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# Coupled Self-Organization of Seismicity Patterns and Networks of Faults, and Basis for Evaluating Seismic Risk and Precursors

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## *Summary*

Our last year studies focused on two research directions aiming to improve the physical basis for evaluating seismic risk and precursors. In the first effort, we designed and performed six brittle fracture experiments in collaboration with Dave Lockner (USGS, Menlo-Park) in an effort to obtain additional constraints to the damage rheology of Lyakhovsky et al. [1997]. In the second direction, we investigated analytically and numerically properties of accelerated seismic release and related aspects of seismicity patterns. Results from our last year studies in these directions are described below.

## *Analysis of Acoustic Emission and Stress-Strain Lab Data with a Damage Rheology Model*

Lyakhovsky et al. [1997] developed a damage rheology model to describe evolving non-linear properties of rocks under conditions of irreversible deformation. The model adds to the parameters of linear Hookean elasticity $\lambda$, $\mu$ a third parameter $\gamma$ to account for the asymmetry of the response of rocks under loading or unloading conditions, and makes all three parameters a function of an evolving damage state variable $\alpha$. Conceptually, damage evolution in rock deformation leading to brittle failure can be divided into the following three stages: frozen initial damage, distributed material degradation, and localization of damage culminating with macroscopic failure. In the first stage, the elastic moduli $\lambda$, $\mu$ and $\gamma$ are all constants and $\gamma$ is equal to zero for damage-free rocks. During the second stage with distributed damage, effective moduli of stress-strain can be used to describe evolution of average elastic properties in the deforming solid. In the third localized stage, the heterogeneity of the material must be taken into account. Along with damage evolution, we also consider damage-dependent viscous deformation. On the time scale of laboratory experiments, viscous strain based on values of viscosity $\eta$ typically used for crustal deformation (e.g. $\eta \geq 10^{19}$ Pa s) is too small to contribute appreciably to deformation. However, the viscous deformation may be accelerated by increasing damage and we thus assume that the viscosity $\eta$ is a function of the rate of $\alpha$.

To obtain additional constraints to the damage rheology model, we designed and performed in January-February 2000 six brittle fracture experiments in collaboration with Dave Lockner (USGS, Menlo-Park). The experiments measured acoustic emissions, axial strain, and transverse strain during deformation leading to brittle failure of 3 materials – granite, basalt, and sandstone – with different initial porosity (damage) under low and high confining pressures. The analysis done so far focused on data associated with the granite experiments of this year and those of Lockner et al. [1992], and was based on simplified calculations involving a uniform damage evolution. The results show good overall agreement between model predictions and observations [Liu et al., 2000]. The predicted stress-strain curve deviates from linearity near the observed sharp increase in acoustic emission rates, and matches the observed stress-strain curve almost up to the final brittle failure where the assumption of uniform damage evolution obviously fails. The faulting angle estimated from the damage rheology model is compatible with the observed value. During the continuing studies we will analyze the data of the granite experiments with more realistic 3D calculations, and will apply similar analysis procedures to the data of the basalt and sandstone experiments. We will also continue to develop the connections, discussed in general terms by Lyakhovsky et al. [1997], between the damage rheology and phenomenology of rate- and state-dependent friction.

### *Accelerated Seismic Release and Related Aspects of Seismicity Patterns on Earthquake Faults*

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. Ben-Zion and Lyakhovsky [2001] examined 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-Richer 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.

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