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Scaling Between Fault Length, Damaged Zone Thickness and Width of Secondary Fault Fans Derived from Fracture Mechanics

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The interaction between earthquakes, fault network geometry and fault zone structure is a key question motivating the integration of dynamic rupture and long-term crustal deformation modeling. Here, we address the scaling between fault structural properties from the perspective of dynamic and quasi-static processes involved in fault system evolution. Faults are surrounded by materials damaged through quasi-static and dynamic processes, forming damaged zones whose thickness and damage intensity may vary as a function of fault maturity and length. In the vicinity (typically less than a few hundred meters) of their principal slip surface, faults develop an “inner damage zone”, usually characterized by micro-fracture observations. At a larger scale, faults develop an “outer damage zone” of secondary macroscopic fault branches at their tips, which organize into fans of splay faults.
Inner damage zones can significantly affect earthquake ruptures, enhance near-field ground motions and facilitate fluid transport in the crust. Fault zone trapped waves can generate pulse-like rupture and oscillatory rupture speed, facilitate supershear rupture transition and allow for steady rupture propagation at speeds that are unstable or inadmissible in homogeneous media. The effects of a fault damage zone crucially depend on its thickness. Field observations of inner damage zone thickness as a function of cumulated slip show linear scaling at small slip but saturation at large slip, with maximum damage zone thickness of a few hundred meters. We previously developed fracture mechanics theoretical arguments and dynamic rupture simulations with off-fault inelastic deformation that predict saturation of the thickness of co-seismic damage zone controlled by the depth extent of the seismogenic zone. In essence, the stress intensity factor at the front of a rupture, which controls the distance reached by the large off-fault stresses that cause damage, scales with the shortest characteristic length of the slipping zone. This length is limited by the seismogenic depth. The theory also provides relations between damage scaling properties and the overall stress at which faults operate.
Field observations indicate that the width of fault fans forming outer damage zones scales with the length of the parent fault, without saturation. Here we propose a fracture mechanics model to explain this observation. The stress intensity factor K at the tips of a fault cutting through the whole depth of an elastic plate (the lithosphere) overlying a linear viscoelastic half-space (the asthenosphere) is time-dependent and shows two regimes. At short times, K depends on seismogenic depth, as expected in an elastic half-space. At times much longer than the characteristic viscous relaxation time of the asthenosphere, K depends on rupture length, qs expected for a through-going crack in an elastic plate decoupled from the mantle (essentially a 2D plane strain configuration). A model of long-term growth of splay fault fans driven by stress concentration near the propagating tip of the main fault, governed by the long-term scaling of K, predicts a scaling between outer damage zone width and fault length, consistent with the geological observations.