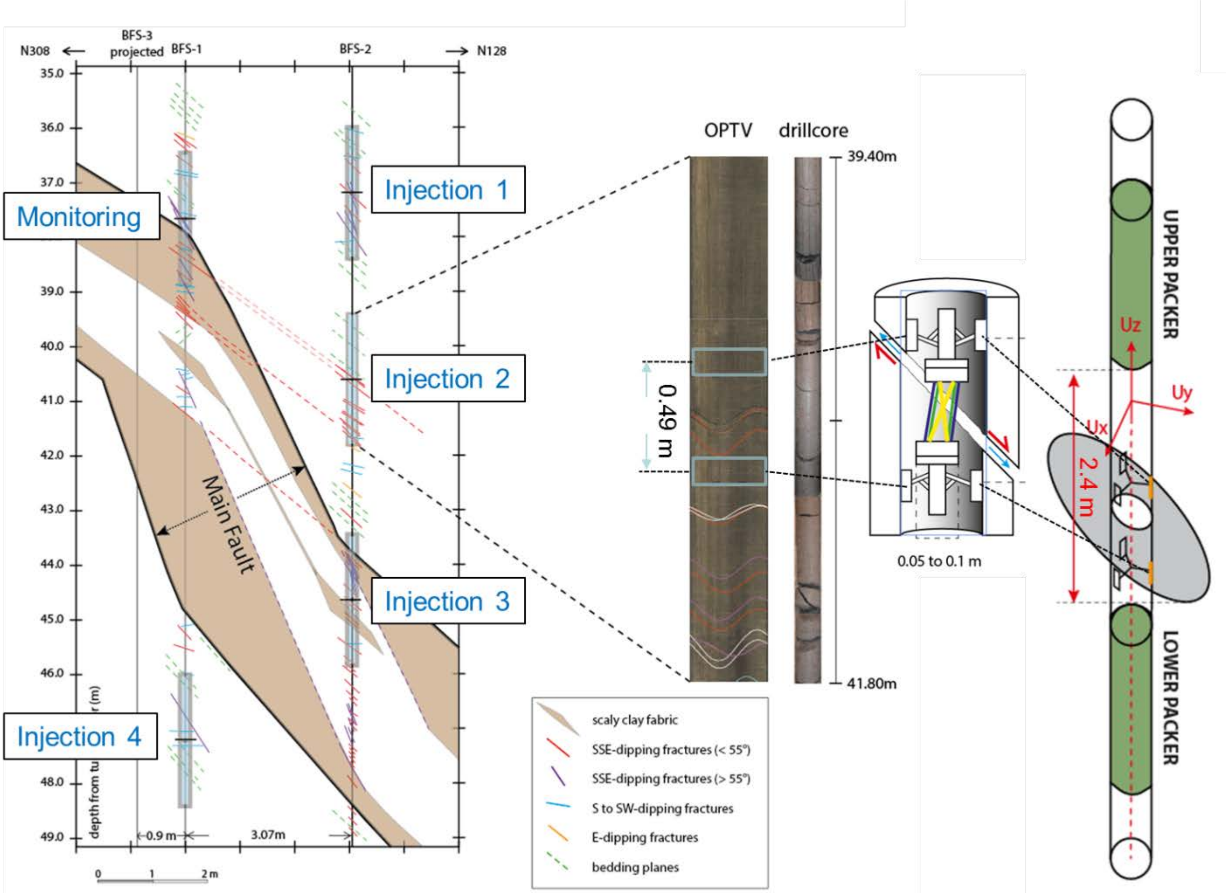

Fig. 1: Left: detailed geology of the Main Fault and positions of the four injection intervals and the monitoring interval. Middle: example of optical image log and corresponding drillcore of injection 2 interval. Right: hydromechanical SIMFIP probe (Straddle Intelligent Monitoring of Fracture Initiation Pressures)

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