Southern California Earthquake --- SCEC3 Research Summary
Title of Project: A Collaborative Project: Comparison and Validation of Earthquake Simulators
Name of PI: Steven N. Ward **Institution:** University of California, Santa Cruz

Simulators help us understand the mechanics of earthquakes. They help us learn whether aspects of earthquakes may be predictable and, if so, how those predictions might be done. For earthquake simulators to be useful however, they must behave in a manner that has elements of reality. Determining how realistic simulator results might be is a difficult task. Since 2009 there has been a concerted effort in SCEC3 toward the comparison and evaluation of a variety of earthquake simulators to gain a better understanding of which features are common to them all and which features depend strongly upon variable details of input and assumption. The efforts of the Earthquake Simulator Group lie in three areas: benchmark test problems, full statewide simulator runs, and comparison of results.

Test Problems. Consider two problems: (1) Single straight fault with halves of variable strength ratio 1:A. (2) Offset and overlapping faults. A PowerPoint presentation in Quicktime Format of the results of Problem (1) is available here http://es.ucsc.edu/~ward/powerpoint/Problem3.mov For certain values of A, exactly N events on the weak side were needed to break the strong side (Figure 1). For other values of A, transitions were found where the ratio of events was variable. When the slope of the slip or velocity weakening friction is made more gentle, this simple mode behavior becomes more complicated because ruptures are no longer all-or-nothing complete stress drop events. Decreasing the slope of slip or velocity weakening always makes for richer rupture behaviors. Figure 2 shows one example of Benchmark Problem (2). Here rupture propagation starts on one fault at the left and jumped onto a second fault that overlapped by 5 km and was offset by 1 km in the tensional direction – see animation here... http://es.ucsc.edu/~ward/jump[5+1]s.mov . In this case, rupture did jump the gap, but further experiments suggest that the likelihood of such a jump drops very quickly as the offset grows. Increasing the offset to just 2 km, for example, stopped the jump - see http://es.ucsc.edu/~ward/jump[5+2]s.mov

Statewide Runs. During SCEC3, the ALLCAL fault system expanded in scope (number of faults included) and scale (number of elements). The current simulator, ALLCAL2, uses ~15,000 nearly square (3x3 km) fault elements arranged such to avoid most large tears and overlaps with depth on contorted faults. The ALLCAL2 simulator generates dynamic ruptures from magnitude 8+ down to about magnitude 3, so a 4000 year run produces ~300,000 events. Please view the movie at: http://es.ucsc.edu/~ward/ALLCAL3D-300.mov Each of the thousands of flashes in this movie is a genuine 3-D dynamic rupture. Much of the ALLCAL effort involves tuning the simulator and testing its outputs. 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.

Comparison of Results. *T*he group has developed standard output formats such that long catalogs from any of the simulators can be run through software tools placed in an open and developing "toolbox' housed on SCEC servers. Tools include plotting scaling laws (Figure 3), conditional and non-conditional PDFs, average moment release, slip/time predictability, earthquake rate density and perhaps a dozen others. These tools help us explore where simulators might hold predictive information. They also help us identify outliers in behavior and search for explanations. For example, Is this or that behavior due to physical assumptions, programming considerations, parameter selection or simple blunder?

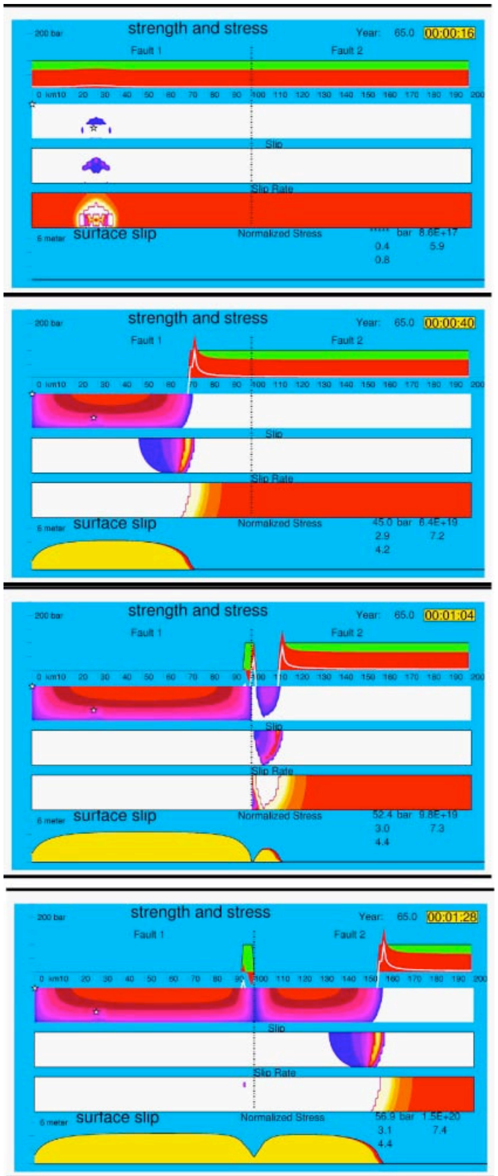

Figure 2. Example of Benchmark 2, rupture jumping between two parallel but offset faults.

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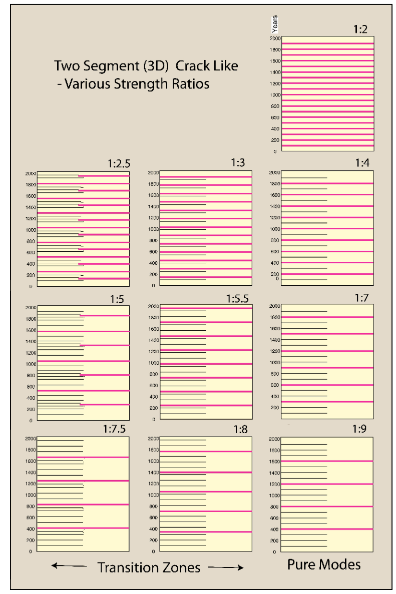

Figure 1. Benchmark Test 1. As the strong side (right) of the fault gets stronger, it takes more and more weak side breaks to knock it off -- two weak side breaks to knock off the strong side at (1:4), three weak side breaks to knock off the strong side at (1:7), etc. (right column). Not unexpected behaviors really. Transition intervals exist (eg. 1:2.5 and 1:5 panels) between nicely behaved rupture modes.

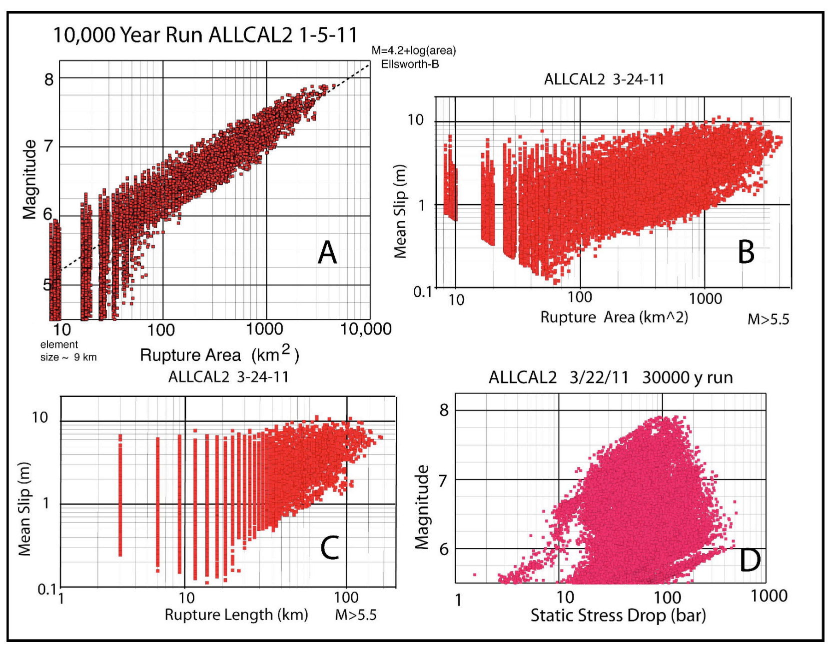

Figure 3. Various consistency tests for ALLCAL2 output. (A) Magnitude versus Fault Area, (B) Slip versus Fault Area, (C) Slip versus Rupture Length, (D) Magnitude versus Static Stress Drop. Plots like these are part of the "toolbox" being developed by the simulator group to compare and validate simulator results.

Annual Report, 2011
SOUTHERN CALIFORNIA EARTHQUAKE CENTER

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Simulators help us understand the mechanics of earthquakes. They help us learn whether aspects of earthquakes may be predictable and, if so, how those predictions might be done. For earthquake simulators to be useful however, they must behave in a manner that has elements of reality. Determining how realistic and useful simulator results might be is a difficult task. Toward this end, this project continues a process of comparison and evaluation of a variety of earthquake simulators to gain a better understanding of which features are common to them all, and which features depend strongly upon variable details of input and assumption.

The efforts of the Earthquake Simulator Group lie in three areas: benchmark test problems, tuning full statewide simulator runs, and comparison of results. In 2011, benchmark test problems were moved to the back burner and emphasis placed on statewide runs and comparison.

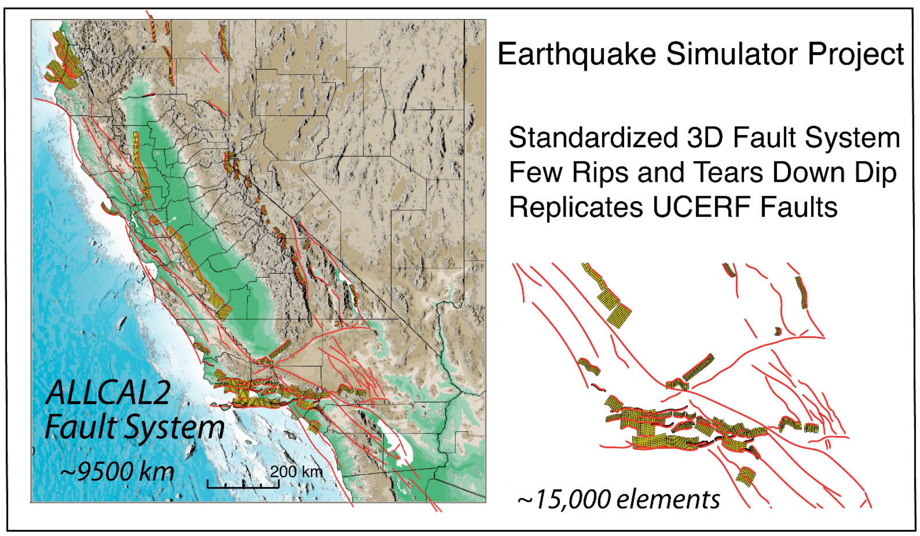

Figure 1 (*Left*). Current ALLCAL2 fault set. (*Right*) "Mean strike" scaling of element location eliminates most tears down dip. The Earthquake Simulator Group is working toward a standardized set of fault elements with which to compare output products.

Fault Systems. In 2011, the geometry of the ALLCAL fault system pretty much stabilized in scope (number of faults included) and scale (number of elements). The current ALLCAL2 simulator, uses ~15,000 nearly square (3x3 km) fault elements arranged such to avoid most 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 to the set used in the UCERF program. There has been discussion about refining the system still further to (2x2 km) or (1x1 km) elements. The idea for this would be to test whether element size has meaningful effect on earthquake statistics. I am prepared to generate these finer grid fault sets, but so far there has not been a ground swell within the group to do so. For years now, UCERF has promised to release an "Official Fault System" which supposedly could be adapted for simulator use. Further fault system development within the Simulator group seems to be on hold until that happens.

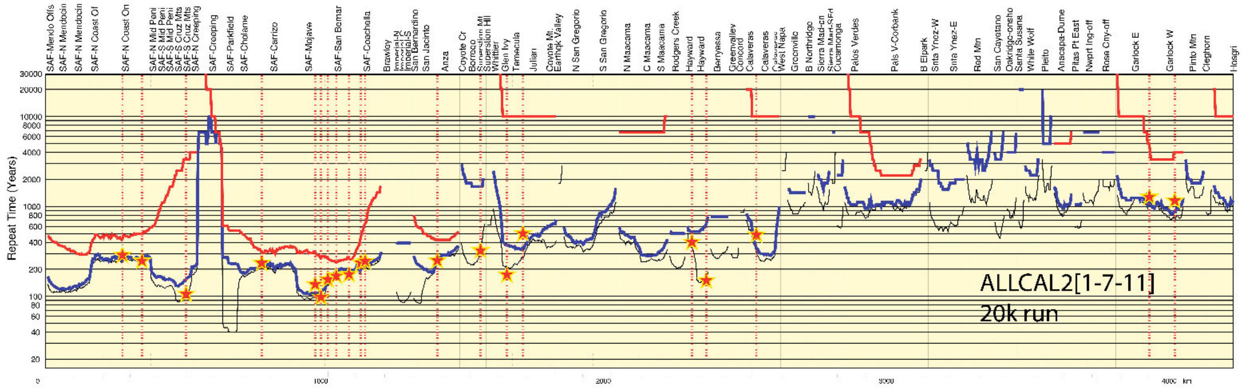

Figure 2 ALLCAL2 model recurrence intervals at points along strike of about 4500 km of ALLCAL's 10,000 km fault system. M>7.5 (red), M>7.0 (blue) and M>6.5 (black) 20,000 year run in January, 2011. Stars locate UCERF2 paleoseismic recurrence data.

Tuning. Simulator tuning is a significant effort that does not show at first glance. All simulators involve fault friction law parameters including "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 given some initial condition. Not surprisingly, given 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 and scaling relations. Conversely if a fault is too weak, segment quakes may be too small and intervals too short. Tuning involves running the simulator for ~10,000 years, plotting observed versus calculated recurrence intervals (like Figures 2 and 3) and making small strength adjustments for any of ~180 segments. The process then repeats. I don't view tuning as "cheating". Tuning just adjusts the machine to perform as it is supposed to. I liken this process to a clock maker. He builds a clock and then winds it up on the first occasion. Not likely the clock will keep good time off the mark without adjustment. Moreover, different clocks that the maker builds will need different adjustments. Unlike clock makers, simulators face more complex observational issues in tuning; in particular, how can we tune things to match paleoseismic recurrence intervals if it is never quite clear to what magnitude the interval refers: M>6.5, M>7.0, M>7.5? Interaction between geologists and simulators is increasingly called for.

Comparing results. Comparison of results is where the group has its strengths. Where are simulator results convincing? Where do they need work? Beyond the simplest of test cases, due to the

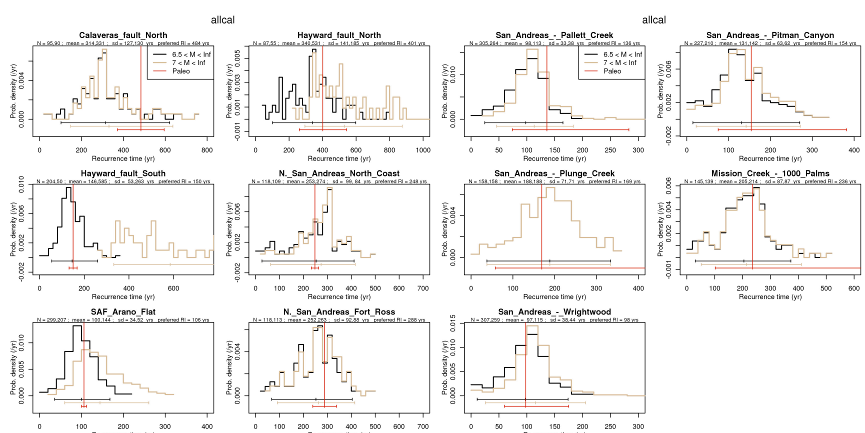

Figure 3 Panels plot ALLCAL2 PDFs for recurrence intervals M>6.5 and M>7.0 at 11 of 20 paleoseismic sites that were employed by UCERF. Simulator tuning means slowly adjusting ~180 segment strengths to generally (but not explicitly) match observed recurrence intervals (vertical lines) where available. These types of plots are examples of display and analysis tools developed by the Earthquake Simulator group to compare and validate output.

non-linearity of earthquake failures, it is not expected that the simulators will give identical predictions in a deterministic way. A major effort of the group is to explore simulator outputs in a statistical sense in a search for common ground. This sounds easy, but it is not really. 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 cut and dry.

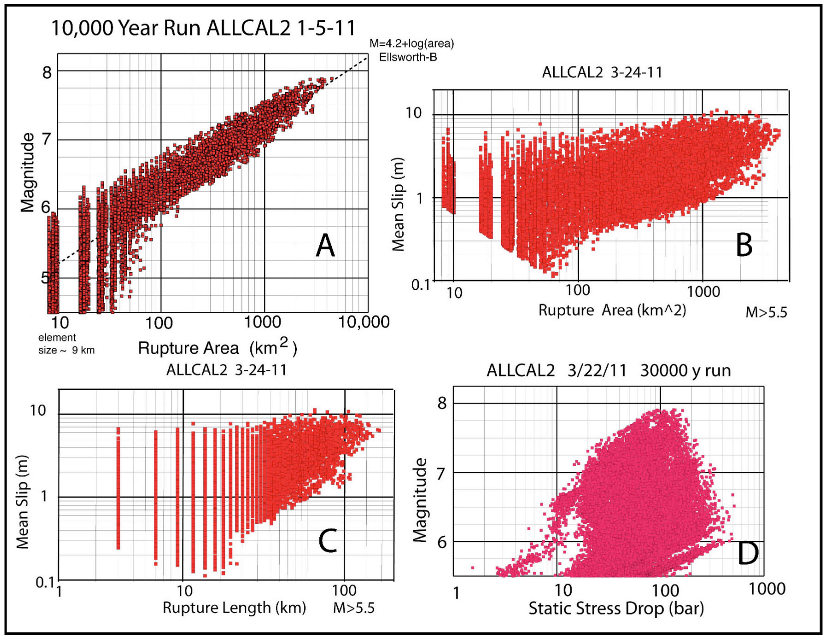

Figure 4. Various consistency tests for ALLCAL2 output. (A) Magnitude versus Fault Area, (B) Slip versus Fault Area, (C) Slip versus Rupture Length, (D) Magnitude versus Static Stress Drop. Plots like these are part of the "toolbox" being developed by the simulator group to compare and validate simulator results.

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http://scec.usc.edu/research/eqsims/

and

http://scec.usc.edu/research/eqsims/private/

Tools include plotting scaling laws (Figure 4), conditional and non-conditional PDFs, average moment release (Figures 5), slip/time predictability (Figure 6), earthquake rate density (Figure 7) and perhaps a dozen others. These tools help us explore where simulators might hold predictive information. They also help us identify outliers in behavior and search for explanations. For example, Is this or that effect due to physical assumptions, programming considerations, parameter selection, or simple blunder?.

Many comparisons of ALLCAL output and other simulators will be included in the 2011 Annual Report Summarizing Group Activities by Terry Tullis.

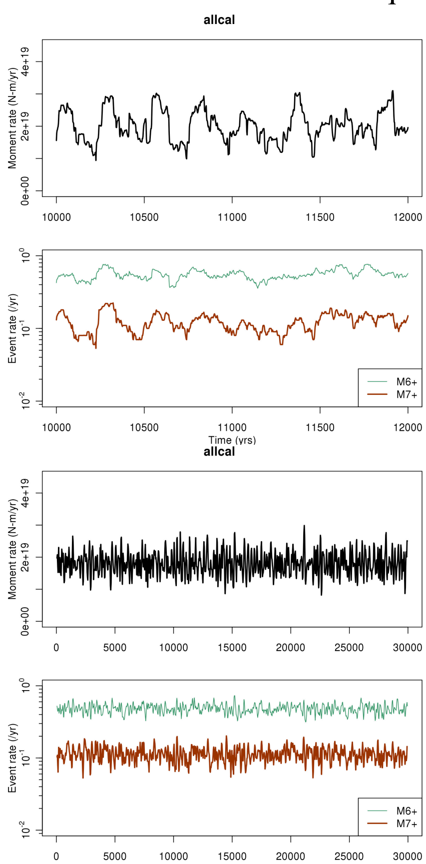

Figure 5. 100 year moving averages of Moment Rate (black) and Event Rate M7+ (green), M6+ (red) as output from ALLCAL2. Top box covers a 2000 year span. Bottom box covers a 30,000 span. These plots give an idea of the variability that you might expect in the current catalog rates.

ALLCAL2 simulator results were presented in May, 2011 in conjunction with the ACES meeting in Maui.

The simulator group plans a group submission of papers to BSSA in Spring 2012.

Ward, S.N., 2012 ALLCAL, *Bulletin Seism. Soc. Am.* (in preparation).

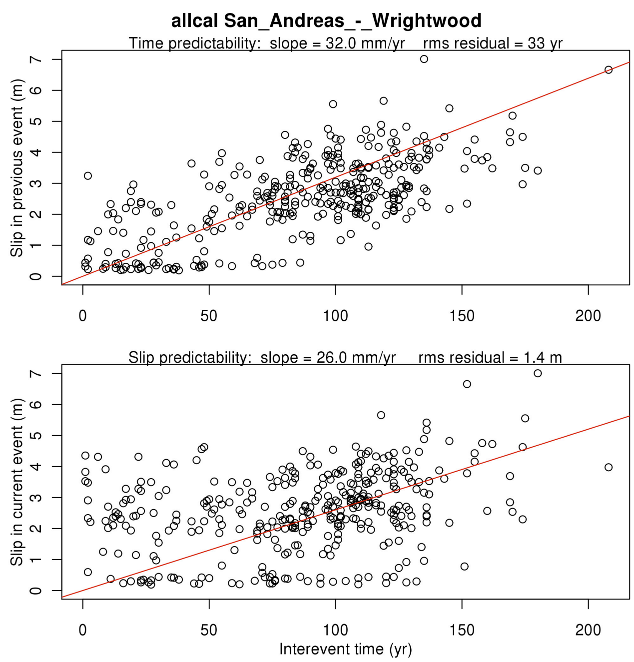

Figure 6. ALLCAL Slip Predictable/Tme Predictable Test. These panels plot slip in previous event versus time till next event (top) and slip in current event versus time since last event (bottom).

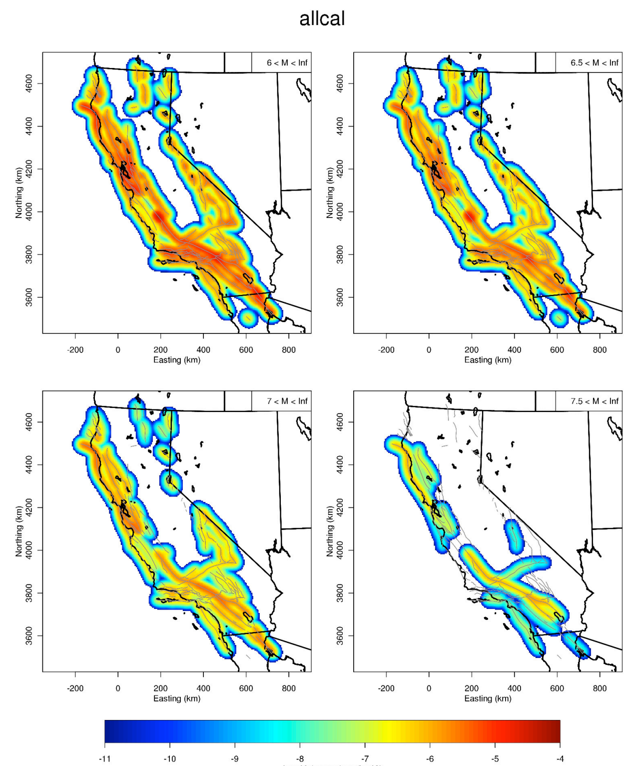

Figure 7. ALLCAL2 earthquake rate density for M6+, M6.5+, M7+ and M7.5+