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Source mechanisms of micro-earthquakes induced in hydraulic fracturing experiment at the HDR site Soultz-sous-Forêts (Alsace) in 2003 and their temporal and spatial variations

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We have investigated source mechanisms of microearthquakes induced in the 2003 hydrofracturing experiment in the GPK3 borehole of the Soultz-sous-Forêts Hot Dry Rock facility (located in the Rhine Graben) and their time and space distribution. During this massive hydrofatcturing a total of 34000m^3 fluids with the wellhead pressure up to18 MPa were injected and about 5000 microearthquakes in the magnitude range of -0.9 $\leq$ M $\leq$ 2.9 were recorded by the surface local network. Depths of induced events varied between 3.5 km and 5.5 km. Seismic activity continued ten days after the injection shut in, during this period the largest events occurred. A peculiarity of the 2003-seismicity was a relatively high rate of larger microearthquakes which occurred during whole experiment. We investigated set of 45 microearthquakes of magnitudes M $\approx$ 1.6 to 2.9 covering the whole injection both in time and space. Unconstrained moment tensor (MT) expression of the mechanism was applied, allowing description of a general system of dipoles, i.e. both double-couple (DC) and non-DC sources like tensile fractures. Each of the resultant moment tensors was tested for stability to the reduction of the stations used, incorrectness of the amplitude readings due to distortion by noise, and structure mismodelling.
The resultant moment tensors indicate dominance of the double-couple components - mostly larger than 90%, minor non-double-couple parts were found to be insignificant; this implies that all the larger microearthquakes were nearly pure shear slips. The focal mechanisms show fairly large variability and are of a normal dip-slip, oblique normal to strike-slip types. The T-axes are fairly stable, being concentrated sub-horizontally roughly in the E-W direction. On the contrary, P-axes plunge varies largely from horizontal to vertical being well constrained in the N-S direction. This points out that the Soultz upper crust is the extension stress regime (similar magnitudes of the maximum and the medium stresses, σ1 and σ2), in which the normal dip-slip, oblique normal and strike slip faulting is possible. The temporal and spatial distribution of events investigated indicates a link of induced seismicity to two fault segments, I and II in our notation, showing different source mechanism pattern. Segment I located close to the GPK3-borehole was active during the whole experiments while segment II only after the GP3-shut in. The largest events occurred within both segments, a few days after the GPK3 shut in. This however shows that the 2003-Soultz seismic activity developed to a great extent independently of the injection strategy. Injected fluids acts only to decrease the Coulomb friction by reducing the normal stress on the fractures and to 'lubricate' the fault walls, enhancing a shear slip along the pre-existing fractures. In this respect the 2003-Soultz seismic activity resembles tectonic foreshock-mainshock-aftershock earthquake sequence. Furthermore we infer that general assumption that highly pressurized fluids generate tensile fracturing of the rock mass need not be correct. It holds only if the injection pressure is higher than the tensile strength of the material.