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Seismicity triggered by stress transfer from a fluid injection-induced fracture activation

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Fluid pressures into fault zones and fractured reservoirs are known to produce seismic events. However, the precise mechanisms relating fluid pressures and seismicity remain unclear. Here, we studied the effects of stress transfer on seismicity triggered in the near field of an active fluid pressure source controlled by a step-rate hydraulic injection (a few MPa). The experiment was conducted in a critically stressed fractures zone intersecting a carbonate reservoir layer at 250 m-depth into an underground gallery. The pressurized fractures zone corresponds to the damage zone of a 10 m-thick strike-slip fault. This experiment seeks to explore the field measurements of temporal variations in subsurface fluid and stress through continuous monitoring of seismic waves, fluid pressures and mechanical deformations between boreholes and gallery surface. Data showed that as the applied fluid pressures on rock were changed, damage and seismicity were caused by the slip along pre-existing fractures. A factor-of-3 increase in fracture permeability was associated with $\sim$100 triggered seismic events. Both normal opening (a few microns) of the fluid-injected fracture and the associated tilt (< 1 micro-radian) of the gallery wall displayed partly inelastic behavior characterized by irreversible deformations (amounting to about 1/3 to 1/2 of the maximum measured deformations) synchronously occurring in the injected fracture and in the rock volume around, not affected by the hydraulic diffusion of the injected fluid. All seismic hypocenters were located along fractures in this rock volume outside the injection fracture. Using a plane-strain finite-difference coupled hydromechanical model, we analyzed this complete data set and showed that (1) the observed seismicity is caused by shear failure of weak zones subjected to stress transfer from the injection zone into the surrounding fractured layer, and (2) the softening of the layer's strength properties strongly influences the injected fracture slip and increase in permeability. Finally, our continuous and long-term monitoring provided dense and repeated measurements of induced fluid pressure, strain and seismicity changes suggesting that significant flow and permeability enhancement within a stiff rock mass is mainly localized along fractures where patches of aseismic tensile and seismic shear failure can coexist.