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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 efforts aiming to improve the physical basis for evaluating seismic risk and precursors. In the first work, we used a regional lithospheric model consisting of a seismogenic upper crust governed by damage rheology over a layered viscoelastic half space to study the coupled evolution of earthquakes and faults. In the second work, we used models of a disordered single fault system in a 3D elastic half-space to quantify the establishment and destruction of stress correlations associated with large earthquake cycles in the system. Essential aspects of the works are discussed below.

Coupled Evolution of Earthquakes and Faults

Figure 1 shows a regional lithospheric model [Ben-Zion et al., 1998; Lyakhovsky et al. ms. in preparation] consisting of a seismogenic upper crust governed by damage rheology over a Maxwell viscoelastic substrate. The model calculates the coupled evolution of earthquakes and faults in a framework incorporating damage rheology compatible with observed nonlinear and irreversible features of strain, and essential 3-D aspects of lithospheric deformation. The damage rheology, described in detail by Lyakhovsky et al. [1997], has two types of functional coefficients: (1) a "generalized friction coefficient" separating states associated with material degradation and healing, and (2) damage rate coefficients for positive (degradation) and negative (healing) changes. As shown by Lyakhovsky et al. [1997], our damage rheology duplicates a wide variety of laboratory observations including acoustic emission rates and fracture and friction data. The evolving damage modifies the effective elastic properties of material in the seismogenic zone as a function of the ongoing deformation. This simulates the creation, evolution, and possible healing of fault systems in the upper brittle crust. The seismogenic zone is coupled viscoelastically to the substrate, where steady plate motion drives the lithospheric deformation. The viscous crustal deformation is calculated using variables that are vertically averaged over the crust thickness (H+h in Figure 1), while the elastic deformation is calculated with a 3-D Green function for an elastic half-space.

Figure 2 gives map views of simulated damage in the upper crust at different times, illustrating the evolution of fault zones in the model. The boundary conditions and large scale geometrical, rheological, and damage parameters used to generate the results are indicated in Figure 1 and the inset of Figure 3. The assumed parameter values for the upper crust (thickness H, rigidity for zero damage μ_0, generalized friction coefficient ξ_0, Poisson's ratio ν), lower crust (thickness h, viscosity η, rigidity μ_a, Poisson's ratio ν), and imposed plate motion at the base of the lower crust, were determined by fitting model calculations to average observed geodetic deformation associated with the San Andreas fault (SAF) in California, and additional regional constraints from observed seismological and geodetic data [Lyakhovsky et al., ms. in preparation]. With these parameters and small uncorrelated random noise in the spatial distribution of ξ_0, we find the following: Low healing/loading rate (upper curve in inset of Figure 3) leads to the development of geometrically regular fault systems and frequency-size (FS) event statistics compatible with the CE distribution. High healing/loading rate (lower curve in inset of Figure 3) leads to the development of a network of disordered fault systems, and the GR distribution. These results are compatible with the observed fault-trace complexity and earthquake statistics of Wesnousky and co-workers [e.g., Stirling et al., 1996], and our previous theoretical results for seismicity in disordered single fault systems in a 3D elastic half-space [Ben-Zion and Rice, 1993, 1996].

For damage rate coefficients between the upper and lower curves in the inset of Figure 3, the evolving fault (damage) zones maintain geometrical disorder similar to those present in the last three frames of Figure 2. Remarkably, for such cases the seismic response of the model alternates between time intervals of intense seismic activity containing clusters of large events, and lower activity periods during which only small to moderate earthquakes occur. The time interval of each mode of activity scales with the average repeat time of large model earthquakes in the more active periods. During the low activity intervals the rate of strain energy release in the crust is lower than the rate of energy accumulation from loading, while during the high activity intervals the opposite is true. The model alternates between these two modes, rather than settling on a steady response with energy release rate equal the rate of energy accumulation. The FS statistics of earthquakes in the intervals with and without clusters of large events are compatible with the CE and GR distributions, respectively. As discussed in our last year report, Dahmen et al. [1998] found a similar mode switching of seismicity in an independent theoretical analysis based on a mean field approximation to the model of Ben-Zion and Rice [1993]. The observation of mode switching in natural seismicity requires long records containing many large earthquake cycles. Although data sets of such long duration are not very common, available paleoseismic [e.g., Marco et al., 1996; Leonard et al., 1998], historical [Ambraseys et al., 1994], and geological [Wallace, 1987] data indicate that mode switching of seismic activity of the type simulated here occurs in nature. These results can have profound implications for estimates of seismic hazard potential in different space-time domains and, more generally, the understanding of the seismic response of the crust to tectonic loading. The continuing studies will attempt to clarify further model parameters and signals associated with mode switching activity and other dynamic regimes, as well as various aspects of spatio-temporal evolution of earthquakes and faults in model configurations tailored for southern California faults.

Establishment and Destruction of Stress Correlations

Recent studies suggest that large earthquakes occur when a fault system reaches a critical state associated with the establishment of long range correlations of stress or other dynamic variables. Li and Ben-Zion [1998] started to quantify this process using stress and earthquake histories generated by the model of Ben-Zion [1996] for a disordered strike-slip fault system in a 3D elastic half-space. The analysis is done on the central part of the model seismogenic zone, covering a depth range of 4 km to 8 km and horizontal extent of 55 km. For each depth interval of 0.55 km, we analyzed the temporal evolution of the spatial distribution of stress using the following steps: (1) We compute the auto-correlation coefficients of the stress at each depth interval as a function of space offset. (2) We calculate the standard deviations of the auto-correlation functions and use these as estimates for the width of the stress correlation. To examine the evolution of stress correlation in different wavelength bands, we perform this analysis also in a spectral domain, using a spectral analysis called the Empirical Mode Decomposition [Huang et al., 1998]. This method gives, like wavelet analysis, sharp identifications of energy distribution at any time in both the space and wavelength domains.

The results show non-repeating cyclic establishment and destruction of stress correlations on the fault with the following features: A cycle begins when each large event destroys the long range correlations of stress, leading to a sharp drop in the width of the correlation function. The combined occurrences of the subsequent small to intermediate size events increase the spatial correlation of stress on the fault. The correlation length of the evolving stress reaches a maximum value after 1/3 to 1/2 of the cycle time, when the ongoing model events establish "stress bridges" across the entire system. Then the correlation length fluctuates around the maximum value until one small event cascades to become the next large earthquake. This destroys the long range stress correlation and starts a new cycle. The above process may be used to define a large earthquake cycle on a spatially extended heterogeneous fault system. Continuing analysis of this process, combined with quantitative analysis of the associated seismicity patterns, may provide new target signals for statistical earthquake forecasting. This is discussed in our next year proposal.

References

Ambraseys N, Melville C. and Adams R., Seismicity of Egypt, Arabia and the Red Sea, Cambridge University Press, London, 1994.

Ben-Zion, Y., Stress, slip and earthquakes in models of complex single-fault systems incorporating brittle and creep deformations, J. Geophys. Res., 101, 5677-5706, 1996.

Ben-Zion, Y. and J. R. Rice, Earthquake failure sequences along a cellular fault zone in a 3D elastic solid containing asperity and nonasperity regions, J. Geophys. Res., 98, 14109-14131, 1993.

Ben-Zion, Y., K. Dahmen, V. Lyakhovsky, D. Ertas and A. Agnon, Self-Driven Mode Switching of Earthquake Activity on a Fault System, submitted to *Earth Planet. Sci. Lett.*, 1998.

Dahmen, K., D. Ertas and Y. Ben-Zion, Gutenberg Richter and Characteristic Earthquake behavior in Simple Mean-Field Models of Heterogeneous Faults, Phys. Rev. E, 58, 1494-1501, 1998.

Leonard G., D. M. Steinberg, and N. Rabinowitz, An indication of time-dependent seismic behavior - an assessment of paleoseismic evidence from the Arava fault, Israel, Bull. Seismol. Soc. Amer., 88, 767-776, 1998.

Li, C.-P. and Y. Ben-Zion, Quantification of an Earthquake Cycle with Establishment and Destruction of Stress Correlations in the System, *EOS Trans. Amer. Geophys. Union*, 79, F643, 1998.

Lyakhovsky, V., Y. Ben-Zion and A. Agnon, Distributed Damage, Faulting, and Friction, J. Geophys. Res., 102, 27635-27649, 1997.

Lyakhovsky, V., Y. Ben-Zion and A. Agnon, Earthquake cycle, faults and seismicity patterns in rheologically layered lithosphere, EOS Trans. Amer. Geophys. Union, 79, F648, 1998.

Marco, S., M. Stein, A. Agnon and H. Ron, Long term earthquake clustering: a 50,000 year paleoseismic record in the Dead sea graben, J. Geophys. Res., 101, 6179-6192, 1996.

Stirling, M. W., S. G. Wesnousky and K. Shimazaki, Fault trace complexity, cumulative slip, and the shape of the magnitude-frequency distribution for strike-slip faults: a global survey, *Geophys. J. Int.*, **124**, 833-868, 1996.

Wallace, R. E., Grouping and migration of surface faulting and variations in slip rates on faults in the great basin province, Bull. Seismol. Soc. Amer., 77, 868-876, 1987.

Last Year Publications Supported by SCEC Studies

Papers:

Ben-Zion, Y., K. Dahmen, V. Lyakhovsky, D. Ertas and A. Agnon, Self-Driven Mode Switching of Earthquake Activity on a Fault System, submitted to *Earth Planet. Sci. Lett.*, 1998.

Dahmen, K., D. Ertas and Y. Ben-Zion, Gutenberg Richter and Characteristic Earthquake behavior in Simple Mean-Field Models of Heterogeneous Faults, *Phys. Rev. E*, 58, 1494-1501, 1998.

Li, C.-P. and Y. Ben-Zion, Quantification of a Large Earthquake Cycle with Evolving Stress Correlations on a Fault in Elastic Solid, in preparation for JGR.

Lyakhovsky, V., Y. Ben-Zion and A. Agnon, Earthquake Cycle, Faults, and Seismicity Patterns in a Rheologically Layered Lithosphere, in preparation for JGR.

Abstracts:

Agnon, A., V. Lyakhovsky and Y. Ben-Zion, Continuum Physics Of Rock Friction: Implications For Modeling Earthquakes, The XXVI General Assembly of the European Seismological Commission, August, 1998.

Ben-Zion, Y., Recent Developments In Earthquake Dynamics, Proceedings of the 22nd Mathematical Geophysics meeting, 1998.

Ben-Zion, Y., Deviations Of Earthquake Statistics In Elastic Solid From Self Similarity, The XXVI General Assembly of the European Seismological Commission, August, 1998.

Ben-Zion, Y., V. Lyakhovsky and A. Agnon, Non Stationary Evolution of Earthquakes and Faults in a Rheologically Layered Model of the Lithosphere, EOS Trans. Amer. Geophys. Union, 79, S222, 1998.

Ben-Zion, Y., K. Dahmen, V. Lyakhovsky, D. Ertas and A. Agnon, Self-Driven Mode Switching of Earthquake Activity on a Fault System, *EOS Trans. Amer. Geophys. Union*, 79, F634, 1998.

Dahmen, K., D. Ertas, D. S. Fisher and Y. Ben-Zion, Gutenberg Richter and Characteristic Earthquake behavior in Simple Mean Field Models of Heterogeneous Faults, Proceedings of the 22nd Mathematical Geophysics meeting, 1998.

Li, C.-P. and Y. Ben-Zion, Quantification of an Earthquake Cycle with Establishment and Destruction of Stress Correlations in the System, *EOS Trans. Amer. Geophys. Union*, 79, F643, 1998.

Lyakhovsky, V., Ben-Zion, Y. and A. Agnon, Earthquake Cycle, Faults, and Seismicity Patterns in a Rheologically Layered Lithosphere, *EOS Trans. Amer. Geophys. Union*, 79, F648, 1998.

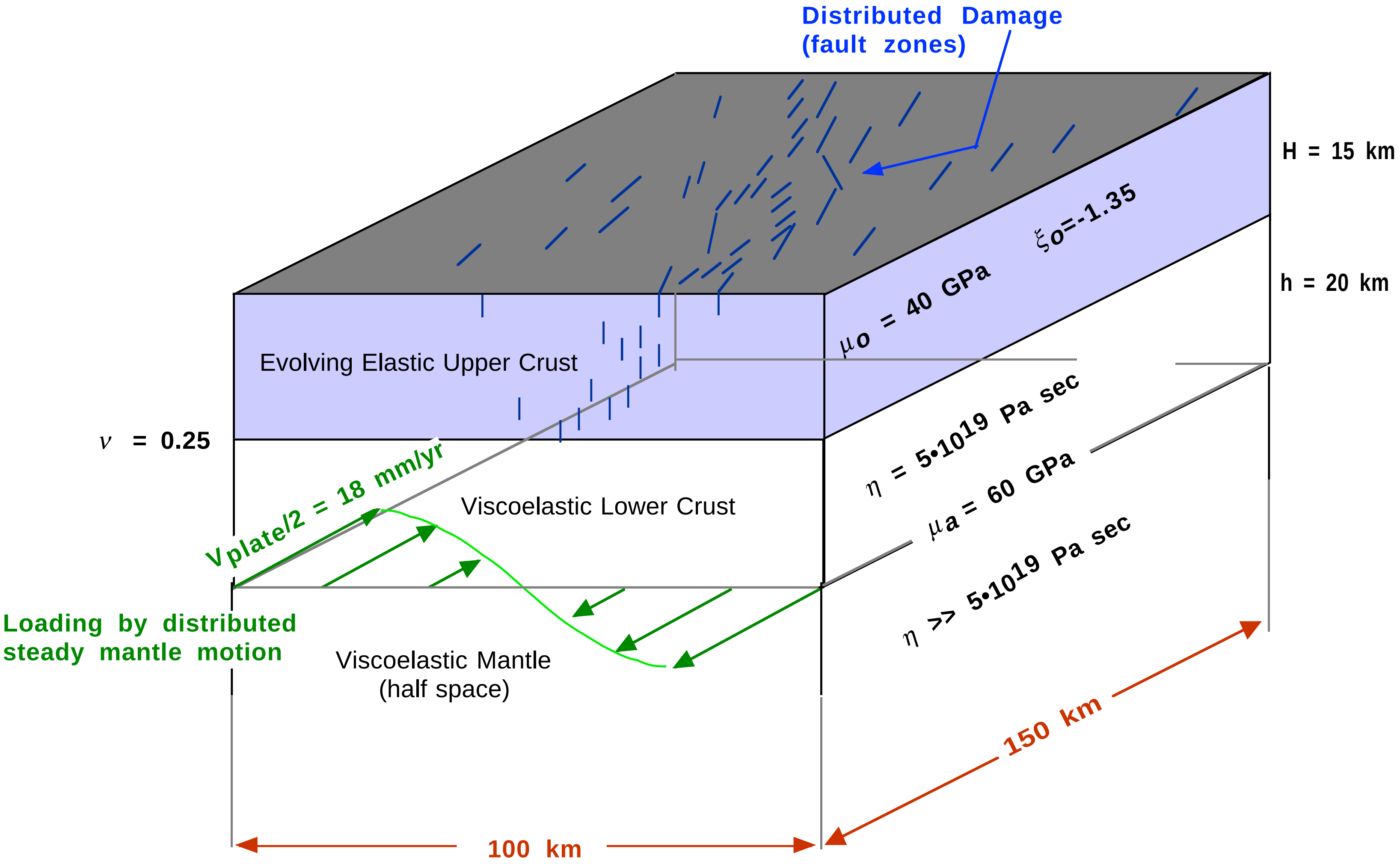

Figure 1. Geometry and parameters for a regional lithospheric model for coupled evolution of earthquakes and faults. The crust consists of a brittle seismogenic zone governed by damage rheology over a viscoelastic lower crust driven by steady mantle motion from below. H and h mark thickness of upper and lower crust layers, respectively. Parameters μ, ξ, h, and ν denote rigidity, generalized friction coefficient, viscosity, and Poisson's constant, respectively. The boundary conditions are constant stress at the left and right edges and periodical repeats at the front and rear boundaries.

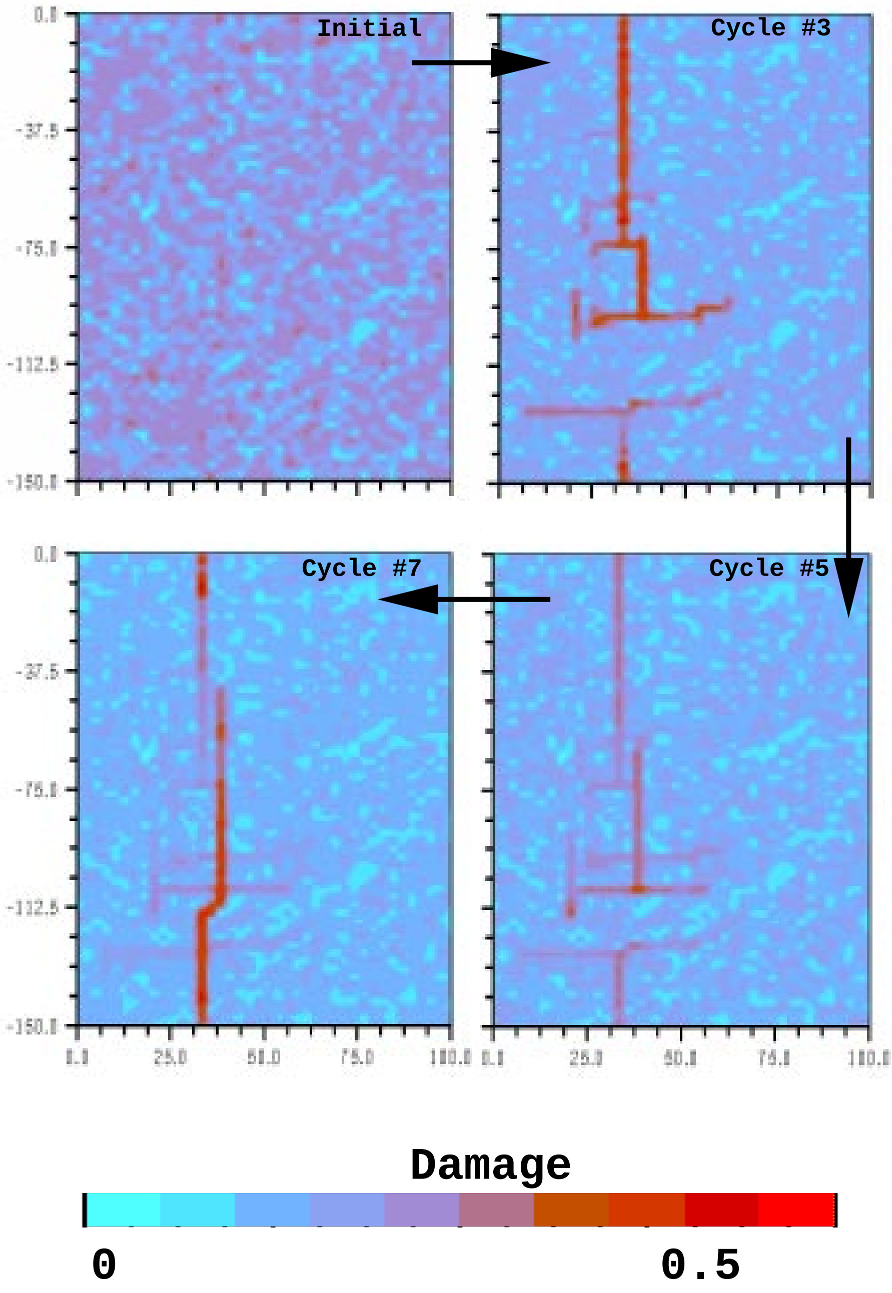

Figure 2. Map views of damage distribution at four snapshots for damage healing rate following the middle (green) curve in the inset of Figure 3. The model is initiated with random damage distribution peaked at about α=0.5. At time t/T = 3, with T denoting average time of a large earthquake cycle, the damage localizes to a single major disordered fault zone with a large (30 km) gap and related complications in the lower part of the model. The gap is bounded by conjugate (right lateral) faults 20−30 km long. A 10 km step−over (dilatational jog) develops at the middle portion of the model. At t/T = 5 the gap narrows (20 km) and the overall structure is smoother. As shown in Figure 3, this period is an intermediate interval of low seismicity between clusters of higher activity. At t/T = 7 an almost continuous disordered fault zone is established with two conjugate stepovers (dilatational and compressional). This stage represents an activation of a new cluster of high seismic activity. Further structural evolution cycles between patterns similar to those of the last three panels.

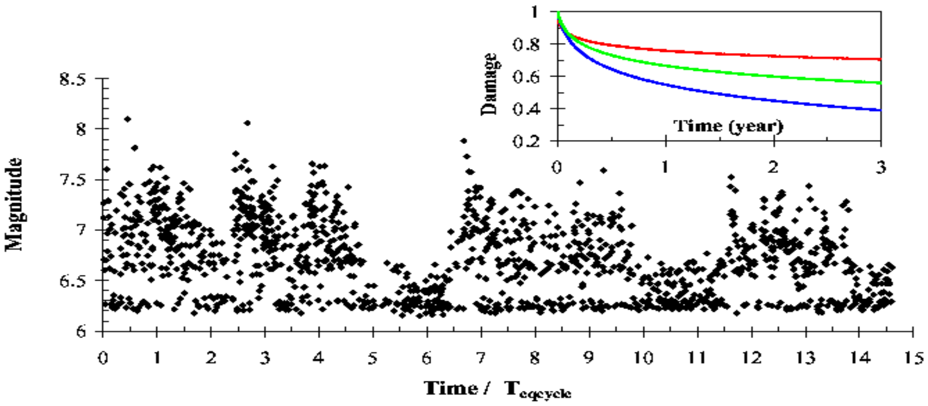

Figure 3. A long record of model earthquakes showing mode switching of activity consisting of cluster periods lasting a few large earthquake cycles, separated by relatively quiet intervals of similar length. The inset shows damage evolution for different damage−healing parameters discussed in the text.