Experimental study of reservoir seismicity using different injection strategies

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Summary

This experimental work aims to understand the effect of fluid pressure variations on the long-term integrity of a porous reservoir. To this end, stress controlled triaxial experiments (creep tests) were performed on a quartz-pure sandstone. Terzaghi effective pressure (P_c-P_f) was kept constant 30 MPa, i.e. pressure representative of typical targeted reservoirs, and fluid pressure was oscillated at different amplitudes and periods. During sample deformation, the rock mechanical properties and induced high-frequency acoustic emission (AE) signals were monitored to investigate the physics underlying the rupture processes at hand. Our experimental results showed that repeated pore fluid oscillations (dynamic hydraulic fatigue) affected the strain rate, stresses needed for failure, as well as the rate and energy released of the AE. In particular, rather than its amplitude, the period of the oscillation appeared to strongly affect the reservoir integrity.

Introduction

Fluid pressure is acknowledged as a key parameter affecting reservoirs integrity (e.g. McGarr, 2014). Fluid injection into a deep reservoir increases the pore pressure and reduces the effective stress acting on the rock mass that contributes to its integrity, and thus facilitates rupture. As a consequence, the fluid injection strategy is an important parameter controlling induced seismicity level (e.g. Zang et al., 2013). Creep test have been previously performed on sandstones (see Brantut et al. (2013) for a review) and showed that strain rate, time to failure and AE hit and energy rates are sensitive to applied deviatoric stress, temperature and effective confining pressure.

In this work, we aim to understand long-term (creep) behaviour of sandstone reservoirs while subjected to pore pressure oscillation.

Sample and method

The sample used for this study is a 7% porosity Fontainebleau sandstone. It is an almost pure quartz (99.9% quartz) sandstone composed of 200-300 µm grains cemented together by a quartz cement. Its permeability at the Terzaghi effective pressure of 30 MPa is 3.10^{-16} m², so that the time constant for water to flow across the sample length is $t_d < 2$ s (e.g. Fischer and Paterson, 1989) . For the experiments, oscillation periods (T) of 30 s and 3000 s were chosen so that the sample is always drained (i.e. $T >> t_d$).

Creep experiments were performed in a Hoek cell placed under a uniaxial press. Both lower and upper pistons were equipped with a pore fluid system and large band AE sensors. All samples were deformed at 35 MPa confining pressure (P_c) and 5 MPa mean fluid pressure (P_f). Then deviatoric stress (Q=σ_{ax}-P_c) was increased at a rate of 10^{-5} s^{-1} up to a target Q and pore fluid pressure was oscillated at a chosen peak-to-peak amplitude (A, between 1 and 8 MPa) and period. Creep experiments used the stress stepping method (described in Heap et al., 2009), with Q kept constant during (and increased every) 24 hours.

During the experiments, we recorded the stresses, axial displacement (converted to axial strain), ultrasonic AE, and fluid pump pressure and volume. Then, strain rate and AE hit rate (proxy of accumulating damage in the sample) were computed from the time dependence of those signals.

Results

Experimental results, in terms of strain rate and AE rate as a function of Q are presented in Fig. 1. A reference experiment of creep stress under constant pore fluid pressure was tested as a comparison. For all experiments, as expected, the minimum strain rate and AE hit rate are exponentially related to the differential stress.

At constant T=30 s, and for all the investigated A, no effect is observed on either the strain rate (Fig. 1a), AE hit rates (Fig. 1b) and stresses at failure: they all fit the reference experiment. However, AE showed a periodicity of 30 s, mostly concomitant with maximum pore pressure phases.

For a constant A=4 MPa, interestingly, a strong effect of T is observed on both strain (Fig. 1c) and AE hit rates (Fig. 1d). While the experiment with a smaller oscillation period (T=30 s) is similar to the reference experiment, strain rate and AE hit rate increase dramatically when increasing the period to T=300 or 3000 s. Moreover, the failure stress also decreased by a notable difference of about 25 MPa.

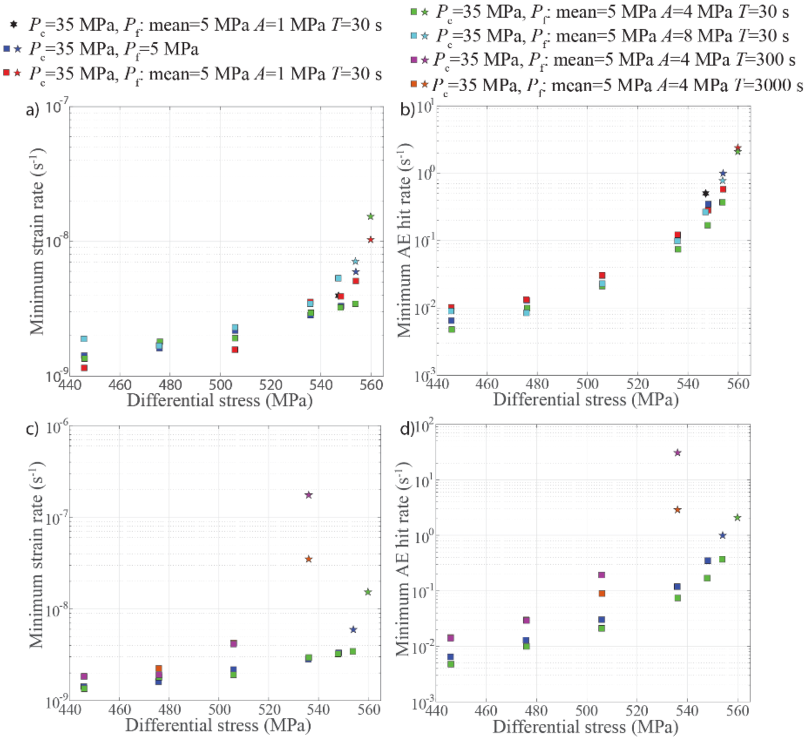

Fig. 1: Minimum creep strain and AE emission rates as function of applied differential stress. a) and b) experiments with constant *T* but varying *A*. c) and d) experiments with constant *A* but varying *T*. Each colour represents an experiment, the dots and stars present respectively the values at each step and at rupture

Discussion and conclusion

Our experiments show that the minimum strain rates and the AE hit rates are an exponential function of *Q*, consistent with earlier results (e.g. Brantut et al., 2013) . Pore fluid oscillations at small periods do not seem to affect the sample strength, even for amplitudes as high as 8 MPa. However, a hydraulic fatigue mechanism seems to occur at very high period of oscillations.

Surprisingly, the three periods chosen here (i.e. 30, 300 and 3000 s) are much larger than the time constant t_d, obtained from the quasi-static permeability measurement, so that the rock sample is drained macroscopically in both cases. Comparing other experimental studies tend to similar result: no fatigue effects were observed on rock submitted to fast oscillations by Chanard (2015) (Fontainebleau sandstone, T=240 s,) whereas Farquharson et al. (2016) reported strength lowering when the samples were submitted to slow pressure oscillations (porous andesite, T=2000 s). Upscaling to reservoir scale, our experiments show that cyclic injections can lead to hydraulic fatigue and thus affect the reservoir integrity.

References

Brantut, N., Heap, M.J., Meredith, P.G., Baud, P., 2013. Time-dependent cracking and brittle creep in crustal rocks: A review. Journal of Structural Geology 52, 17–43. https://doi.org/10.1016/j.jsg.2013.03.007

Chanard, K., 2015. Rôle des hétérogénéité géométriques et rhéologiques sur les ruptures sismiques. Ecole Normale Supérieure.

Farquharson, J., Heap, M.J., Baud, P., Reuschlé, T., Varley, N.R., 2016. Pore pressure embrittlement in a volcanic edifice. Bulletin of Volcanology 78. https://doi.org/10.1007/s00445-015-0997-9

Fischer, G.J., Paterson, M.S., 1989. Dilatancy During Rock Deformation at High Temperatures and Pressures. Journal of Geophysical Research 94, 17607–17617. https://doi.org/10.1029/JB094iB12p17607

Heap, M.J., Baud, P., Meredith, P.G., Bell, A.F., Main, I.G., 2009. Time-dependent brittle creep in darley dale sandstone. Journal of Geophysical Research: Solid Earth 114. https://doi.org/10.1029/2008JB006212

McGarr, A., 2014. Maximum magnitude earthquakes induced by fluid injection. Journal of Geophysical Research: Solid Earth 119, 1008–1019. https://doi.org/10.1002/2013JB010597.Received

Zang, A., Yoon, J.S., Stephansson, O., Heidbach, O., 2013. Fatigue hydraulic fracturing by cyclic reservoir treatment enhances permeability and reduces induced seismicity. Geophysical Journal International 195, 1282–1287. https://doi.org/10.1093/gji/ggt301