Annual Report, 2009
SOUTHERN CALIFORNIA EARTHQUAKE CENTER

Title of Project:
ALLCAL – An Earthquake Simulator for All of California

Name of PI: Steven N. Ward
Institution: University of California, Santa Cruz

I. ALLCAL Earthquake Simulator

In 2009, we continued to improve understanding of earthquake predictability and hazard by means of designing and tuning of earthquake simulators. Unlike previous years there has been a concerted effort by the newly formed Earthquake Simulator Group to collectively advance the field. This collaboration called the "Earthquake Simulator Project" has spawned a number of new research directions.

The ALLCAL earthquake simulator produces spontaneous, dynamic rupture on geographically correct and complex system of interacting faults. The simulator involves a truly 3-dimensional fault system that covers the entire state of California. The heart of the ALLCAL simulator involves computation of displacements and stresses from slip on whole space fault elements. In 2009, the geometry of the fault elements has evolved from "picket fence" type (short dimension along strike and full dimension down dip, roughly 4 km x 12 km) to a more square type (roughly 3 km x 3 km). This offers a better representation of smaller quakes (~M5.5) and allows variable rupture slip down dip, but it comes at the expense of increased computational effort. The current ALLCAL simulator uses 12000 fault elements arranged such to avoid most large tears and overlaps with depth on contorted faults (Figure 1). Too, the ALLCAL fault system has been altered to more closely conform to the fault set used in the UCERF program. Several questionable faults

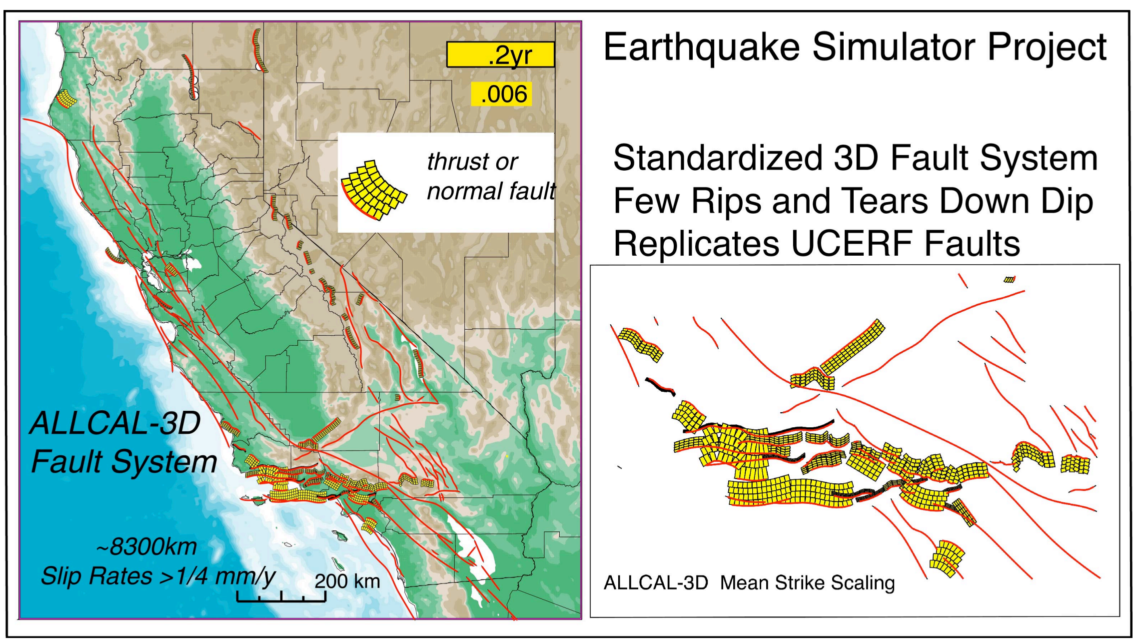

Figure 1. (*Left*). Current ALLCAL fault set. (*Right*) "Mean strike" scaling of element location eliminates most tears down dip although cross cutting faults remain an issue. The Earthquake Simulator Group is working toward a standardized set of fault elements with which to compare output products.

have been removed and several others, mostly in northern California have been added. Now, ALLCAL faults are virtually the same as UCERF faults. The integration of earthquake simulator results to UCERF products should be at the doorstep.

Given the fault element geometry, only fault rake, fault slip rate, fault strength and a two parameter velocity weakening friction law is required for ALLCAL to generate spontaneous dynamic rupture catalogs that include all fault stress interactions. I consider fault geometry, rake and slip rate to be data, so fault strength and the two frictional parameters are the only adjustable quantities in the simulator. Figure 2 shows a few of the 26 M7.7+ events that ruptured the San Andreas Fault during a 4000 year run of the simulator. Please view the Quicktime movie here http://es.ucsc.edu/~ward/SAF3D.mov The frames show current fault strength, current fault stress, slip and slip rate along strike and down dip of the curved fault versus time. You can see the complexity embodied in even a simple simulator –- ruptures stop, jump and sometimes reverse direction as dictated by the existing state of stress and the friction law. The stress state on the fault (bottom boxes, Figure 2) is strongly heterogeneous and the final stress state is much different from the starting one. Because of this, once the simulator is turned on, subsequent quakes may or may not be similar to previous ones. The beauty of ALLCAL is that it incorporates all these diverse processes naturally. In the long run, all possible rupture scenarios will be sampled. Those rupture combinations that are more likely to occur due to physical conditions (geometry, etc) will occur often. Those rupture combinations that are less likely will happen less often.

The newest ALLCAL simulator (Figure 3) generates dynamic ruptures from magnitude 8+ down to about magnitude 3, so a 4000 year run produces ~500,000 events. Please view the movie at: http://es.ucsc.edu/~ward/ALLCAL3D-300.mov Be aware that every one of the thousands of flashes in this movie is a genuine 3-D dynamic rupture like those in Figure 2. Quakes now can nucleate at the fault bottom and rupture upward or visa versa. Some ruptures do not break the surface at all. Don't be mislead into thinking that simulators somehow "white wash" the rupture process.

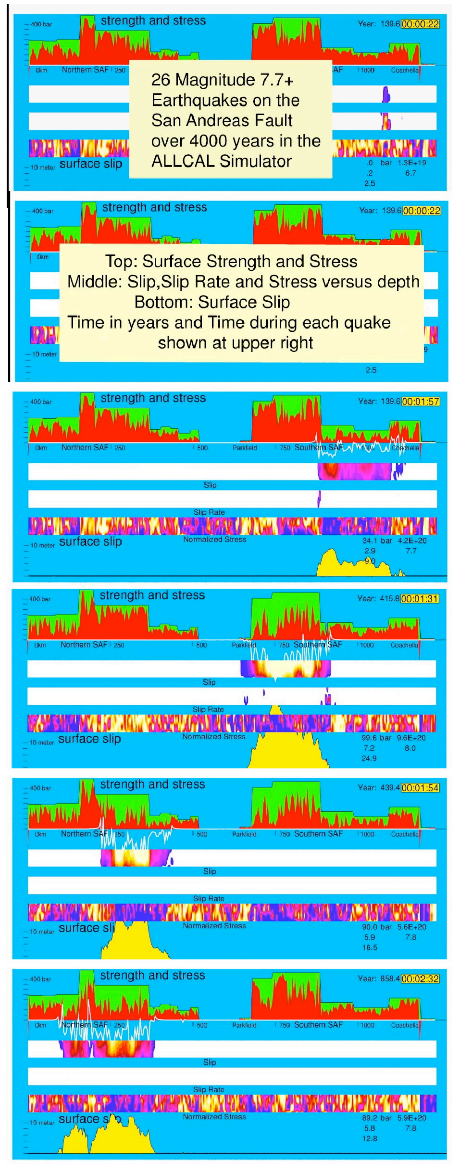

Figure 2. A few of the 26 M7.7+ ruptures on the San Andreas Fault during a 4000 year run. Three boxes in center show slip, slip rate, and normalized stress from the surface to depth along strike close to the end of the rupture. To see the full rupture histories please check out the movie http://es.ucsc.edu/~ward/SAF3D.mov

An exciting ALLCAL development is that a new method (alternative to backslip) to drive the system has been devised such that stresses and displacements both on and off the faults can be tracked (Figure 4). The method involves finding a continuous interseismic velocity/stress field for Western North America that: (1) gives no shear stress on the free surface, (2) satisfies the static equations of force balance, (3) reasonably reproduces interseismic surface velocities at all geodetic sites and (4) stresses the faults such that they slip at rates close to those estimated geologically. The ultimate goal is to employ both geological and geodetic data to constrain ALLCAL and to progress toward a self-consistent system-level model for stress accumulation by tectonic deformations and subsequent release by slip on faults.

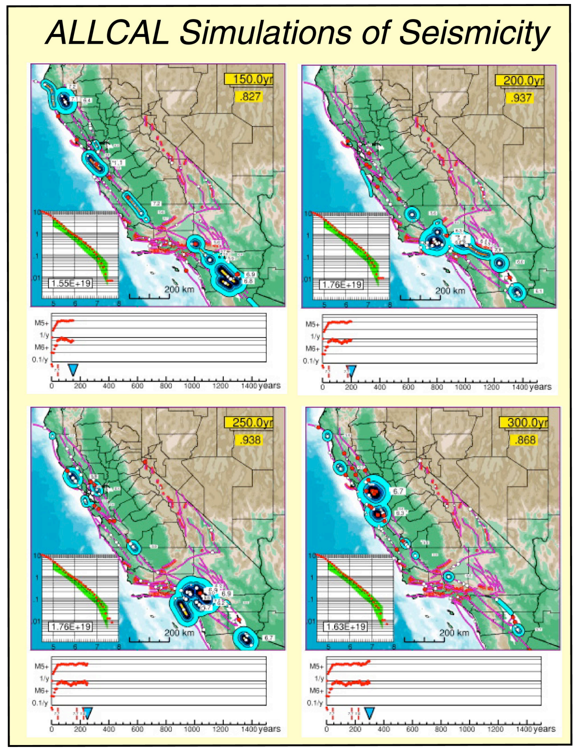

Figure 3. Four frames from a run of ALLCAL. The movie plots all earthquakes M>4.5. For events M>6, PGA is contoured around the rupture and a magnitude number is shown. Left is a graph of the cumulative number of M4.5+ quakes (red dots) overlaid on the actual rates (green zone). View a 300 year sample at http://es.ucsc.edu/~ward/ALLCAL3D-300.mov

II. Reality Checks on Earthquake Simulators

ALLCAL is not a pie-in-the-sky theoretical product. It is tuned with real earthquake data and tested against real earthquake data. The tuning is accomplished by comparing computed earthquake recurrence intervals versus magnitude to observed intervals. The testing is accomplished by comparing a variety of simulator predictions to information not directly built into the model.

Tuning. Inputs to tuning include measured *slip rates*, *recurrence interval* and *slip per event* provided through projects like SoSAFE. While fault slip rate is a direct constraint in ALLCAL, slip per event and recurrence interval are applied indirectly. In the simulator, these observables spring from the fundamental physics of the system through fault slip rate, fault strength and friction law parameters. Like slip rate, fault strength is thought to be preserved through many earthquake cycles. Strong fault segments tend to have larger slip per event and longer recurrence intervals, but the correlation is imperfect because of the non-linear nature of the system and the complex memories of all preceding earthquakes. For these reasons, iterative segment strength adjustments are made to the model to match reasonably well paleoseismic recurrence data. In ALLCAL, a fault segment is merely a collection of fault elements that share the same mechanical properties. Each rupture decides for itself how closely it will obey segmentation.

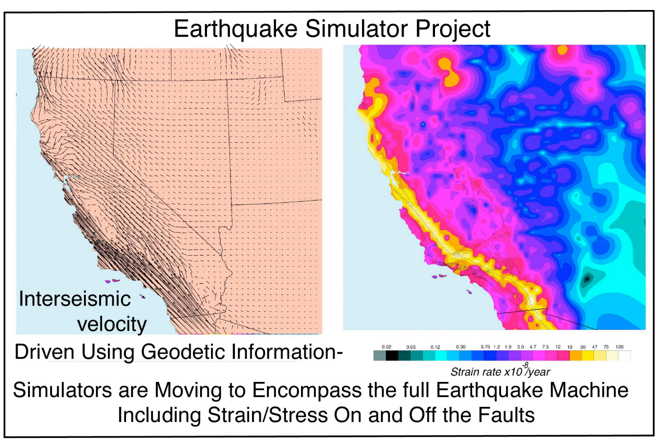

Figure 4. Surface strain rates from the ALLCAL interseismic driving velocities. The goal is to employ both geological and geodetic data to constrain ALLCAL and to progress toward a self-consistent, system level model for stress accumulation by tectonic deformation and subsequent release by slip on faults.

Testing. The primary product of earthquake simulators is a long series of earthquakes that act as surrogates for real, but time-limited catalogs. We can inquire of simulator catalogs any bit of information that we choose to test against data or hypotheses. (Figures 5 and 6). For example, earthquake scaling laws, M_{max} and b-value that are *input* into most earthquake hazard estimates are *outputs* of the simulator. Figure 5 (bottom right), plots earthquake magnitude versus rupture area from a recent 4000 year run of ALLCAL. Overlaid on the model values (red squares) is an observed scaling relation currently favored by WGCEP. You can see that ALLCAL's synthetic earthquakes scale compatibly with real world ones. Agreements like these give evidence that ALLCAL is producing a meaningful product.

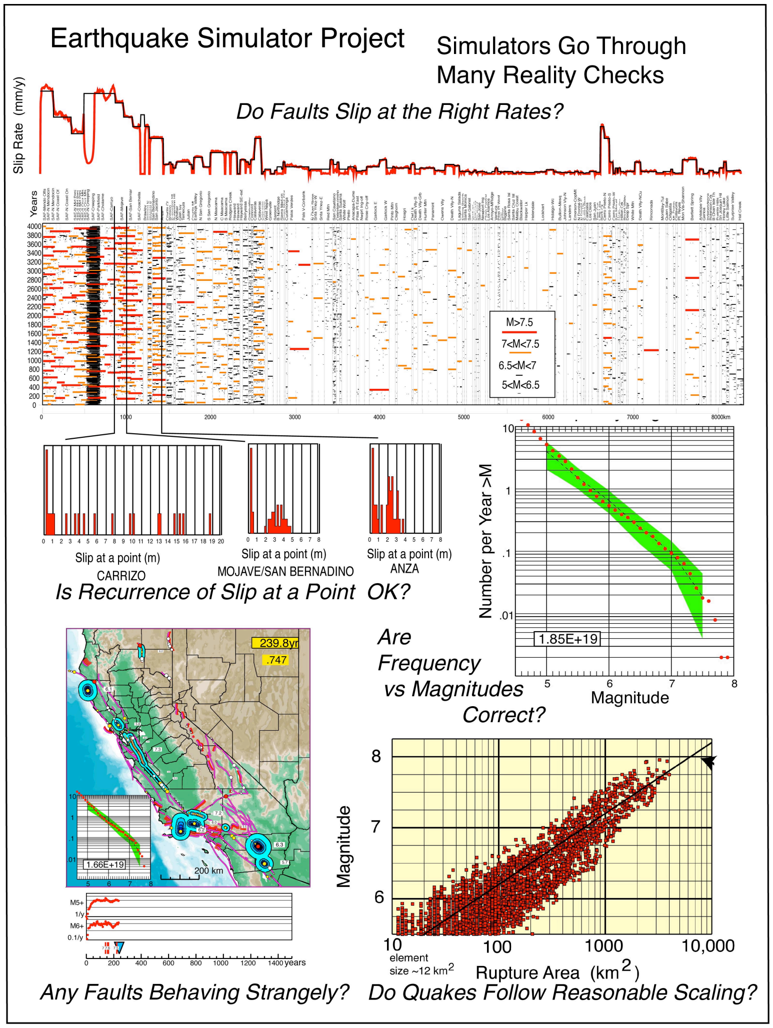

Figure 5. Reality tests for Earthquake Simulators. The agreement in the numbers of quakes versus magnitude with the observed catalog, the reproduction of accepted earthquake scaling relations and slip per event recurrence both tests and lends credence to ALLCAL products.

Current Project Objectives

Foster the efforts of the Earthquake Simulator Group. This new group is struggling through issues like: Which simulator problems to consider - complex or simple? What output do we compare? How do we make the comparison - deterministically, empirically, statistically? Because the range of physical assumptions built into the various earthquake simulators is large and sometimes incompatible, decisions are not as cut and dry as some other working groups.

Construct Community Fault Models for Earthquake Simulations (CFM-ES). SCEC's existing CFMs are well documented and vetted but because they were not designed with simulators in mind, they don't quite meet our needs (i.e. CFMs are Southern California Only). Providing standardized sets of CFM-ES that cover both the full suite and subsets (e.g. strike slip only) of California faults to any SCEC scientist interesting at trying his hand at earthquake simulation would be of real value. CFM-ES surely has cross-over uses to non-simulators like UCERF. I have already distributed two CFM-ES -- a full ALLCAL version and a limited Northern California version.

Integrate geodetic information into ALLCAL. Existing ALLCAL procedures were only interested in earthquakes and earthquake potential on the faults. In conjunction with a parallel SCEC proposal, proposed ALLCAL procedures will concern themselves with off fault deformations and geodetic constraints on fault slip rates.

You Tube Movie

You Tube style videos are one modern method to reach out to a younger generation of might-be scientists with visual, succinct, compelling but short bites of science. It's not easy task to package ones research this way, but I have given it a shot. Please watch my "Tube" entitled *Earthquake Simulators*   http://www.youtube.com/watch?v=iIuwAAPAEFw

International Symposium

In March, 2010 I was invited to speak at an International Symposium titled on "*Trends and goals of research on earthquakes*" in Messina, Italy. The presentation was largely based on my SCEC funded research. I also presented a video of an Earthquake Simulator that I had built for Italian fault system in 2008.

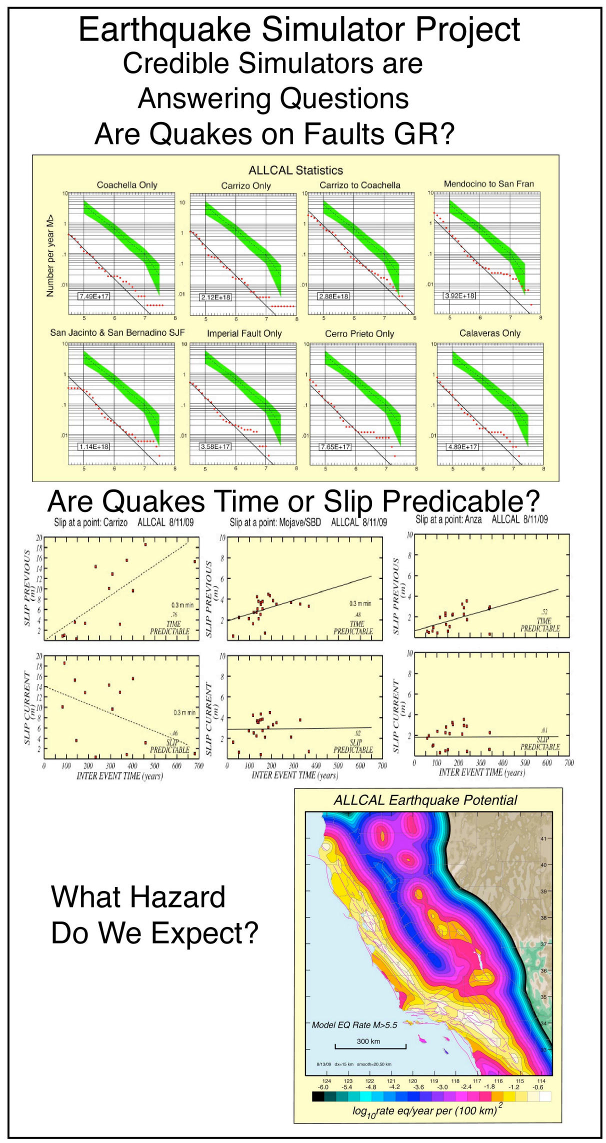

Figure 6. Once you have a credible earthquake simulator you can ask "What exactly does it predict?" and "How can I use that information to further my understanding of quakes and the goals of SCEC?"