Analysis of persistent seismic multiplets at the EGS reservoir of Soultz-Sous-Forêts, France

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Introduction

Although aseismic motions are manifest in geothermal reservoirs, their detection and characterization result to be an arduous task as they often derived from indirect seismological observations because of the limited direct measurements. For instance, the slow slip movements during the 1993 hydraulic stimulation of the Soultz-sous-Forêts EGS reservoir, France, would have been hardly confirmed from the micro-seismicity monitoring without a direct observation from an extended time lapse borehole geometry monitoring (Cornet et al, 1997). An important issue is to develop reliable seismological techniques to evidence aseismic deformation in reservoirs since they might have significant implications on their short and long term management: permeability evolution, seismic risk management, well stability, etc.

To address this objective, we propose to re-explore the induced seismicity at Soultz-sous-Forêts despite the already numerous studies (Cornet and Jones, 1994; Helm, 1996; Moriya et al, 2003; Asanuma et al, 2005; Charlety et al, 2007; Bourouis and Bernard, 2007; Michelet and Toksöz, 2007; Cuenot et al, 2008). It provides a unique database for testing new approaches for aseismic movement identification from micro-seismicity data (Schaming et al, 2016). Indeed, an abundant fluid-induced seismicity was observed throughout the aforementioned stimulation and has been associated to both fluid pressure increase during stimulation and aseismic creeping movements. Especially, a large number of repeated earthquakes, with high-correlated comparable waveforms, were identified, suggesting common sources locations and mechanisms. Families of these repeated events (namely, multiplets) are interpreted as asperities operating several times and are generally thought to be driven by the surrounding slow slip movement (Bourouis and Bernard, 2007).

In this study, we investigate the multiplets activity associated with the 1993 hydraulic stimulation of Soultz-sous-Forêts in order to better understand the relationship, if any exists, with the hydraulic parameters driving the injection. The work is at last aimed at improving our knowledge on the aseismic motions in geothermal reservoirs from the study of the repeated earthquakes.

Data and Multiplets Identification

We analyzed large datasets recorded from 4 borehole accelerometers in proximity of the injection source. In 1993, contrarily to the only few events recorded on the surface network, 15153 fluid-induced events associated with the hydraulic stimulation were recorded at depth, enabling therefore an accurate analysis of the reservoir. We classified these events for the similarities in waveforms by firstly performing a cross-correlation analysis and clustering the events according to a correlation threshold set at 0.75. Secondly, we verified that the repeated earthquakes are indeed co-located.

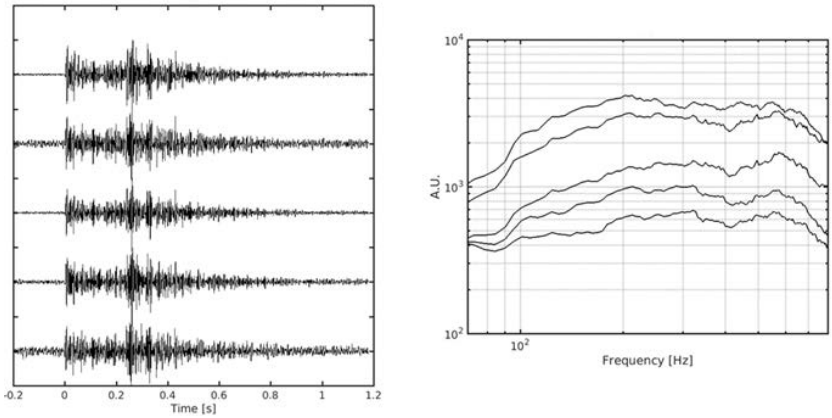

Fig. 1: Example of a family of 5 repeated earthquakes (multiplet) recorded between the 5th and 8th of September 1993 (sequence of 57 hours): on the left, the vertical components normalised in amplitude; on the right, their associated amplitude spectra. The corner frequencies are identified at 160Hz

For this latter step, we compared the sources dimensions to the inter-event distances. We assessed the sources dimensions by identifying the corner frequencies through amplitude spectra modeling with a Brune's model. We then applied the spectral ratios method (Lengliné et al, 2014) allowing us to refine the obtained sources radii (considering a circular source model). We estimated the distances between events within a family of similar waveforms through the analysis of delay-times variations between the P- and S-waves arrival times, computed from a cross-correlation analysis. Following this two-steps procedure, we identified in this manner about 4500 repeated events and classified them into more than 600 multiplets.

Multiplets activity during hydraulic stimulations

We firstly noticed that the repeated earthquakes have comparable sources dimensions on a single asperity but present instead a significant variation in amplitude (see Figure 1). This is interpreted as a large variation in stress drop and consequently, of the seismic slip. It therefore provides a local measurement of the variation of seismic slip at the scale of the patch. We observed that the activity of the repeated earthquakes is related to the fluid injection process. Indeed, the repeated earthquakes seismic moments increase with the time of the stimulation (for about one order of magnitude). We hypothesize that the associated slip variation is therefore related to parameters driving the injection process as the 1993 hydraulic stimulation is characterised by an increasing flow rate over the time of the experiment (therefore accompanied by increasing fluid pressure, injected volume and energy). Furthermore, consistently with observations from other geothermal contexts as Basel, Switzerland, low stress drop values are obtained in proximity of the injection well (Goertzmann et al., 2011) and the b-values associated with magnitude distributions computed from multiplets catalogues, decrease with the distance from injection source supporting a hydraulic control on the event amplitude distribution (Bachmann et al., 2012). Additionally, the impact of the fluid injection on the multiplets activity is also revealed from their duration, as the injection shut-in leads to the prompt completion of the repeated earthquakes sequences.

Finally we applied the identical analysis to the seismicity associated to the hydraulic stimulation carried on at Soultz-sous-Forêts in 2000, for which a large number of repeated earthquakes were also identified, suggesting therefore the involvement of slow slip movements. Preliminary results for this dataset show that the multiplets activity have similarities with the 1993 stimulation, including the amplitudes behaviour on the single asperities. The analysis over several fluid injection experiments will lead to an improved understanding on the repeated earthquakes activity, in turn clarifying their significance in terms of the aseismic motions manifest in geothermal reservoirs.

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