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Influence of fault heterogeneity on the frequency-magnitude statistics of earthquake cycle simulations

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Numerical models are useful tools for investigating natural geologic conditions can affect seismicity, but it can often be difficult to generate realistic earthquake sequences using physics-based earthquake rupture models. Rate-and-state earthquake cycle simulations on planar faults with homogeneous frictional properties and stress conditions typically yield single event sequences with a single earthquake magnitude characteristic of the size of the fault. In reality, earthquake sequences have been observed to follow a Gutenberg-Richter-type frequency-magnitude distribution that can be characterized by a power law scaling relationship. The purpose of this study was to determine how fault heterogeneity can affect the frequency-magnitude distribution of simulated earthquake events.

We considered the effects fault heterogeneity at two different length-scales by performing numerical earthquake rupture simulations within a rate-and-state friction framework. In our first study, we investigated how heterogeneous, fractal distributions of shear and normal stress resolved along a two-dimensional fault surface influenced the earthquake nucleation, rupture, and arrest processes. We generated a catalog of earthquake events by performing earthquake cycle simulations for 90 random realizations of fractal stress distributions. Typical realizations produced between 4 to 6 individual earthquakes ranging in event magnitudes between those characteristic of the minimum patch size for nucleation and the size of the model fault. The resulting aggregate frequency-magnitude distributions were characterized well by a power-law scaling behavior. In our second study, we performed simulations of injection-induced seismicity using a coupled fluid flow and rate-and-state earthquake model. Fluid flow in a two-dimensional reservoir was modeled, and the fault mechanics was modeled under a plane strain assumption (i.e. one-dimensional faults). We generated a set of faults with an average strike of +/- 30 degrees from the direction of maximum principal stress and with a fractal distribution of lengths. The faults were randomly prescribed an initial shear stress ranging between critically-stressed and subcritically-stressed within one stress drop. High-rate injection into a single well in an infinite reservoir ultimately triggered a sequence of earthquakes. We investigated the sensitivity of the frequency-magnitude statistics to the different distributions of fault sizes and initial proximity to failure.