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Spontaneous Arrest of Natural and Induced Earthquake Ruptures Nucleated by Localized Loads

Jean Paul Ampuero (1), Martin Galis (2), P. Martin Mai (3), Frédéric Cappa (1,4)

(1) Université Côte d'Azur / IRD / CNRS / Observatoire de la Côte d'Azur, Géoazur, Nice, France, (2) Comenius University, Bratislava, Slovakia, (3) King Abdullah University of Science and Technology, Thuwal, Saudi Arabia, (4) Institut Universitaire de France, Paris, France

Injection-induced seismicity is a hazard but also an opportunity to gain insight into earthquake processes. In a sense, induced earthquakes are the closest we have to a natural-scale earthquake physics experiment. Common features of anthropogenic and natural earthquakes may be exploited to achieve insight on the latter from observations of the former. In particular, in both situations rupture nucleation can be driven by a concentrated load: induced earthquakes can start in a confined area of a fault that has been weakened by increased fluid-pressure, whereas natural earthquakes can nucleate along the base of the seismogenic zone where stresses are concentrated due to deeper steady creep. Here, we summarize characteristics of ruptures nucleated by localized loads that are predicted by numerical models and by fracture mechanics theory, and have potentially observable seismic signatures.

In a basic model, nucleation starts at a highly stressed (or weakened) patch on a fault with otherwise uniform pre-stress. Ruptures grow dynamically beyond the perturbed area and are either self-arrested (they stop spontaneously when they run out of elastic energy) or runaway (they stop only when they reach the ends of the fault). We recently derived theoretical estimates, validated by simulations, of the size of self-arrested ruptures as a function of the size and amplitude of the stress excess in the nucleation area (Galis et al., 2017). Applied to induced seismicity, the model yields a non-linear relation between the seismic moment of the largest arrested earthquakes and the net injected volume. The relation is consistent with maximum magnitudes of induced earthquakes observed across a wide range of injected volumes, from laboratory to field scales. The result suggests that, while runaway ruptures are possible, most injection-induced events so far have been self-arrested ruptures.

The model predicts qualitatively a tendency for larger magnitude earthquakes to be induced later during injection. This tendency is also found in rate-and-state models of earthquake sequences and may be observable in properly declustered catalogs. In smoothly pre-stressed faults, self-arrested ruptures slow down progressively, leading to weaker radiation efficiency than runaway ruptures. This difference may be observable if not masked by rupture complexity caused by heterogeneous fault stress and strength.

Applied to natural earthquakes nucleating near transitions between locked and creeping parts of a fault, the model predicts accelerating moment release by intermediate-size earthquakes, foreshocks and slow slip. However, it does not constrain the partitioning between seismic and aseismic slip. The model also provides insight on supercycles in which intermediate-size earthquake confined near the bottom of the seismogenic zone occur in between mega-earthquakes breaking the whole seismogenic width. The process of nucleation at the edges of the seismically coupled zone contributes to a low average fault stress (long-term apparent friction).

M. Galis, J. P. Ampuero, P. M. Mai and F. Cappa (2017), Induced seismicity provides insight into why earthquake ruptures stop, Science Advances, 3 (12), eaap7528, doi:10.1126/sciadv.aap7528