Coupled evolution of earthquakes and faults in a seismogenic upper crust governed by damage rheology over a viscoelastic substrate

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We review results on coupled evolution of earthquakes and faults in a regional lithospheric model consisting of a seismogenic upper crust governed by damage rheology over a layered viscoelastic half-space. The damage rheology [Lyakhovsky et al., JGR, 1997] accounts for evolving non-linear properties of rocks under conditions of irreversible deformation. The framework adds to the parameters of linear Hookean elasticity λ and μ a third parameter γ to account for the asymmetry of the response of rocks under loading or unloading conditions, and makes the elastic moduli functions of an evolving damage state variable α representing the local microcrack density. An undamaged solid with $\alpha = 0$ is the ideal linear elastic material governed by the usual Hooke's law ($\gamma = 0$ for $\alpha = 0$). At the other extreme, a material with $\alpha = \alpha_c \leq 1$ is densely cracked and can not support any load. Our damage rheology model calculates the instantaneous values of the elastic moduli for all intermediate states of the damage parameter ($0 < \alpha < \alpha_c$) based on the balance equations of energy and entropy and the above generalization of linear elasticity.

Lyakhovsky et al. [1997] give full derivation of the governing equations and comparisons of model predictions with friction, fracture, and acoustic emission data, used both to verify the overall validity of the formulation and to constrain model parameters. Liu et al. [GJI, 2002] provide detailed comparisons of model predictions with stress-strain data of triaxial deformation experiments leading to brittle failure of intact granite, basalt, and sandstone under different confining pressure. Ben-Zion and Lyakhovsky [PAGEOPH, 2002] show analytically that the damage rheology leads to a singular power law time-to-failure relation proportional to $(t_f - t)^{-1/3}$ and a corresponding non-singular power law relation for cumulative Benioff strain proportional to $(t_f - t)^{1/3}$.

The evolving damage modifies the effective elastic properties of material in the upper crust as a function of the ongoing deformation. This simulates the creation and healing of fault systems in the upper seismogenic zone. Ben-Zion et al. [EPSL, 1999], Lyakhovsky et al. [JGR, 2001] and Ben-Zion and Lyakhovsky [2002] used the above framework to perform a large parameter-space study. The results indicate the existence of three basic dynamic regimes. The first is associated with large simulated fault zone disorder, frequency-size (FS) statistics of earthquakes compatible with the Gutenberg-Richter power law distribution, random or clustered temporal statistics of intermediate and large events, and phases of accelerated seismic release (ASR) following power law time-to-failure relation before large earthquakes. The second is associated with relatively regular simulated fault zones, FS statistics compatible with the characteristic earthquake distribution, quasi-periodic temporal occurrence of large events, and no ASR phases before large events. For a range of parameters, there is a third regime in which the response switches back and forth between the forgoing two modes of behavior. The results are compatible with observations covering wide ranges of space-time scales and additional theoretical studies for a discrete fault system with quenched heterogeneities in elastic solid [e.g., Ben-Zion, JGR, 1996; Dahmen et al., PRE, 1998] and a smooth homogeneous fault in a continuum solid [e.g., Ben-Zion and Rice, JGR, 1997; Lapusta et al., JGR, 2000].