

Progress Report 1998: Model of the Southern California Fault Network

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Introduction

In order to assess seismic hazards it is important to understand what limits the size of earthquakes. This problem is very challenging given the complexity of observed earthquake size distributions in space and time. A major obstacle to understanding the size distribution of large earthquakes is that historical catalogs have insufficient numbers of large earthquakes. It does seem however, that for shallow earthquakes with slip areas that become larger than the seismogenic thickness, the size distribution changes such that the probability of a larger event is less than that inferred by smaller quakes (e.g. Pacheco et al. 1992).

It is clear that geometrical barriers such as fault jogs and bends play some role in limiting the size of large earthquakes. However it is more difficult to understand why such barriers exist and what sets the length scale between such barriers.

Over the past year we have developed and used numerical models to study faulting and earthquakes in the shallow crust. Several models are discussed here. All of them are based on exact solutions of three-dimensional elasticity. In some of the models faulting quakes are confined to a single vertical plane, while in others faults can form anywhere in a horizontal plane, leading to the development of fault systems

Two types of fault rheological models are used. The first model, henceforth called the “smooth model” is a simplified version of the Dieterich-Ruina rate and state dependent friction law (e.g. Beeler et al., 1994) with the parameter a , that controls the direct velocity effect, set to zero. In the second model, called the “heterogeneous model”, the yield strength is a random variable, governed by a probability distribution. The specific form of the probability distribution has been shown to be a reasonable model for fault strength heterogeneity (Heimpel, 1996; Heimpel, 1997). For all of the models, dynamical rupture is approximated by allowing the static stress field that results from fault slip to expand at a single velocity from slip motions.

The scale of fault segmentation in smooth models of repeating earthquakes

We have investigated the relationship between the depth of seismogenic crust and a general dissipation process using a pseudo-dynamical model of repeated seismic rupture on one- and two-dimensional faults embedded in a three-dimensional elastic half-space. The objective

of this study is to understand to how characteristic length scales may arise in a model system where complexity has been stripped away. It is shown that the aspect ratio A (where $A = \text{fault-length}/\text{seismogenic-depth}$) of the brittle crust sets the characteristic scale of fault segmentation for these models. This may be understood either in terms of the detailed form of the stress field ahead of a rupture or in terms of the transfer of stress (or dissipation) out of the seismogenic zone. To show how dissipation sets a characteristic length scale we compare models with a finite seismogenic depth to models using plane strain elasticity and parameterized dissipation proportional to the slip (or slip velocity). When the total dissipation is equal for these two different models the resulting scale of fault segmentation is similar.

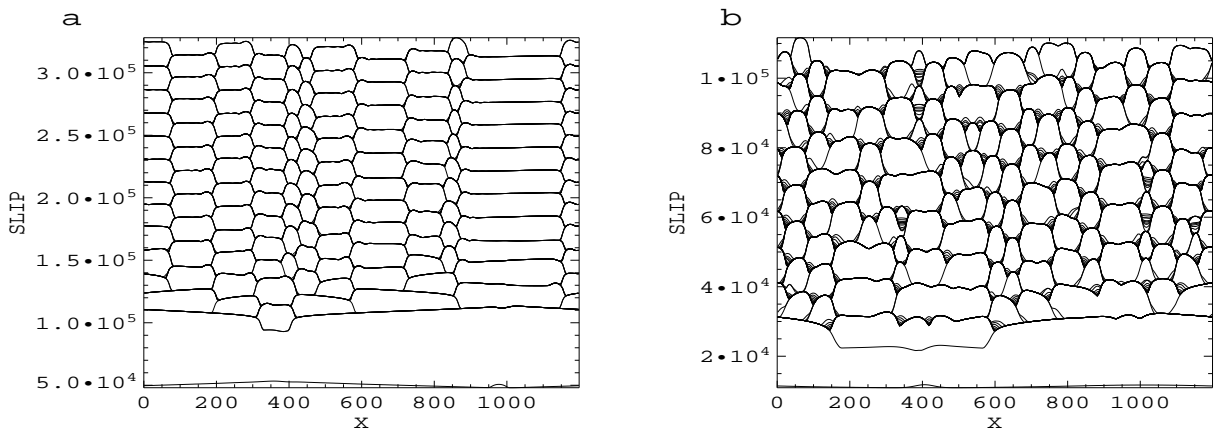


Figure 1: Slip plotted at equal time intervals for the smooth model. (a) For the elastic half-space model with aspect ratio $A = 24$. (b) For plain strain with parameterized dissipation set to be equivalent to that in (a).

To show how dissipation sets a characteristic length scale two versions of the smooth model are compared (figure 1). The first type uses 3-D elasticity with a free-surface boundary condition, a finite seismogenic depth, and periodic side boundaries. Figure 1a shows resulting slip pattern over several quake cycles for the model with $A = 24$. After an initial phase where quakes repeatedly rupture the entire model domain, the fault settles into a quasi-periodic pattern in space and time. The fault is divided into roughly 12 segments, ranging in length from about $1/50$ to $1/5$ of the total fault length, on which similar quakes occur almost periodically. The second type of model (figure 1b) is in most respects similar to the first, except that plane strain replaces 3-D elasticity, and a dissipation parameter is introduced that is proportional to the slip (or slip velocity). When the total dissipation is equal for these two different models the resulting scale of quakes and segmentation over time are comparable. However, localized dissipation results in greater time-dependence of fault segmentation.

Self similarity and characteristic quake sizes in heterogeneous models

Although the models described above provide a mechanical explanation for fault segmentation, they do not yield earthquake size distributions that bear much resemblance to those observed in natural seismogenic regions. Earthquake statistics are often characterized by power-law size-frequency relations in which the powerlaw exponent has a value that reflects self-similarity of the source (e.g. Andrews, 1980). Simply stated, self-similarity implies that b is a constant in the Gutenberg-Richter distribution. However, it is well known that in the shallow crust, self-similarity is expected to break down for large earthquakes due to the effect of the depth (or aspect ratio) of the seismogenic zone. To study the effect that the aspect ratio has on earthquake size frequency relations we use a numerical model similar to those described above but where the strong strength heterogeneity is introduced. The heterogeneity yields self similar earthquake statistics for elastic models lacking an inherent length scale (Heimpel, 1996, Heimpel, 1997). Thus the models are well suited for studying departures from self-similarity where a characteristic length-scale (such as the seismogenic thickness) exists.

As with the smooth model, the results of the heterogeneous model show that the introduction of finite seismogenic depth results in a characteristic earthquake size. For the smooth model the quake size distribution peaks at the characteristic quake size. However, for the heterogeneous model, the size-frequency distribution is self-similar for quakes up to a characteristic size, beyond which the distribution drops off exponentially for larger quakes.

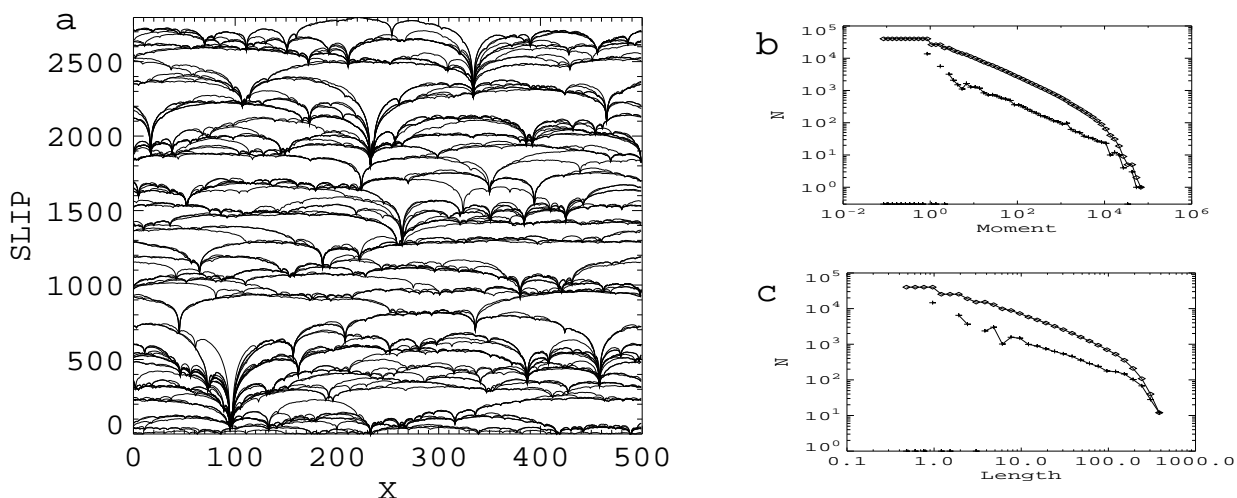


Figure 2: Heterogeneous model. (a) Slip plotted at equal time intervals. (b) Cumulative and binned moment-frequency distribution. (c) Length-frequency distribution.

Figure 2 shows the results of a model with strong strength heterogeneity and length to

depth aspect ratio $A = 32$. It is difficult to pick out a characteristic length by looking at the slip distribution in space and time (figure 2a). The moment vs. frequency and rupture-length vs. frequency is shown in figures 2b and 2c respectively. The roll-off point in the statistics give the characteristic size. The characteristic rupture length is about 1/5 of the length of the entire fault. This is more than six times the seismogenic thickness of the model.

Slip on and in the region of a compressive fault bend

Recent models of a single continuous fault with smooth bends have shown that the bending fault segments act as geometrical barriers to earthquakes (Nielsen and Knopoff, 1998). We have used model simulations to investigate the relationship between a main fault that bends, and secondary faulting and seismicity in the bend region. The simulations are designed to give insight into the mechanics of earthquakes and faulting in Southern California. In model presented here, friction is set to be systematically lower on the main fault than in the rest of the model domain. As with the Big Bend in the San Andreas fault, the main model fault bends in such a way that compressional normal stress on the bend segment increases with increasing right lateral slip.

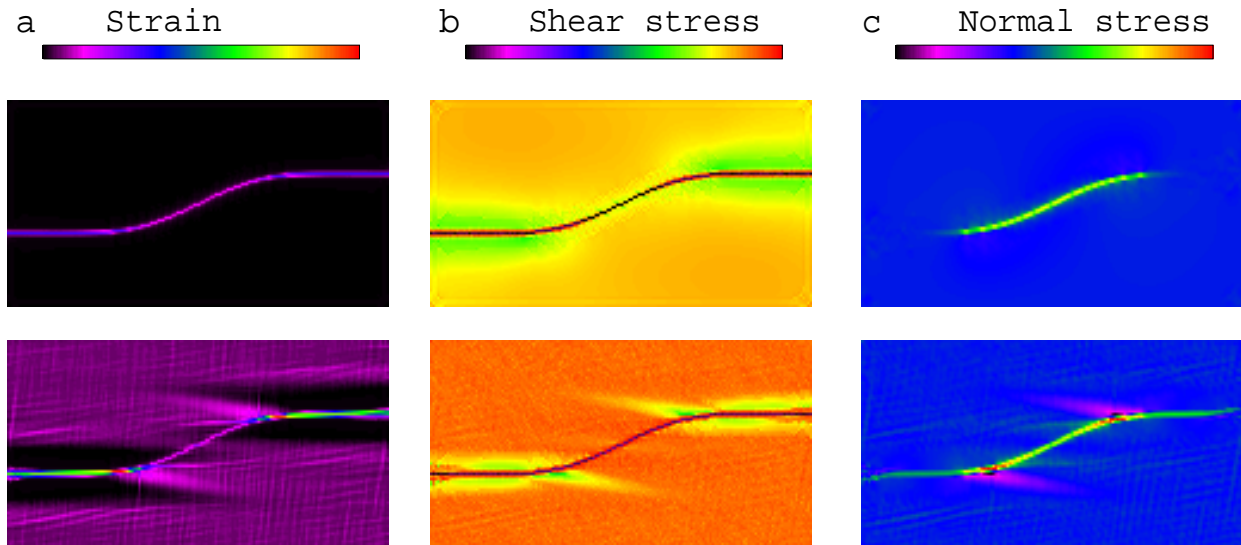


Figure 3: Fault bend model. (a) Strain field, (b) shear stress field, and (c) normal stress field early (top) and later (bottom) in a model simulation.

Similar to the models described above, this numerical model is based on exact solutions of elasticity in a three-dimensional half-space. However, whereas in the above models slip was confined to a single fault plane, for this model faulting and earthquakes, governed by the Coulomb-Navier yield criterion, can occur anywhere in the two-dimensional, horizontal

model domain. The model contains 160×80 square cells. The aspect ratio is $A = x/d = 32$, where x is the longer horizontal length and d is the depth of faulting. Thus, assuming that the San Andreas fault has an average depth of 15 kilometers in the Big Bend region, our model scales to a region of $240\text{km} \times 480\text{km}$.

A typical result is that seismicity and slip accumulation on the bend segment of the main fault is suppressed with respect to that on straight segments. Figure 3 shows the strains, and stresses over the model domain. Early in the simulation (top frames) increasing strain (figure 3a) occurs exclusively, and is evenly distributed, on the main fault due to the lower friction there. Corresponding to the strain on the bend segment is a decrease in shear stress. The normal stress increases sharply with strain on the bend segment (where we have defined positive normal stress = compression). Smaller and more diffuse decreases in normal stress (indicated by purple regions in figure 3c) occur on the convex sides of the bend. We note that, due to the finite depth of the model fault, the stress changes are confined to a smaller region than would be the case for plane-strain elasticity. As the model run proceeds, due to the high compressive stress on the bend segment of the main fault, strain accumulates preferentially on the main fault outside of the bend segment (this is an intermediate step, not shown in figure 3). This leads to a slip deficit on the bend segment of the main fault. To make up for this deficit in slip, secondary faults form in the bend region. Such secondary faults first form as relatively diffuse accumulations of right-lateral slip, emanating along strike from the straight, main segments into the bend region, guided by the regions of lowered compressional stress on the convex sides of the main fault segment.

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