" Dynamic Models of Earthquakes, Fault Systems, and Earthquakes on Fault Systems "

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Program Element I

Investigations undertaken

This project concerns the development of more realistic models of faults, more realistic models of fault systems, and, ultimately, the combination of these two modeling efforts towards models which reproduce realistic elastodynamic events on fault systems. Further, having developed the models, we seek to characterize their behavior in ways which can connect with seismological observations to obtain constraints on earthquake physics.

In developing more realistic models of faults, I developed a three dimensional scalar elastodynamic model of a fault, with depth variable friction and a free surface on top. This model, while expensive due to being three dimensional, is nevertheless efficient enough to be run for repeated ruptures. This is the first three dimensional elastodynamic model I am aware of that nas been run in the mode where there are repeated ruptures, so now the attractor of the dynamics can be explored. This is important because one of the big unknowns, the initial stress, no longer needs to be specified, and comes out, in a self-consistent way, as a consequence of the dynamics. As in lower dimensional models, complex sequences were seen to develop when there is sufficient frictional weakening. A further advance came from trying to find observational constraints on this modeling effort. While working to develop a model with depth variable friction, I was led to pose a question of seismicity in real earthquakes which provided an important new measurement of the constitutive relations for stable sliding at depth. In particular, by using the time dependence of repeating earthquakes, we obtained measurements of the constitutive behavior of neighboring stable sliding regions. These results are described more fully in the next results section.

A second thrust of the research was the development of a model of a fault system. We modeled a brittle layer overlying a ductile layer, with both subject to slowly loaded tensile deformation. Systems of interacting faults developed. Figure 1 shows an example of the system of faults which grows with increasing deformation in the model. To further test this numerical model, we compared measurements of this against an analogue laboratory system, consisting of a clay layer overlying a rubber substrate. We measured the cracks which formed in the clay as the rubber was stretched.

In the realm of quantifying the model behavior in order to compare it with seismological observations, I made new measurements of the radiated energy emitted by elastodynamic models with different underlying frictional instabilities. As we will see in the next results section, this pointed to new seismological measurements that could be useful in constraining the physics of the earthquake source.

Results

Work this last year supported by this grant resulted in one paper appearing in print, and four papers being submitted for publication. Below, I briefly summarize each paper and some of the main results.

"Far Field Radiated Energy Scaling in Elastodynamic Earthquake Fault Models" [Shaw, 1998] appeared in the *Bulletin of the Seismological Society of America, 88*, 1457, 1998. Here I presented a new way of characterizing the elastodynamic models, by looking at the far field radiated energy. Using conservation of energy, I was able to measure the far field energy very accurately and efficiently. I studied a range of frictions, from velocity-weakening to slip-weakening, in order to examine the effects of the physics of the rupture source on the radiated energy. Examining the scaling of radiated energy as a function of moment and rupture length, I found differences for slip-weakening as compared to velocity-weakening friction. I found distinct differences in how the apparent stress scales with moment, and also how the apparent stress divided by the stress drop scales with moment for the different frictions. Most dramatically, the apparent stress divided by the stress drop is significantly smaller for slip weakening relative to velocity weakening. This suggests measurements of radiated energy versus moment and rupture length in earthquakes, combined with forward elastodynamic modeling, can be used to constrain possible source physics.

"Postseismic Response of Repeating Aftershocks" [Schaff, Beroza, and Shaw, 1998] was submitted and accepted for publication in *Geophysical Research Letters* and will appear in 1999. Here, we measured the recurrence intervals of repeating earthquakes on the San Andreas Fault in the Loma Prieta aftershock zone, and found that they follow the characteristic $1/t$ decay of Omori's law. A model in which these earthquakes occur on isolated patches of the fault that failed in stick-slip with creep around them could explain the observations. In this model the recurrence interval is inversely proportional to the loading rate due to creep. Logarithmic velocity strengthening friction, as observed in laboratory friction measurements, predicts $1/t$ decay in creep rate following the mainshock. The time dependence of recurrence is inconsistent with a viscous constitutive relationship, which predicts an exponential decay of loading rate. Thus our observations imply postseismic slip at seismogenic depth under a power law rheology.

"Transition Regimes for Growing Crack Populations" [Spyropoulos, Scholz, and Shaw, 1998] was submitted for publication. Here we developed a model for growing crack populations, modeling populations of normal faults. The model assumed a brittle layer overlying a ductile substrate which was slowly deformed. The long time scale

physics incorporated in the model are slip-weakening friction, strain-hardening rheology for coupling the two layers, and randomly distributed yield strengths of the brittle layer. We investigated how the evolution of populations of faults depends on these three effects, and how it changes with strain. We observed that the distribution of lengths of faults makes a transition from a power law at low strains, where crack nucleation prevails, to a more exponential-like (or a two power law with a kink) distribution at higher strains, where coalescence dominates. There is evidence of these two different length distributions in continental and oceanic normal faults. For continental deformation the strain is low and the faults have power law frequency-size distributions. For mid-ocean ridges the strain is greater, up to an order of magnitude higher than continental strain, and fault have exponential-like distributions. We approximate the short time dynamics of events, and show that the approximation of the short timescale dynamics does not affect the long timescale fault evolution: it is cumulative strain, not strain increments, which govern the fault system evolution. This implies that faults which grow with creep, and faults which grow with earthquakes, have the same time and space evolutions. As a consequence, one does not need to capture the short timescale earthquake events to capture the long timescale fault evolution.

"Experimental Evidence for Different Strain Regimes of Crack Populations in a Clay Model" [Spyropoulos, Griffith, Scholz, and Shaw, 1998] was submitted for publication. Here we report results from clay extension experiments used as a laboratory analogue model for the non-linear evolution of a population of faults due to their stress interactions. Cracks show two different kinds of frequency-size distributions; a power law for strains of around 1-2%, and an exponential for strains around 10-15% with a gradual transition between these end-members. This agrees with observations of fault populations in Nature in low and high strain settings.

"Rethinking Earthquake Prediction" [Sykes, Shaw, and Scholz, 1998] was submitted for publication. Here we re-examine and summarize what is now possible in predicting earthquakes, what might be accomplished (and hence might be possible in the next few decades) and what types of predictions appear to be inherently impossible based on our understanding of earthquakes as complex phenomena.

Nontechnical summary

This research aims to understand what the basic physics of earthquakes is. What is happening at the source? Can we write down mathematical equations that behave in ways that are similar to earthquakes? In addition to developing better models of the earthquake process, we seek to develop better ways of quantifying the complex behavior that is seen in the models. This helps us to better understand what is happening in the models, to compare the behavior produced by different models, and, most importantly, to compare with the behavior of seen in the Earth, and, perhaps, to suggest new ways of looking at the data from the Earth.

Reports Published

With support from this grant, the one paper has been published, one paper has been accepted for publication, and three other papers have been submitted. They are:

Bruce E. Shaw,
'Far Field Radiated Energy Scaling in Elastodynamic Earthquake Fault Models',
Bulletin of the Seismological Society of America, 88, 1457, 1998.

David P. Schaff, Gregory C. Beroza, and Bruce E. Shaw
'Postseismic Response of Repeating Aftershocks',
was accepted for publication in *Geophysical Research Letters* and will appear in 1999.

Chrysanthe Spyropoulos, Christopher H. Scholz, and Bruce E. Shaw,
'Transition Regimes for Growing Crack Populations',
submitted, 1998.

Chrysanthe Spyropoulos, William J. Griffith, Christopher H. Scholz, and Bruce E. Shaw,
'Experimental Evidence for Different Strain Regimes of Crack Populations in a Clay Model',
submitted, 1998.

Lynn R. Sykes, Bruce E. Shaw, and Christopher H. Scholz,
'Rethinking Earthquake Prediction',
submitted, 1998.

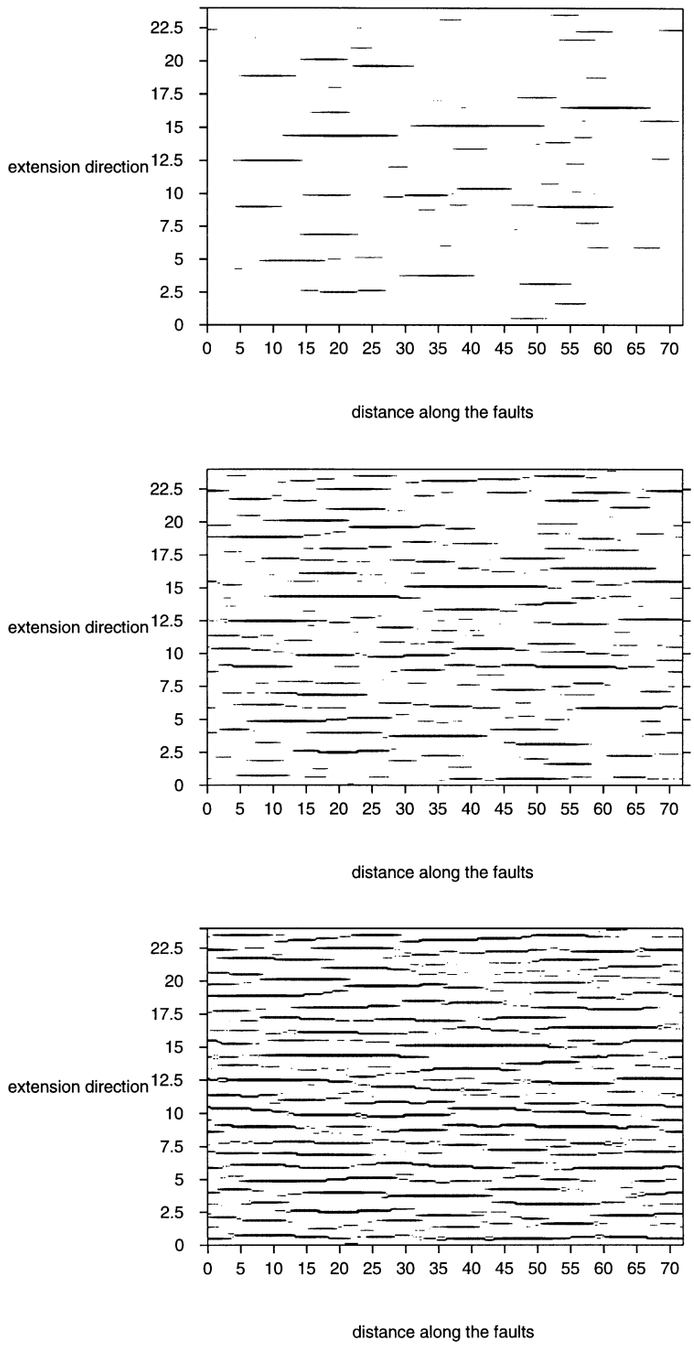

Figure 1: Crack evolution with strain ϵ. (a) $\epsilon = .064$, (b) $\epsilon = .072$, (c) $\epsilon = .08$. From [Spyropoulos, Scholz, and Shaw, 1998].