2008 SCEC Report

Quasi-Dynamic Parallel Numerical Modeling of Earthquake Interactions Over a Wide Magnitude Range Using Rate and State Friction and Fast Multipoles

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STATEMENT OF THE PROBLEM AND PREVIOUS WORK

Introduction and background. This is a progress report on our SCEC-supported research project to address some issues important to SCEC that involves realistic modeling of sequences of earthquakes with a wide range of magnitudes.

Until the development of this code, the problem in studying a fault system with a very large number of fault elements was that the compute time increases with the square of the number N of elements because the stress on each element results from the slip on every other element. This has meant that no more than several thousand elements could be included in a 3D model. This restricted studying small fault systems and only a very limited range of earthquakes sizes, prohibiting investigating models that involved the spontaneous occurrences of both large earthquakes and microseismicity. However, supported by funding from NASA, we developed a parallel computer code (http://www.servogrid.org/slide/GEM/PARK/) that implements the Fast Multipole Method for which the compute time increases as N log N rather than N^2. The essence of the method is that the stress on each element can be computed from the appropriately averaged slip on groupings of fault elements that are sufficiently far away, rather than from the slip on each remote element treated individually. In developing this earthquake simulation code we have been using, in consultation with John Salmon, a Fast Multipole Library written by John Salmon and Michael Warren [*John K. Salmon*, 1991; *J. K. Salmon and Warren*, 1997], the performance of which won them the Gordon Bell Prize for the best achievement in high-performance computing in both 1992 and 1997.

Our grid has been designed to mimic the spatial distribution of seismicity at Parkfield. All of the areas that slipped during earthquakes ranging in magnitude from 1.0 to 5.1 are covered with fine

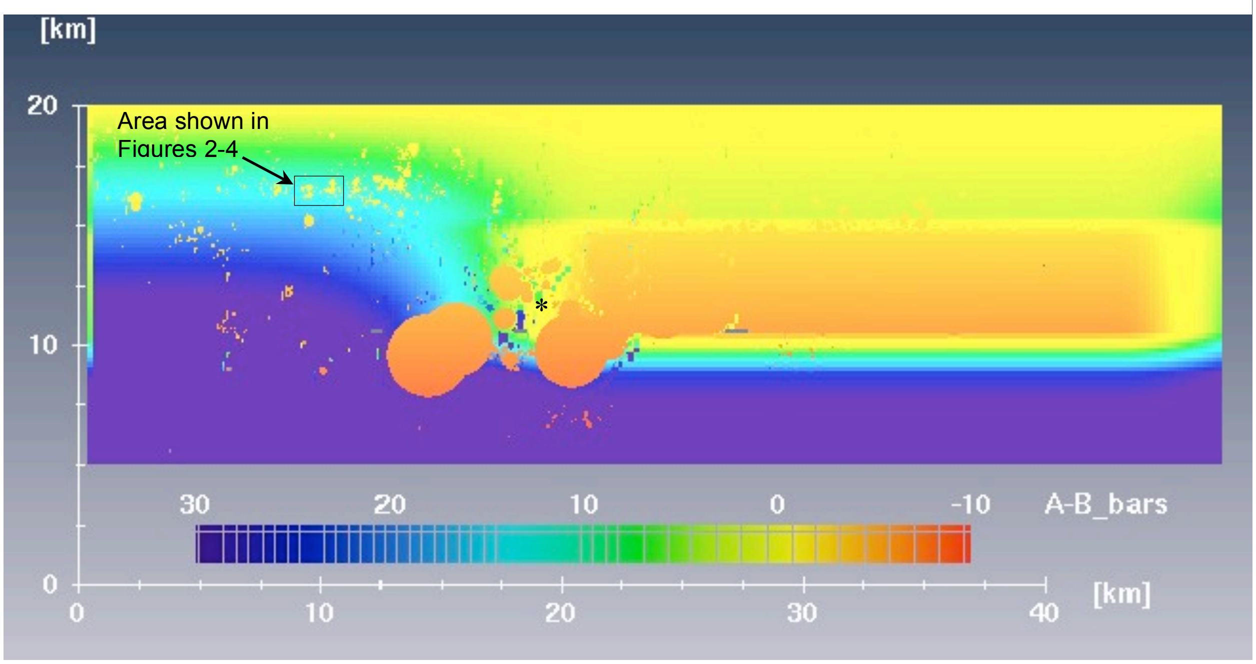

Figure 1. Cross-section along the plane of the San Andreas fault near Parkfield, CA showing the rate and state constitutive parameter A-B. The distribution of A-B is based on laboratory values of *a-b*, increasing normal stress with depth, increasing temperature with depth according to the Parkfield geotherm, and the distribution of both relocated micro-seismicity (Jeanne Hardebeck, personal communication) and the M6 Parkfield earthquake (1966 hypocenter shown by *). The horizontal coordinate axis increases to the SE and Middle Mountain is at about 20 km. The multiscale grid underlying the model, the details of which are based on the location of microseismicity, has 1,464,433 elements, and in the areas where the microseismicity occurs the elements are 7.4 m in dimension and range up to 200m.

elements. The entire area that slipped during M6 Parkfield earthquakes, as well as the surroundings, are described with elements ranging in size from 7.4 to 200 m. The finest 7.4 m elements in the multi-scale grid are sufficiently small that, following the guidelines developed by *Rice* [1993], *Zheng and Rice* [1998], and *Lapusta et al*. [2000], they can be used to represent accurately the behavior of a continuum using rate and state friction parameters close to laboratory values, namely with a D_c as small as 0.7 mm. This size of element is sufficient for accurately modeling earthquakes as small as M 1.0. These 7.4 m elements are used to define all the areas of the observed seismicity at Parkfield except the M6 earthquake itself, assuming a 3 MPa stress drop [*Waldhauser et al.*, 2004].

Progress in 2008. We have made considerable progress in the past year. Shown in Figure 1 is an overview of an area 47 km in length along the San Andreas Fault and 15 km deep. The color scheme shows the values of the constitutive parameter A-B = (*a-b*) * normal_stress. There are 1,464,433 elements in this figure, a number that could not possibly be studied without the use of the Fast Multiple approach. Due to computer time limitations it may not be possible to run a simulation for a useful number of time steps with this large number of elements and a reduced number such as the 377,225 in the grid we developed in 2005, or ever fewer, may be needed. However, this larger grid has been chosen because it represents the resolution that is desirable to properly represent a continuum with small Dc and because, when sub-samples of the grid are used, its greater refinement is a significant improvement over the initial grid we developed earlier. Sub-samples of this grid will be used for smaller simulations in the near term as we develop experience in the behavior of the simulations with a variety of choices of other constitutive parameters and laws. Thus, we are also exploring the role of changing *a, a-b,* and Dc for one form of the rate and state friction evolution equations that will be used, as well as the effect of using different evolution laws, the slip law, the slowness law and the composite law [*Kato and Tullis*, 2001; 2003].

Our most recent studies have been of the behavior of a collection of earthquake of various sizes as shown in Figures 2-4. The location of these events is shown in the box outlined in Figure 1. The behavior of these events are most easily seen in a video as we presented at our poster at the 2008 SCEC Annual Meeting [*Tullis and Beeler*, 2008] two frames of which are given in Fig. 4. The behavior of the simulation as seen in the movies is interesting and does show events ranging in magnitude from about one to about 3, based on their slipped areas. However, as discussed in the figure caption, the slip velocities are too slow and we are investigating the explanation for this and how to make them more realistic. It appears that the grid size may still be too small, following the guidelines of [*Rubin and Ampuero*, 2009], which show that a smaller grid size is needed to allow nucleation than is suggested by the analysis of *Lapusta et al.* [2000]. We have done simulations of events for this area using both the slip and slowness laws for the evolution of state; the figures illustrate the behavior for the slowness law. There are arguments for using each of these laws as well as for using a composite law [*Kato and Tullis*, 2001; 2003], but space does not permit discussing them here. We are continuing to explore the effect of using different evolution laws.

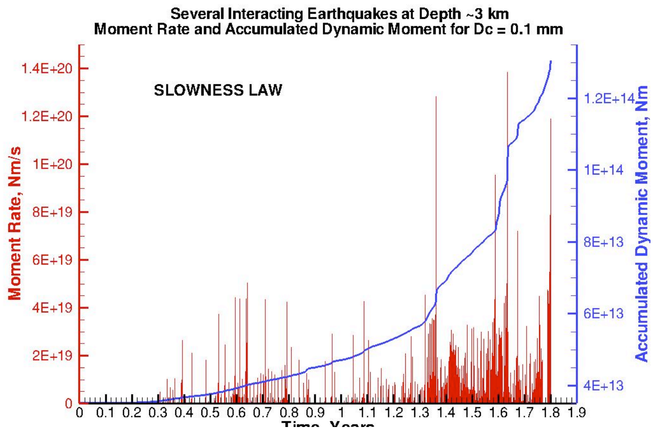

Figure 2. Behavior of a group of unstable patches within the creeping section in the area outlined Fig. 1. The distribution of A-B for this area is shown in Fig. 3. This figure shows the initial run-up from an initial condition in which the slip rate is 10 mm/s in the unstable areas and 35 mm/yr in the stable areas and the stress is at steady-state. Snapshots during the events at 1.635 yrs and 1.8 yrs are shown in Fig. 4A and B respectively.

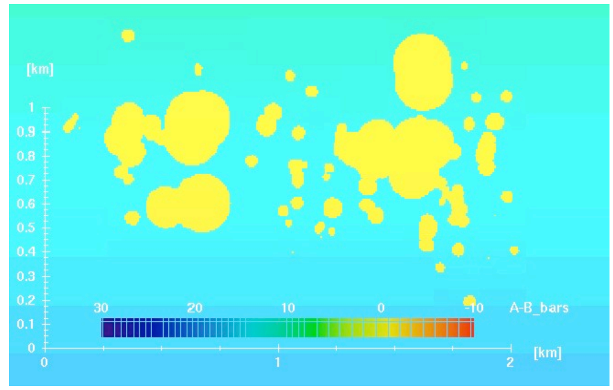

Figure 3. Distribution of A-B that generated the population of microearthquakes in Figs. 2 and 3. The yellow areas are unstable with A-B that is slightly negative; the blue and green areas are stable with positive A-B.

One of the things we have learned from the simulations shown in Figs. 2-4 is that even this small subset of the area of Figure 1 has such complex behavior that it is difficult to understand what is happening and what interactions may be occurring between the events of different sizes, one of the eventual goals of our study. For this reason we have begun our continued work on this project under this proposed grant by looking at some simpler systems. We have begun informal collaborations with Kate Chen and Roland Burgmann who have been taking the same approach to studying the interactions between actual small earthquakes at Parkfield [*Chen*, 2008; *Chen et al.*, 2007]. They have been investigating the way in which nearby repeating earthquakes "talk" to each other as seen by looking at the relative time of occurrence of repeaters of nearly the same

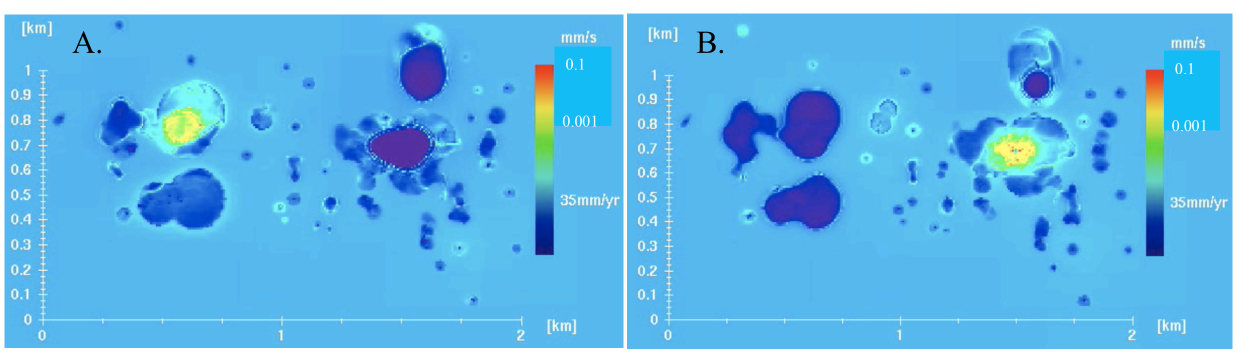

Figure 4. Two frames of a movie that shows the distribution of slip velocity in a long complex series of events that result from loading the area shown in Fig. 3 by slip at 35 mm/yr in the surrounding portion of the fault plane. Many sequences of repeating events occur on the smaller relatively isolated unstable patches. These correspond to many of the smaller moment-rate spikes in Fig. 2. The larger areas undergo complex events, two of which are shown in progress here (at 1.635 and 1.8 yrs). The complexity results in part from the geometrically complex shapes of the unstable areas shown in Fig. 3 that are taken from the locations of actual microearthquakes at Parkfield. The slip velocity for most of these events is relatively low and they may be better thought of as creep events. This can be changed by adjusting the values of Dc used, the grid sizes used, and the amount of radiation damping used to limit the slip velocity; work is underway to explore the parameter space.

size. They have also been looking at how the time of occurrence within regular sequences of repeaters is altered by nearby M4 events. This is searching for the same kind of an effect, but on a smaller scale, as that seen following the 2004 M6 event which caused an immediate increase in the rate at which small repeaters occurred, followed by a gradually decreasing rate.

In order to make our simulations as relevant to observations as possible, we have begun initially to focus on the behavior in isolation of a smaller number of repeating earthquakes to see whether their interactions in our simulations will be similar to that seen by *Chen et al.* [*Chen et al.*, 2007] for the same repeating earthquakes. We will be looking at the interactions between the cluster of nearby events that they label as N14, N23, and N24 because these show interesting interactions.

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