Progress report for 2007 SCEC Proposal

Title of Project

Coupled Evolution of Earthquakes and Faults in a Regional Model with Damage Rheology

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Proposal Category
Integration and Theory

Science Objectives:
A7, A3, A10

Summary

Studies under this project continue our investigations on the coupled evolution of faults, earthquakes and related deformation fields in a rheologically layered model of the lithosphere. The basic questions we ask are how do localized and distributed zones of damaged rocks form and evolve in the brittle upper curst over many thousands of earthquake failure episodes, and how does the evolution of a regional network of fault zones changes in turn the properties of seismicity patterns and aseismic deformation fields? Our last year studies focused on the following three research directions: (1) Spatio-temporal evolution of large strike-slip fault zones including the depth distribution of on- and off-fault damage, geometrical properties and coupling to the ductile substrate. (2) Scaling relations of earthquakes and aseismic deformation in models that include generation of rock damage during brittle failures. (3) Inferring from observed ratios of aftershock productivity and analytical damage rheology solution on the degree of seismic coupling in different regions. The results have led to 1 published paper, 1 submitted paper and 2 papers in preparation. Below we summarize the main results from these studies.

Scaling relations of earthquakes and aseismic deformation in a damage rheology model

V. Lyakhovsky and Y. Ben-Zion (GJI, 2008)

Abstract

We perform analytical and numerical studies of scaling relations of earthquakes and partition of elastic strain energy between seismic and aseismic components 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. 3-D 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.

Correlations between aftershocks productivity and regional conditions: Observational test of damage model predictions

W. Yang and Y. Ben-Zion (GJI, 2008)

Abstract

Aftershock sequences are commonly observed but their properties vary from region to region. Ben-Zion and Lyakhovsky (2006) developed a solution for aftershocks decay in a damage rheology model. The solution indicates that the productivity of aftershocks decreases with increasing value of a non-dimensional material parameter R given by the ratio of timescale for brittle deformation to timescale for viscous relaxation. The parameter R is inversely proportional to the degree of seismic coupling and is expected to increase primarily with increasing temperature, and also with increasing thickness of sedimentary cover. To test these predictions we use aftershock sequences from several southern California regions. We first analyze properties of individual aftershock sequences generated by the 1992 Landers and 1987 Superstition Hills earthquakes. The results show that the ratio of aftershock productivities in these sequences spanning 4 orders of event magnitudes is similar to the ratio of the average heat flow in the two regions. To perform stronger statistical tests we systematically analyze the average properties of stacked aftershock sequences in five regions. In each region we consider events with magnitudes between 4.0 and 6.0 to be mainshocks. For each mainshock, we consider events to be aftershocks if they occur in the subsequent 50 days, within a circular region that scales with the magnitude of the mainshock, and in the magnitude range between that of the mainshock and 2 units lower. This procedure produces 28-196 aftershock sequences in each of the five regions. We stack the aftershock sequences in each region and analyze the properties of the stacked data. The results indicate that the productivities of the stacked sequences are inversely correlated with the heat flow and thickness of sedimentary cover, in agreement with the damage model predictions. Using the observed ratios of aftershock productivities along with simple expressions based on the damage model, we estimate the relative values of the material parameter R and seismic coupling coefficient in the different regions. The employed methodology for estimating the seismic coupling of fault systems can be useful for seismic hazard studies.

Evolution of structural properties and deformation patterns of strike-slip faults: Numerical simulations incorporating damage rheology

Finzi, Y., E. H. Hearn, Y. Ben-Zion, and V. Lyakhovsky (ms. in preparation, 2008)

Abstract

Material and geometric properties of fault zones control the seismicity patterns and spatial distribution of the deformation. The goal of this work is to characterize the evolving structures and associated deformation along large strike slip faults. To simulate fault zone evolution, we use a thermodynamically-based continuum damage framework constrained by laboratory data of fracture and friction experiments (e.g., Lyakhovsky et al., 1997; Hamiel et al., 2004; Ben-Zion and Lyakhovsky, 2006). Three dimensional simulations with the damage rheology model are used to investigate fault evolution from

a single segment scale to long-term plate-boundary scale. We first present how the damage healing parameters were constrained based on geophysical data from large strike slip faults. This calibration validates the use of our 3D code with the damage rheology for the study of natural fault system evolution. We also present results showing surface deformation patterns associated with the evolution of simple and complex strike slip fault systems. Our 3D simulations for a layered crust governed by damage rheology underlain by a visco-elastic upper mantle indicate that damage zones of strike slip faults form a flower structure with depth. The flower structure consists of broad damage in the top few kilometers that becomes highly localized at depth. The results also indicate that tectonic strain is primarily concentrated along the highly damaged cores of the main fault zones. A small portion of the strain is accommodated over a broader domain correlating with the overall width of the damage zone. Broader strain distribution could result from viscoelastic deformation of the lower crust and mantle. In our models of segmented faults, the results indicate that fault stepovers are locations of ongoing interseismic deformation. During the entire earthquake cycle, the material within the fault stepovers remains damaged to depth of about 10 km, exhibiting significantly reduced rigidity and shear wave velocity. We suggest that damage zones within fault stepovers could have important implications for earthquake dynamics, and that these zones of increased sustainable damage should be detectable by means of geophysical surveys.

Evolving fault structures in a damage rheology model

V. Lyakhovsky and Y. Ben-Zion (ms. in preparation, 2008)

Abstract

We perform quantitative analyses of the evolution of large crustal faults using a 3-D lithospheric model consisting of a seismogenic crust governed by damage rheology over a viscoelastic substrate. We first show that the initial trajectories of a pre-exiting narrow damage zone subjected to oblique loading agree well with the analytical solution of Erdogan and Sih [1963] for the propagation path of a crack under mixed-mode conditions. This is followed by simulations of the nucleation and development of strike-slip fault zones in several realizations of a 3-D layered lithospheric model. The structural development in a basic model with planar horizontal boundaries between the lithospheric layers is characterized by progressive evolution toward increasing localization and geometrical simplicity. A model realization with an assumed upward bulge in the topography of the Moho boundary produces persisting complexities of fault zone structure and related deformation fields. The results demonstrate that the deformation process in the upper mantle and resulting crustal fault zone structure can depend strongly on large scale perturbations and the regional thermal regime.

Publications Supported by this grant

Papers

Finzi, Y., E. H. Hearn, Y. Ben-Zion, and V. Lyakhovsky, Evolution of structural properties and deformation patterns of strike-slip faults: Numerical simulations incorporating damage rheology, ms. in preparation for *Geophys. J. Int.*, 2008.

Lyakhovsky, V. and Y. Ben-Zion, Scaling relations of earthquakes, aseismic deformation and evolving fault structures in a damage rheology model, *Geophys. J. Int.*, **172,** 651-662, doi: 10.1111/j.1365-246X.2007.03652.x, 2008.

Lyakhovsky, V. and Y. Ben-Zion, Evolving fault structures in a damage rheology model, ms. in preparation for *Earth Planet. Sci. Lett.*, 2008.

Yang, W. and Y. Ben-Zion, Correlations between aftershocks productivity and regional conditions: Observational test of damage model predictions, submitted to *Geophys. J. Int.*, 2008.

Abstracts

Finzi, Y., E H Hearn, V Lyakhovsky, Y Ben-Zion, Damage zone structure and deformation patterns along segmented strike slip faults, SCEC Annual Meeting., 2007.

Yang, Y, Y Ben-Zion, Comparisons between observed properties of aftershock sequences in southern California and predictions of a damage rheology model, Eos Trans. AGU, 88(52), Fall Meet. Suppl., Abstract S11C-0708, 2007.