

# General Earthquake Models: Progress & Prospects

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## Abstract

**General Earthquake Models (GEM's) are being constructed to investigate the statistical and stochastic physics of earthquake fault networks from a dynamical systems point of view. Earthquake faults occur in networks that have dynamical modes not displayed by single isolated faults. Using simulations of the network of strike-slip faults in southern California, we find that the physics depends critically on both the interactions among the faults, which are determined by the geometry of the fault network, as well as on the stress dissipation properties of the frictional physics, similar to the dynamics of other nonlinear networks, including integrate-and-fire neural networks. In this talk, I shall give an overview of our recent progress, and summarize current and future directions.**

## Introduction

Recent work on the dynamics of earthquakes has focussed on models for single isolated faults. Yet it is expected from analysis of other driven nonlinear complex systems that emergent modes may appear that are not properties of single faults [1,2]. Modes of behavior [3-9] on fault networks in nature that are not observed on isolated faults include enhanced seismic triggering, retardation, and "stress shadowing", mode-locking and temporary quasi-periodic behavior such as that observed at Parkfield, California, and the appearance of space-time patterns of behavior such as Mogi donuts, precursory quiescence and activation, and clustering. An example from a different system is an integrate-and-fire neural network, in which complex dynamical patterns in space and time arise through the dynamical interactions of much simpler voltage-threshold neural cells [1,2,10]. Here we examine the dynamics of the geometrically complex network of horizontally-slipping strike-slip faults existing in southern California to develop clues for understanding the failure modes characterizing interacting fault networks.

To summarize our results: We have found that strongly correlated, geometrically complex mean field fault networks have dynamics very different from single isolated faults, arising from the elastic inhibiting interactions not present on single faults. We also find that the stress-dissipation properties of the fault friction law plays an important role in determining the dynamics of stress roughening and smoothing, in the activity switching dynamics

on the network, as well as in the nature and configuration of the failure modes. Finally, we have developed a new technique that allows historical earthquake data to be assimilated into the physical properties used in the fault network simulations.

General methods for carrying out the network simulations have been discussed in refs. [8,11], similar in many respects to the methods of Ward [12]. Briefly, one defines a fault geometry in an elastic medium, computes the stress Greens functions (i.e., stress transfer coefficients), assigns frictional properties to each fault, then drives the system via the slip deficit. As has been discussed elsewhere, the elastic interactions produce mean field dynamics in the simulations. Since our focus is on understanding the mean field stochastic space-time dynamics of strongly correlated fault networks, we use the cellular automaton approach with an additive noise term during sliding [8]. Due to computational constraints, we focus here on the major horizontally-slipping strike-slip faults in southern California that produce the largest and most frequent magnitude events. We used the tabulation of strike slip faults and fault properties as published in ref [13] (see also figure 1 and table 1). Each fault was assigned a uniform depth of 20 km, the maximum depth of earthquakes in California, and was subdivided into segments having a horizontal scale size of approximately 10 km each.

A variety of friction laws have been described in the literature, including simple Coulomb failure [14], slip-dependent or velocity-dependent friction [4,14], and rate-and-state [15]. In recent work we are using a parametrization of recent laboratory friction experiments [16], in which the stiffness of the loading machine is low enough to allow for unstable stick-slip when a failure threshold  $\sigma^F(V)$  is reached, where  $\sigma^F(V)$  is a weak (logarithmic) function of the load point velocity  $V$ . Sudden slip then occurs in which the stress decreases to the level of a residual stress  $\sigma^R(V)$ , again a weak function of  $V$ . Stable precursory slip is observed to occur whose velocity increases with stress level, reaching a magnitude of a few percent of the driving load point velocity just prior to failure at  $\sigma = \sigma^F(V)$ . Also, in this friction law, models indicate that nonlinear friction gives rise to an effective viscosity  $\eta$ . One finds a parameter  $\alpha = \eta/K$ , where  $\eta$  is simply the slope of the stress - slip rate curve. Here,  $K$  is the effective stiffness of the material.

For  $\alpha > 0$ , differences in stress decay exponentially in time, a condition that can be called *stress smoothing*. Under more general conditions, it might be possible that either  $\alpha < 0$  or that  $K < 0$ , conditions that can occur in more general elastic or frictional systems [17, 18, 19]. In those cases, it can be seen that variations in stress grow exponentially in time, a condition that can be called *stress roughening*. For general three-dimensional fault network models subject to more general friction laws, we predict that both stress smoothing and stress roughening should occur [18].

Earthquake data obtained from the historical record as well as geological field studies represent the primary physical signatures of how the earthquake cycle is affected by the frictional properties that exist on the faults. The timing, magnitude and complexity of these historical events are a direct reflection of the values of the frictional parameters:  $\alpha$ ,  $\sigma^F$ ,  $\sigma^R$ . Since the computational dynamics depends on the characteristic length scale  $L$  for each segment, all of these frictional parameters should be regarded as scale-dependent functions of  $L$ :  $\alpha = \alpha(\Delta\sigma, L)$ ,  $\sigma^F = \sigma^F(L, V)$ ,  $\sigma^R = \sigma^R(L, V)$ . For simulations in which one or more distinct scales  $L$  are chosen for each fault segment (length and width, for example), one must choose  $\alpha$ ,  $\sigma^F$ ,  $\sigma^R$  in such a way that the historical record of activity on the fault network is matched as closely as possible. This is the *data assimilation* problem for which we have developed a simple, but physically motivated method that will be described.

For historical earthquakes, there can be considerable uncertainty about where the event was located, and specifically upon which fault the event occurred [4]. Moreover, modern field and space-geodetic studies [4,19,20] of earthquakes indicate that slip is often distributed regionally over a number of faults and sub-faults. Therefore our technique assigns a weighted average of the scalar seismic moment  $M_0$  [4] for a given historic or pre-historic event to *all* of the faults in the system. For this method to be physically plausible, the weighting scheme should assign most of the moment  $M_0$  to faults near the location of maximum ground shaking and decay rapidly with distance. Physically, the stress due to an earthquake, which is the forcing field that induces sliding on the fault, decays as the inverse cube power of distance  $r$  [21]. Since the seismic moment is the torque associated with one of the moment tensor stress-traction double couples, it is most reasonable to use the law that describes the decay of stress with distance. Comparisons with data indicate that this method yields average recurrence intervals similar to those found in nature.

Our simulations predict that physical manifestations of the friction laws on fault segments are revealed by the space-time patterns in the network dynamics of fault systems. Dynamical switching should also be observed, in which one part of the network is able to switch activity on or off on other parts of the network by means of the inter-fault interactions. These interactions, along with the frictional surface viscosity term  $\alpha_i$ , also determine whether stress roughening or smoothing transitions occur. Dynamical switching of activity may have already been revealed through observations of real fault networks [3,9], although previous observational studies are for limited durations of only a few years, not the many thousands of years characteristic of the earthquake cycle over which the space-time correlations develop. We are not at present aware of any existing observations in nature relating to stress smoothing or roughening transitions.

Finally, our work has been enabled by development of methods to carry out computations within a modern computing environment. We have investigated the role of modern information technology to support earthquake science both in real-time analysis of major events and in long term theoretical studies of the underlying fundamental mechanisms. We are developing collaboration and portal technology to support the community research [22]. This will enable distributed scientists to work together accessing the world resources within a web environment.

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