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Earthquake triggering via nonequilibrium dynamics

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The physical origin of dynamic triggering of earthquakes (i.e., by transient seismic waves) remains one of the least understood aspects of earthquake processes. Here we show that the dynamic, nonequilibrium dynamics, the elastic-nonlinear behavior of the fault core under the influence of a seismic wave, may be responsible for dynamic triggering of earthquakes. We base our hypothesis on recent dynamic experiments conducted in granular media (a surrogate for fault gouge) under a suite of confining pressures, and on numerous dynamic experiments conducted in rock under a great variety of saturation and pressure conditions. Our experiments show that, under the relatively small effective pressures in the fault core, dynamic waves with strain amplitudes known to trigger earthquakes could cause the material modulus to abruptly decrease. The modulus decrease results in material weakening via a simple deformation and instability model. Our conceptual model is that seismic waves from a distant earthquake impinge on a fault that is critically stressed, temporarily decreasing the core modulus. The modulus decrease corresponds to an abrupt material strength decrease sufficient to induce fault slip. Experiments indicate that strains greater than approximately $10^{-6}$are required to induce modulus reduction (assuming effective pressures are low). Such strain amplitudes are observed only in the aftershock region of large earthquakes with a few notable exceptions. The latter includes the M7.3 Landers, M 7.1 Hector Mine and the M7.9 Denali earthquakes, which exhibited dynamic triggering along azimuths of elevated strains at regional distances due to strong source directivity. In addition to modulus reduction due to the "fast nonlinear dynamics", there is a recovery of the modulus to equilibrium over many hours, termed "slow dynamics", that takes place after the wave energy has dissipated. Slow dynamics progressively induces moderate stresses over time on the system, while keeping the modulus below its equilibrium value during the process. Slow dynamics may well play an additional role in

delayed triggering and/or earthquake clustering. In summary, the nonlinear softening-to-weakening mechanism requires the following conditions to be met within the fault core: (1) a critical pre-stress state; (2) strain amplitudes that exceed $\sim 10^{-6}$; and (3) low effective pressures.