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Seismic and aseismic slip measured during a meter-scale fluid injection experiment into a fault

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In the upper crust, fluid pressures are known to induce both natural and induced earthquakes (Nur and Booker, 1972; Sibson, 1973; Miller, 2002; Majer et al., 2007; Ellsworth, 2013). For instance, an important evidence is the considerable increase of the seismicity rate (4.7 times the background rate) in Oklahoma, Central US, during fluid injections. However, the mechanisms involved are poorly understood and our ability to assess the seismic hazard associated with natural and anthropogenic fluid pressurization remains limited. Moreover, a recent study by Guglielmi et al. (2015) has showed that fluid injection mainly induces aseismic fault slip that then triggers seismicity. Thus, how fluid pressure induces seismicity and aseismicity is a very open question. To study this question, here, we present experimental results collected directly in a fault that is stimulated with a controlled fluid injection at 280 m depth in limestone into an underground laboratory, the Low Noise Underground Laboratory (LSBB, www.lsbb.eu, France). Thanks to galleries, a small segment (10 m) of an inactive normal fault (20 m-thick) oriented N030°-85°E (Jeanne et al., 2012) was drilled with five 20 m-long vertical boreholes. The fault was equipped both in boreholes and at the gallery ground with 31 seismic sensors and an injection probe that allows the simultaneous measurements of fluid pressure and fault deformations (Guglielmi et al., 2014). With this device, we stimulated at meter-scale different areas of the fault's damage zone using a high-pressure (2-to-6 MPa) water injection in order to reactivate pre-existing fractures. Results indicate that only a few tests have generated seismicity even if the ruptures (slip of maximum 1 mm) are observed at the injection point. 205 seismic events have been detected over the course of these experiments. They are characterized by weak magnitudes (-4) and high frequency contents (600-3000 Hz). Rupture and seismicity only occur at high-fluid pressure (5 MPa). We determined the earthquakes' location using the P- and S- arrival travel-times and calibration shots (with an accuracy of 1 m) to validate the location of seismicity. As several seismic signals have similar waveforms, we used cross-correlations for a relative location based on a double-difference method. 145 seismic events have been located and are found from 1 to 6 m away from the injection point. This observation indicates that seismicity does not occur at the injection point contrary to the observed rupture, which is consistent with the results of Guglielmi et al. (2015). Thus, we may assume with confidence that the fluid-saturated zone might be aseismic in this experiment. We then compare the distribution of the seismicity with the pressure and deformation observed at the injection point and its evolution.