Final Report for SCEC2 Studies on
Coupled Evolution of Earthquakes and Faults in a Regional Model with Damage Rheology

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Summary

The brittle portion of the Earth lithosphere is "damaged" in the sense that any macroscopic rock volume in that layer contains an internal distribution of joints and faults. These fractures have in general complex geometries with intersections, stopovers, bends and many other deviations from planarity. The material around such geometrical complexities is subjected to large stress concentrations, which necessarily lead during continuing deformation to the evolution of the elastic properties and geometry of the actively deforming region. These evolving material and geometrical properties should be taken into account in quantitative analysis of earthquakes in large spatio-temporal domains, containing several moderate and large faults and large earthquake cycles. The studies done under this project focused on establishing a physical basis, using a thermodynamically-based continuum damage rheology, for understanding the coupled evolution of earthquakes and faults in a geophysically-relevant framework that incorporates complex fault geometries and the main units of the lithosphere. The studies focused on the following five research directions: (1) developing a physical basis for interpreting the conditions for and properties of accelerated seismic release (2) developing better connections between the damage rheology and laboratory fracture and friction data, (3) developing a physical basis for interpreting the main observed features of aftershock sequences in terms of basic structural and material properties, (4) developing improved theoretical treatment of stress reduction and accumulation of plastic strain during brittle instabilities, and (5) developing an improved numerical model that can be used for long-term simulations of coupled evolution of earthquakes and faults. The main results associate with these research directions are summarized below. The funding from the project provided partial support for 3 PhD students.

Accelerated Seismic Release and Related Aspects of Seismicity Patterns on Earthquake Faults (Ben-Zion and Lyakhovsky, 2002)

Observational studies indicate that large earthquakes are sometimes preceded by phases of accelerated seismic release (ASR) characterized by cumulative Benioff strain following a power law time-to-failure relation with a term $(t_f - t)^m$, where t_f is the failure time of the large event and observed values of m are close to 0.3. We discuss properties of ASR and related aspects of seismicity patterns associated with several theoretical frameworks. The sub-critical crack growth approach developed to describe deformation on a crack prior to the occurrence of dynamic rupture predicts great variability and low asymptotic values of the exponent m that are not compatible with observed ASR phases. Statistical physics studies assuming that system-size failures in a deforming region correspond to critical phase transitions predict establishment of long-range correlations of dynamic variables and power law statistics before large events. Using stress and earthquake histories simulated by the model of Ben-Zion (1996) for a discrete fault with quenched heterogeneities in a 3D elastic half space, we show that large model earthquakes are associated with non-repeating cyclical establishment and destruction of long-range stress correlations, accompanied by non-stationary cumulative Benioff strain release. We then analyze results associated with a regional lithospheric model consisting of a seismogenic upper crust governed by the damage rheology of Lyakhovsky et al. (1997) over a viscoelastic substrate. We demonstrate analytically for a simplified 1D case that the employed damage rheology leads to a singular power law equation for strain proportional to $(t_f - t)^{-1/3}$, and a non-singular power law relation for cumulative Benioff strain proportional to $(t_f - t)^{1/3}$. A simple approximate generalization of the latter for regional cumulative Benioff strain is obtained by adding to the result a linear function of time representing a stationary background release. To go beyond the analytical expectations, we examine results generated by various realizations of the regional lithospheric model producing seismicity following the characteristic frequency-size statistics, Gutenberg-Richter power law distribution, and mode switching activity. We find that phases of ASR exist only when the seismicity preceding a given large event has broad frequency-size statistics. In such cases the simulated ASR phases can be fitted well by the singular analytical relation with $m = -1/3$, the non-singular equation with $m = 0.2$, and the generalized version of the latter including a linear term with $m = 1/3$. The obtained good fits with all three relations highlight the difficulty of deriving reliable information on functional forms and parameter values from such data sets. The activation process in the simulated ASR phases is found to be accommodated both by increasing rates of moderate events and increasing average event size, with the former starting a few years earlier than the latter. The lack of ASR in portions of the seismicity not having broad frequency-size statistics may explain why some large earthquakes are preceded by ASR and other are not. The results suggest that observations of moderate and large events contain two complementary end-member predictive signals on the time of future large earthquakes. In portions of seismicity following the characteristic earthquake distribution, such information exists directly in the associated quasi-periodic temporal distribution of large events. In portions of seismicity having broad frequency-size statistics with random or clustered temporal distribution of large events, the ASR phases have predictive information. The extent to which natural seismicity may be understood in term of these end-member cases remains to be clarified. Continuing studies of evolving stress and other dynamic variables in model calculations combined with advanced analyses of simulated and observed seismicity patterns may lead to improvements in existing forecasting strategies.

A Visco-Elastic Damage Model with Applications to Stable and Unstable fracturing
(Hamiel et al., 2004).

A visco-elastic damage rheology model is presented that provides a generalization of Maxwell visco-elasticity to a non-linear continuum mechanics framework incorporating material degradation and recovery, transition from stable to unstable fracturing, and gradual accumulation of non-reversible deformation. The model is a further development of the damage rheology framework of Lyakhovsky *et al.* (1997a) for evolving effective elasticity. The framework provides a quantitative treatment for macroscopic effects of evolving distributed cracking with local density represented by an intensive state variable. The formulation, based on thermodynamic principles, leads to a system of kinetic equations for the evolution of damage. An effective viscosity inversely proportional to the rate of damage increase is introduced to account for gradual accumulation of irreversible deformation due to dissipative processes. A power-law relation between the damage variable and elastic moduli leads to a non-linear coupling between the rate of damage evolution and the damage variable itself. This allows the model to reproduce a transition from stable to unstable fracturing of brittle rocks and Kaiser effect. Three-dimensional numerical simulations based on the model formulation for homogenous and heterogeneous materials account for the main features of rock behavior under large strain. The model coefficients are constrained, using triaxial laboratory experiments with low porosity Westerly granite and high porosity Berea sandstone samples.

A viscoelastic damage rheology and rate- and state-dependent friction (Lyakhovsky et al., 2005)

We analyze the relations between a visco-elastic damage rheology model and rate- and state-dependent (RS) friction. Both frameworks describe brittle deformation, although the former models localization zones in a deforming volume while the latter is associated with sliding on existing surfaces. The visco-elastic damage model accounts for evolving elastic properties and inelastic strain. The evolving elastic properties are related quantitatively to a damage state variable representing the local density of microcracks. Positive and negative changes of the damage variable lead, respectively, to degradation and recovery of the material in response to loading. A model configuration having an existing narrow zone with localized damage produces for appropriate loading and temperature-pressure conditions an overall cyclic stick-slip motion compatible with a frictional response. Each deformation cycle (limit cycle) can be divided into healing and weakening periods associated with decreasing and increasing damage, respectively. The "direct" effect of the RS friction and the magnitude of the frictional parameter *a* are related to material strengthening with increasing rate of loading. The strength and residence time of asperities (model elements) in the weakening stage depend on the rates of damage evolution and accumulation of irreversible strain. The "evolutionary" effect of the RS friction and overall change in the friction parameters (*a*-*b*) are controlled by the duration of the healing period and asperity (element) strengthening during this stage. For a model with spatially variable properties, the damage rheology reproduces the logarithmic dependency of the steady-state friction coefficient on the sliding velocity and the normal stress. The transition from a velocity strengthening regime to a velocity weakening can be obtained by varying the rate of inelastic strain accumulation and keeping the other damage rheology parameters fixed. The developments unify previous damage rheology results on deformation localization leading to formation of new fault zones with detailed experimental results on frictional sliding. The results provide a route for extending the formulation of RS friction into a nonlinear continuum mechanics framework.

Analysis of Aftershocks in a Lithospheric Model with Seismogenic Zone Governed by Damage Rheology (Ben-Zion and Lyakhovsky, 2006)

Aftershocks are the response of a damaged rock surrounding large earthquake ruptures to perturbations produced by the large events. We perform analytical and numerical studies of aftershock sequences following abrupt steps of strain in a rheologically-layered model consisting of a weak sedimentary layer over a seismogenic zone governed by a visco-elastic damage rheology underlain by a visco-elastic upper mantle. The damage rheology accounts for fundamental irreversible aspects of brittle rock deformation and is constrained by lab data of fracture and friction experiments. Analysis of the relaxation process in a 1-D version of the damage rheology leads to exponential analytical solution for the evolution of the damage rate. The solution depends on a single material parameter R given by the ratio of the timescale for damage increase and timescale for gradual inelastic deformation. The parameter R is also inversely proportional to the degree of seismic coupling across the fault. The analytical solution provides a generalized law for aftershock decay rates that is richer than a universal power law relation. The results associated with the analytical exponential expression can be fitted well for various values of R with the modified Omori power law relation. The same holds for the decay rates of aftershocks simulated using the 3-D layered lithospheric model. The results indicate that low R-values (e.g., $R \leq 1$) corresponding to cold brittle material produce clear long Omori-like aftershock sequences, while high R-values (e.g., $R \geq 5$) corresponding to hot viscous material produce short diffuse response. The frequency-size statistics of aftershocks simulated in 3-D cases with low R-values follow the Gutenberg-Richter power law relation, while events simulated for high R-values are concentrated in a narrow magnitude range. Increasing thickness of the weak sedimentary cover produces results that are similar to those associated with higher R-values.

Increasing the assumed geothermal gradient reduces the depth extent of the simulated earthquakes. The magnitude of the largest simulated aftershocks is compatible with the Båth law for a range of dynamic damage-weakening parameter. The results provide a physical basis for interpreting the main observed features of aftershock sequences in terms of basic structural and material properties.

Scaling relations of earthquakes, aseismic deformation and evolving fault structures in a damage rheology model (Lyakhovsky and Ben-Zion (2007)

We perform analytical and numerical studies of scaling relations of earthquakes, partition of elastic strain energy between seismic and aseismic components, and evolution of fault structures, using a thermodynamically-based continuum damage model. Brittle instabilities occur in the model at critical damage level associated with loss of convexity of the strain energy function. A new procedure is developed for calculating stress drop and plastic strain in regions sustaining brittle instabilities. The formulation connects the damage rheology parameters with dynamic friction of simpler frameworks, and the plastic strain accumulation is governed by a procedure that is equivalent to Drucker-Prager plasticity. The numerical simulations use variable boundary forces proportional to the slip-deficit between the assumed far field plate motion and displacement of the boundary nodes. These boundary conditions account for the evolution of elastic properties and plastic strain in the model region. Three-dimensional simulations of earthquakes in a model with a large strike-slip fault produce scaling relations between the scalar seismic potency, rupture area, and stress drop values that are in good agreement with observations and other theoretical studies. The area and potency of the simulated earthquakes generally follow a linear *log-log* relation with a slope of 2/3, and are associated with stress drop values between 1 and 10 MPa. A parameter-space study shows that the area-potency scaling is shifted to higher stress drops in simulations with parameters corresponding to lower dynamic friction, more efficient healing, and higher degree of seismic coupling. Simulations of evolving fault structures around a pre-exiting narrow damage zone agree with analytical expectations for crack extension path under mixed-mode loading. The numerical results also demonstrate evolution with continuing deformation from an initially-created system of stepping en-echelon segments to a smooth through-going structure.

Publications Supported by this project

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