Annual Report, 2010
SOUTHERN CALIFORNIA EARTHQUAKE CENTER

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

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I. ALLCAL Earthquake Simulator

In 2010, we continued to improve understanding of earthquake predictability and hazard by means of designing and tuning of earthquake simulators. Since 2009 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 2010, the geometry of the fault elements has continued to expand in scope (number of faults included) and scale (number of elements). This expansion offers a better representation of smaller quakes (~M5.5) but it comes with increased computational effort. The current simulator ALLCAL2, uses ~15,000 nearly square (3x3 km) fault elements arranged such to avoid large tears and overlaps with depth on contorted faults (Figure 1). ALLCAL2 includes the Great Basin faults and many new northern California ones such to conform closely with the fault set used in the UCERF program. While it may not look like much, generating fault systems with 1000s and

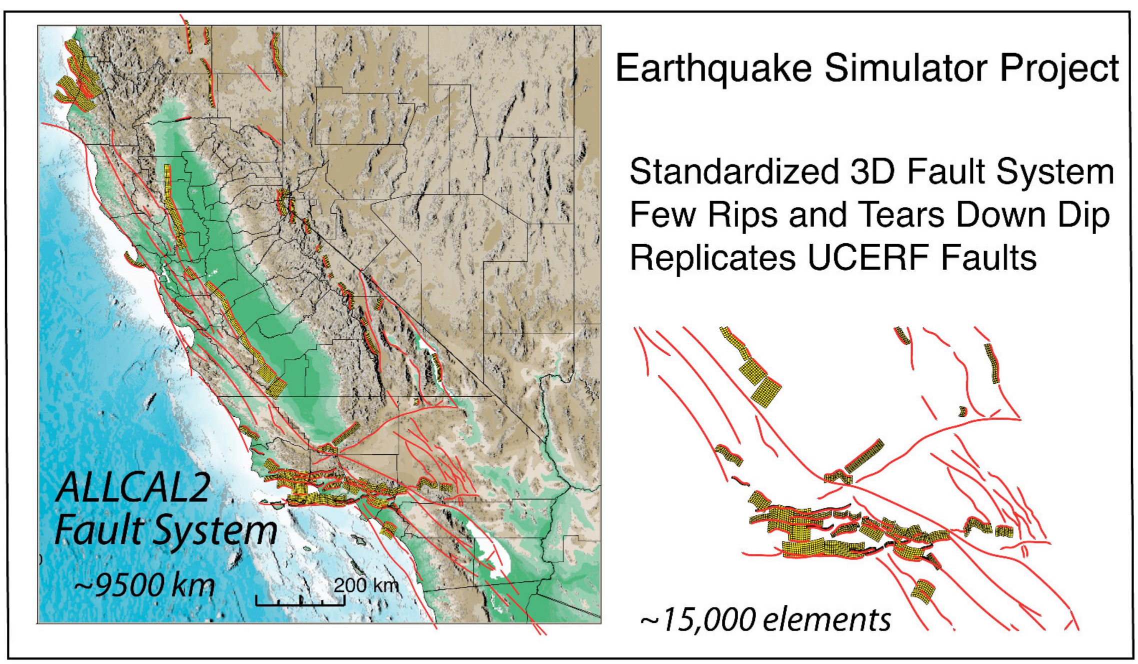

Figure 1. (*Left*). ALLCAL2 fault set. (*Right*) "Mean strike" scaling of element location eliminates most tears down dip. The Earthquake Simulator Group is working toward a standardized set of fault elements with which to compare output products.

1000s of elements is a major effort. In 2010 alone, I have generated three or four different fault systems (e.g. more detailed/less detailed, with thrust faults/no thrust faults, tapered slip/no tapered slip, etc.) that have served as the basis of effort for the simulator group.

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.

To get an introduction to ALLCAL output, the reader might want to watch two sample movies http://es.ucsc.edu/~ward/quake-ex2.mov and http://es.ucsc.edu/~ward/quake-ex3.mov. The first shows rupture of a simple stress concentration on a uniform strength fault. The second shows rupture of the same concentration in the presence of two other stress patches and variable strength along strike. The panels show current fault strength (green), current fault stress (red), slip, slip rate and normalized stress along strike and down dip of a fault versus time. You can see the complexity embodied in even simple cases like ex3.mov –- ruptures stop, jump and sometimes reverse direction as dictated by the existing state of stress and the friction law.

Figure 2 shows "full blown" cases --- a few of the 26 M7.7+ events that ruptured the San Andreas Fault during a 4000 year run of the simulator. Quicktime movie here http://es.ucsc.edu/~ward/SAF3D.mov 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. Populating the statistics of earthquake rupture occurrence for UCREF-like hazard estimates has long been the promise of earthquake simulators.

The ALLCAL2 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

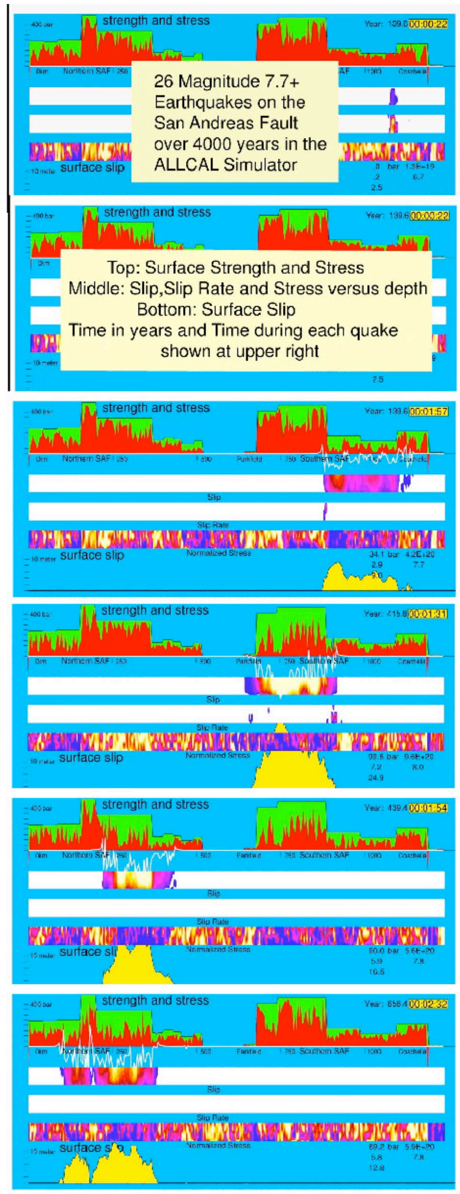

Figure 2. A few of the 26 M7.7+ ruptures on the San Andreas Fault during a 4000 year run. Three boxes in center show slip, slip rate, and normalized stress from the surface to depth along strike close to the end of the rupture.

fault bottom and rupture upward or visa versa. Some ruptures do not break the surface at all.

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.

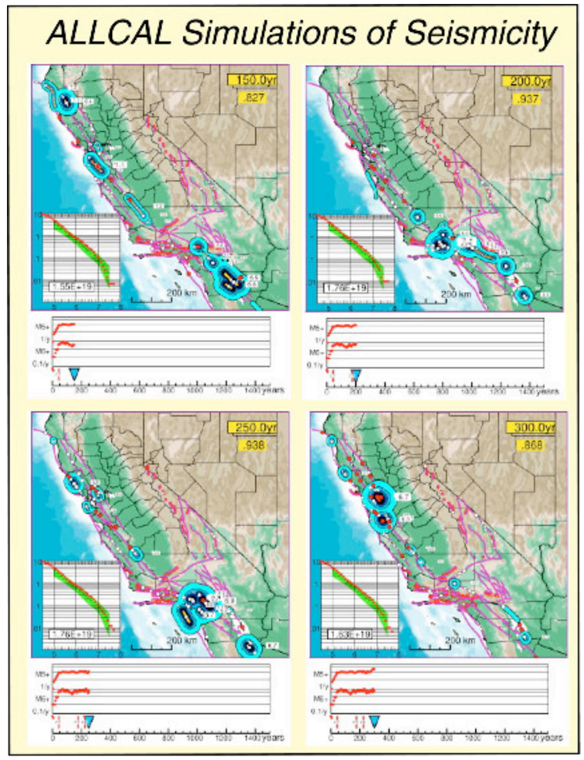

Figure 3. Four frames from a run of ALLCAL. The movie plots all earthquakes M>4.5. For events M>6, PGA is contoured around the rupture and a magnitude number is shown. Left is a graph of the cumulative number of M4.5+ quakes (red dots) overlaid on the actual rates (green zone).

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.

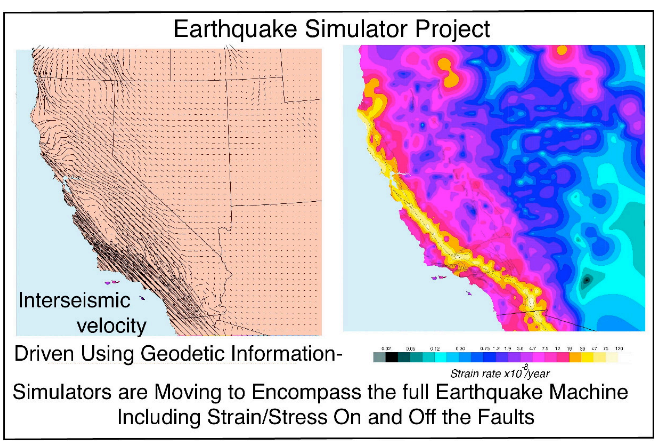

Figure 4. Surface strain rates from the ALLCAL interseismic driving velocities. The goal is to employ both geological and geodetic data to constrain ALLCAL and to progress toward a self-consistent, system level model for stress accumulation by tectonic deformation and subsequent release by slip on faults.

Simulator tuning is a major time effort that does not show much at first glance. All simulators involve fault friction law parameters and "fault strength" that corresponds to largest stress drop possible at a particular location. Different friction law choices (slip weakening, velocity weakening, rate-state) produce more or less complete stress drop. Not surprisingly, given a specified slip rate and fault strength, different simulators return different size quakes and recurrence intervals than others. In general, if the segment or fault is "too strong", recurrence intervals and earthquake magnitudes there will exceed that inferred from paleoseismology or scaling relations. Conversely if a fault is too weak, segment quakes may be too small and recurrence intervals too short. Tuning involves running the simulator for ~10,000 years, plotting observed versus calculated recurrence intervals (like Figure 5), and making small strength adjustments for any of ~180 segments. The process then repeats. Too, many observational issues are involved in tuning, in particular, it is never quite clear, to what magnitude the paleoseismic recurrence interval refers: M>6.5, M>7.0, M>7.5? Interaction between geologists and simulators is increasingly called for.

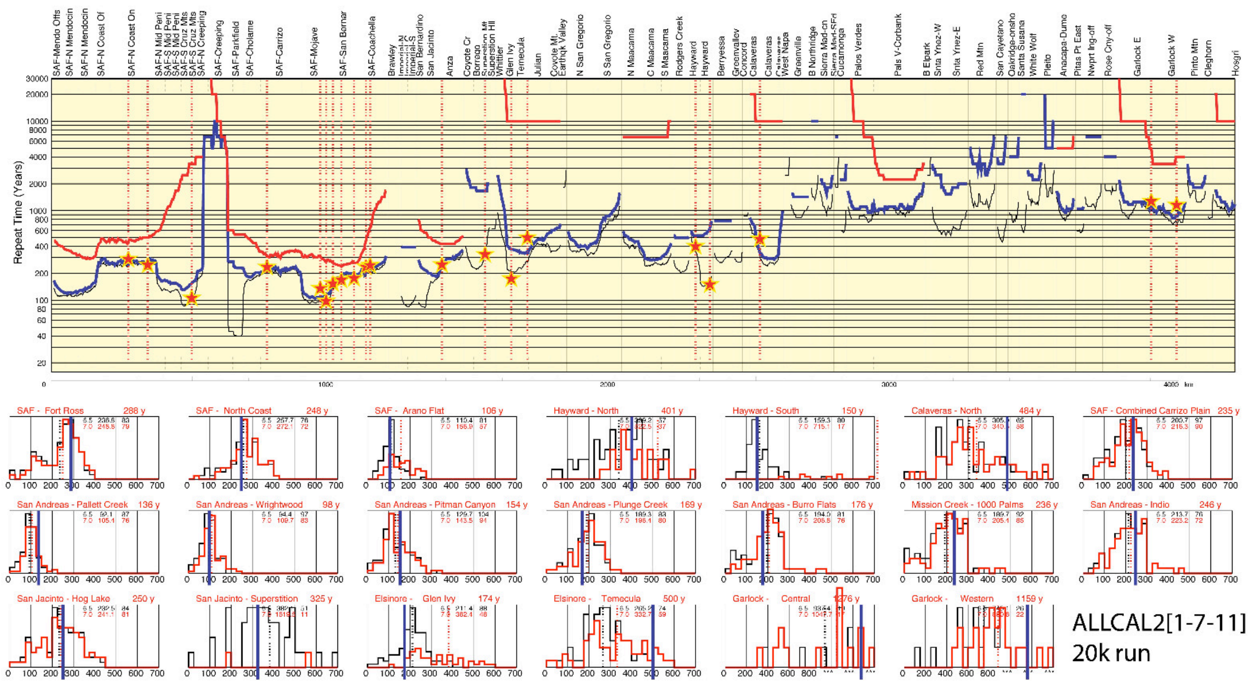

Figure 5. Top panel shows model recurrence intervals a points along strike for M>7.5 (red), M>7.0 (blue) and M>6.5 (black) for a 20,000 year run on January, 2011. Bottom panels plot simulation PDFs for recurrence intervals M>6.5 and M>7.0 at 20 paleoseismic sites that were employed by UCERF. Simulator tuning means slowly adjusting ~180 segment strengths to generally (but not explicitly) match observed recurrence intervals (stars above) where available.

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 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 6 (bottom right), plots earthquake magnitude versus rupture area from a recent 10,000 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. A major effort of the Earthquake Simulator Group

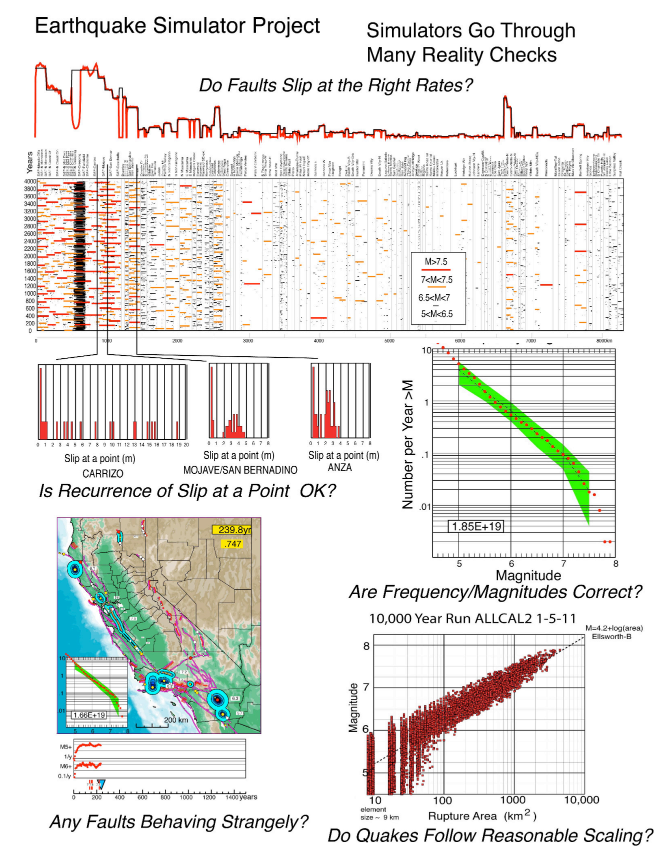

Figure 6. Reality tests for Earthquake Simulators. The agreement in the numbers of quakes versus magnitude with the observed catalog, the reproduction of accepted earthquake scaling relations and slip per event recurrence both tests and lends credence to ALLCAL products.

is to develop "tool sets" to compare standard format output products among the various simulators to see where common ground lies.

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.

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.

Interface with UCERF. For years, one idea was for UCERF to incorporate simulator results into some aspect of their hazard calculations. Not much has come of the idea, but one can always hope. A UCERF meeting is scheduled for June, 2011 where the possible use of earthquake simulators is on the agenda.

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 Symposia

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.

In October, 2010 at the ACES meeting in Otaru, Japan, I lectured on "*ALLCAL: An Earthquake Simulator for All of California*". The presentation included most of the latest work here.