An In-situ Experiment of Fault Reactivation in a Shaly Formation, Massif Central, France

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Introduction

Fluids & Faults (F&F) is a research project involving Total and several French universities and research institutes. The main objective of F&F is to improve our understanding of the hydromechanical behavior of a fault when it is reactivated by an increase in fluid pressure. To reach the aforementioned objective, a fault zone hosted in Toarcian shales was drilled and stimulated by water injection. Eight inclined boreholes were drilled across the fault zone from a tunnel gallery in the Tournemire Underground Research Laboratory (URL). Several water injection experiments were undertaken while a dense network of monitoring devices recorded rock deformation, fluid pressure, resistivity and micro seismicity.

The Tournemire URL

The experimental site (the Tournemire Underground Research Laboratory, IRSN) is located in the Causses basin (Figure 1A), a Mesozoic sedimentary basin located in the Massif Central (France). The URL is nested in a monoclinal tilted 5° to 10° to the North, made of 250 m thick Lower Jurassic shales (Domerian and Toarcian). The Lower Jurassic shales lie between two thick dolomitic layers dated as Middle Jurassic (top) and Lower Jurassic (bottom).

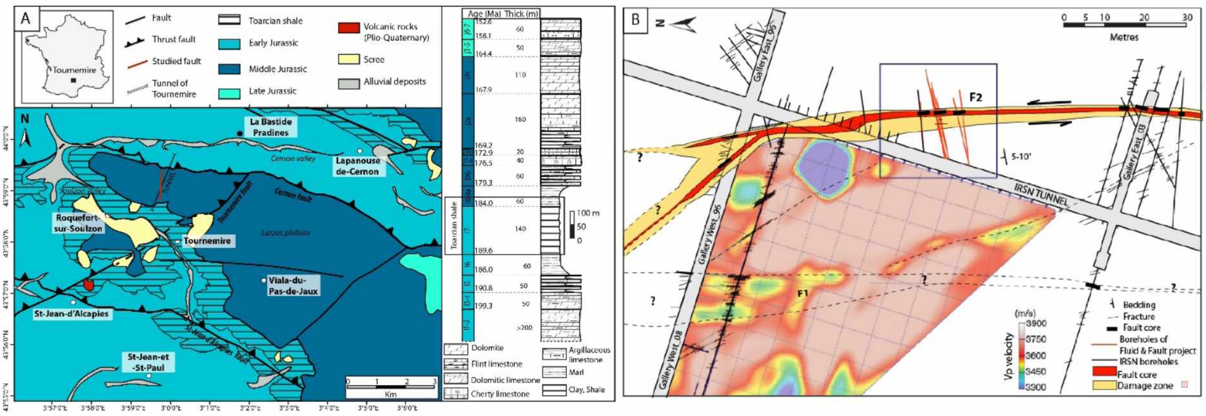


Figure 1. A)Geological map of the Causse region (France) and simplified stratigraphic column. B) Simplified map of the Tournemire URL and P-wave velocity map. Blue square: location of the F&F experiment. Modified from Lefevre et al. (in press).

The central part of the Tournemire URL is crossed by two main fault zones (F1 and F2) (Figure 1B). Both faults are subparallel with trends ranging between N170° to N010°; and dip between 60° to 80°W. The exact age of these faults is unknown but, most likely, they were active during the Pyrenean (Eocene) orogenic phase, first as right-lateral and then as left-lateral faults. However, N-S faults have been shown to be already active during the Mesozoic tectonic phase responsible for the opening of the Causse basin (Lefevre et al., in prep).

The shale's mineral composition is relatively homogeneous, with more than 50 wt.% of clay minerals, dominantly illite and illite/smectite, 10-20 wt.% calcite, and 10-20 wt.% quartz. Other components (less than 10 wt.%) include detrital micas, feldspars, pyrite and Fe-dolomite, and organic matter. Porosity of the unsaturated shale varies between 7 to 13 % and a water content of 4 to 6 wt.%. The hydraulic permeability has been estimated in the laboratory (0.1-1 nD) and in situ (1-1000 nD).

Maximum burial of the Toarcian shales in the Causse basin is still a matter of debate. Different estimates place this value between 1.3 and 3 km. At the present burial conditions of the URL, stress magnitudes are $\sigma1= 4\pm2$ MPa, horizontal and oriented N162°±15°E, $\sigma2= 3.8\pm0.4$ MPa, sub-vertical (plunge=83-82° and azimuth=N072°) and $\sigma3= 2.1\pm1$ MPa, plunge=7-8° and azimuth N072° (Cornet, 2000). Figure 2A shows a minimum stress ($\sigma3\sim \sigma h$) closer to 3.2 MPa when considering only subvertical fractures.

The structural model built for fault F2, and based on observations from boreholes (i.e. optical images, CT-scan and cores), describes the fault as a main fault core disposed in multiple branches intercalated with an asymmetric damage zone (Figure 2B). Secondary fault zones, each one with its core and damage zones, are described in the vicinity of the main fault. A cumulative vertical offset on fault F2 has been estimated to ~10 m with a total length in excess of 100m.

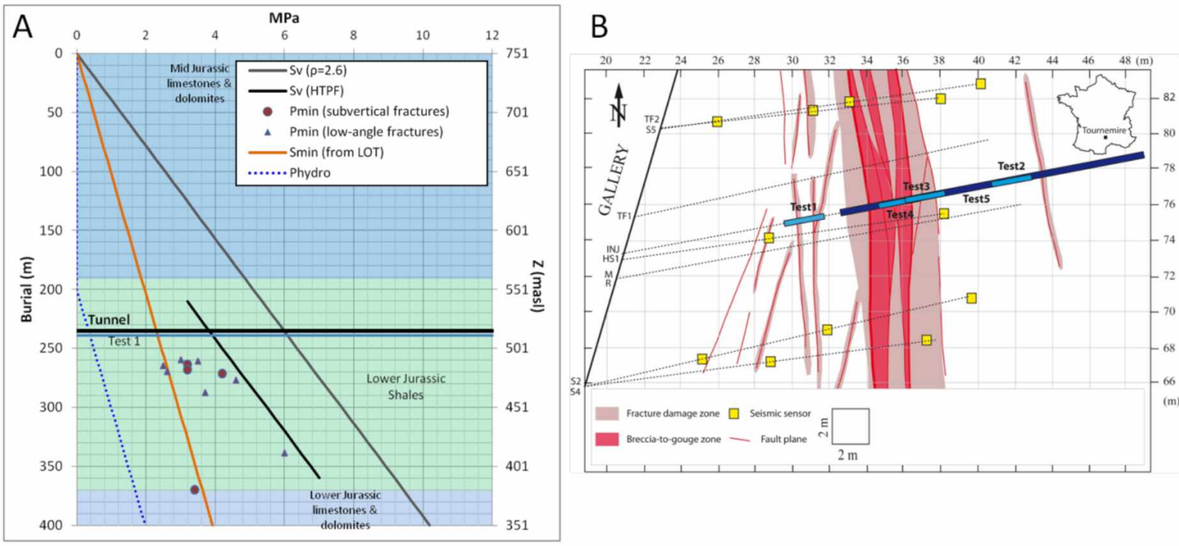


Figure 2. A) LOT data from the Tournemire URL, B) F2 Fault zone architecture and distribution of different tests along the injection well.

Using a Mohr-Coulomb reactivation criteria (Figure 3) and considering a pore pressure = 0.4 MPa (measured previously by IRSN) (Figure 3A), it can be predicted that a 1.0 MPa increase in pore pressure is enough to reactivate a N0° fault. High angle faults oriented NW-SE to N-S to NNE-SSW will be the first to be reactivated in shear displacement.

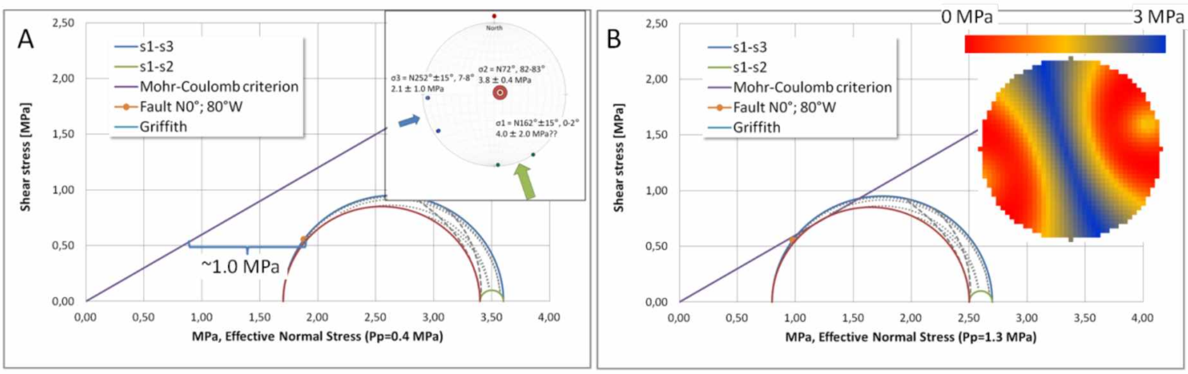
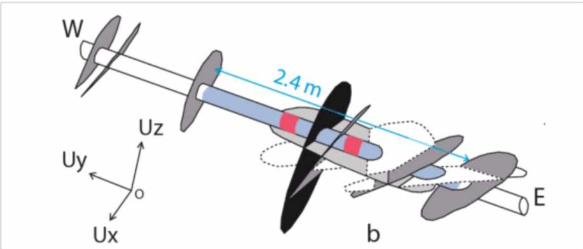


Figure 3. Stress state at the tunnel and Mohr-Coulomb reactivation criteria, A) Effective stress with a hydrostatic Pp profile as shown in Erreur ! Source du renvoi introuvable.**, B) Pore pressure Pp = 0.**

A pressure controlled injection test (i.e. test 1) was carried out in a secondary one-meter thick slickensided fault zone in the western panel (hanging wall) of fault F2 (**Figure** 2B). Macroscopic structures in the tested interval included calcite veins, fractures with calcite fillings (fracture damage zone) and 1 slickensided plane (main fault plane) oriented N0° with dip 80°W (**Figure 4**A). The fault was stimulated by fluid pressurization in a borehole using a straddle packer system isolating a 2.4 m long injection chamber oriented-sub normal to the fault zone. A three-dimensional displacement sensor attached across the main N0-80°W fault plane allowed monitoring fault movements, injection pressure and flowrate. Through water injection, pressure was increased stepwise from ca. 0.3 to 1.75 MPa, well below σh = 2.1 MPa and the normal stress of 1.86 MPa calculated on the main fault plane

(Guglielmi et al., 2015 and FigureB). Flow rate increased from 0 to 9 L/min when pressure exceeded 1.3 MPa. The same pressure threshold corresponded to a sharp decrease in the flow rate during the draw down phase. Deformation data from the injection probe shows that the N0° slickensided fault was activated during test 1 with a left-lateral and normal slip (dip dir. 28°NW and 45 µm) when pressure exceeded 1.3 MPa. The flow rate also increased from 0.2 to 8 L/min when slip was activated (Guglielmi et al., 2015). Displacements measured by the probe during this step-rate test are mainly reversible during the draw down phase.



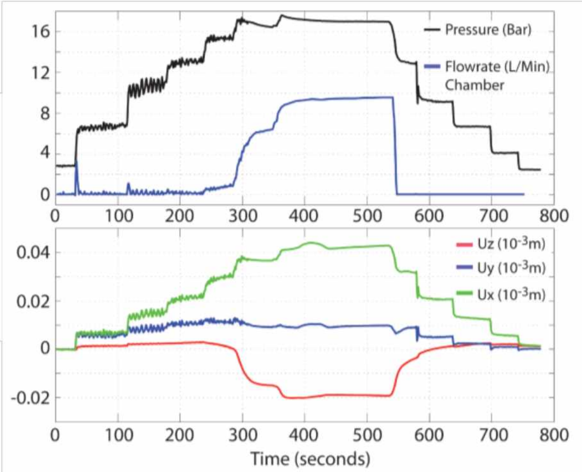


Figure 4. A) Schematic borehole and main intersecting structures. Injection chamber is the blue colored cylinder. Red bands figure the location of the displacement sensor's anchors. When the sensor is anchored to the borehole walls, it moves independently from the straddle packer system (Guglielmi et al., 2013). In test 1, relative displacements of the activated N0-80°W fault plane are measured but the interval structure shows that measurements can also be influenced by the activation of fractures from the fault damage zone in the eastern part of the interval; B) Pressure, flow rate and deformation recorded during test 1. Ux, Uy and Uz are the relative displacements of the western anchor towards the eastern anchor along directions parallel, perpendicular horizontal and vertical to the borehole respectively.

The small partly contractile measured shear dilation cannot explain the observed large change in hydraulic diffusivity from $\sim 2\times10^{-9}$ to $\sim 10^{3}$ $m^2.s^{-1}$. The deformation field and large changes in permeability that contribute to elevated post-failure fluid pressures and continuing fault slip are modulated by dilatant effects occurring off the slip-plane. These critically affect the flow geometry and the form of the slipping patch and may be responsible both for control of the initial deformation as slow-slip and the strong component of back-slip and reseating of the fault following de-pressurization. One possible hypothesis is that most of the observed displacement is caused by non-linear elastic behavior near the threshold for fault activation. Moreover, other fractures in the eastern fault damage zone may have been reactivated in the injection chamber (for example the fractures which are located close to the boundary between the chamber and the top of the lower packer, figure 5B). Opening of these fractures strongly contributed to enhance the overall fault zone hydraulic conductivity. It may be discussed (i) that the opening of these fractures mainly is elastic or because the pore pressure remains lower than the local critical stress on these fractures, potentially explaining part of the strong elastic backslip observed at the end of the test or (ii) that shear slip distributed on more than one plane has only been partly captured by the displacement sensor which is centered across the main fault plane (Figure 5b). In any case, this test shows how the complexity of this secondary fault zone structure may allow for slip and permeability variations to occur at different locations within the fault zone. It also shows that at relatively low injected volumes (about 50L injected in this test), local fault heterogeneity.

Conclusions

The in-situ experiment described here shows the complex hydromechanical behaviour of faults in shaly formations. Small displacements on the main fault plane (i.e. ~30µm), which are in good accordance with a Coulomb elasto-plastic shear, can induce very important increases in the fault hydraulic diffusivity (i.e. 2×10^{-9} to $\sim10^{3}$ $m^2.s^{-1}$). This can hardly be explained by dilation along this plane. Indeed, a small slip on the main fault plane is associated to a strong poroelastic dilation of a larger fault zone that could explain such a hydraulic permeability increase at the fault opening pressure (which is close-to or slightly below the normal stress).

This experiment shows a complex coupling between fault kinematic and its stress dependent permeability, highlighting that permeability increase may mainly occur off the main slip plane. During test 1, where a limited 40L fluid volume was injected during a relatively short time (6 minutes) it is possible that the fluid pressure did not equilibrate within the fault zone, limiting shear failure. The analysis of additional tests carried out during this in-situ experiment in different fault zone facies and with different durations should give additional insight into the fault hydromechanical behaviour in shaly formations.

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