2003 SCEC proposal final report
Principle Investigator: Jeff McGuire
Proposal Title: Does Rupture Directivity Scale with Earthquake Size?
Award Level: $15,000

Large earthquakes typically exhibit clear evidence of rupture propagation along the fault during the course of rupture, such as Landers propagating from southeast to northwest. Our recent study of about 50 M>7 earthquakes demonstrated that this type of unilateral rupture propagation predominates for large events (McGuire, Zhao et al. 2002). In contrast, studies of the finite source properties of small earthquakes typically assume the ruptures were constant stress drop circular cracks allowing a conversion between the measured value of the corner frequency and stress drop (Brune 1970). This assumption has been necessary primarily owing to the lack of an appropriate formalism for interpreting the spatial variations in frequency content and "pulse width" that have long been recognized in short period P and S wave recordings of small quakes. I have recently developed an algorithm for estimating the second degree moments (variances) of small earthquake slip distributions using empirical Green's functions (McGuire 2003). This minimal parameterization (6 quantities) is capable of resolving the fault plane ambiquity, estimating the length, width, and duration of the rupture, and differentiating between unilateral and bilateral ruptures. Moreover, in certain cases it provides an estimate of rupture velocity, one of the most important measurable quantities for determining whether small and large earthquakes are governed by similar physics (Kanamori and Rivera 2003).

Preliminary analysis of high quality datasets from the creeping section of the San Andreas and Japan (Ide 2001) using the second moment technique have indicated that earthquakes smaller than about magnitude 4 are relatively symmetric bilateral ruptures, in contrast to the highly directional unilateral ruptures of big quakes like Denali. If this difference in rupture symmetry between small and large earthquakes is real, constraining the length scale at which the transition occurs will be an important observation for constraining rupture dynamics. In particular, there already dynamic models that predict "moderate" and "large" earthquakes to be highly directional owing to their tendency to nucleate at the end of previous ruptures and then propagate away from the stress shadow of the last event (Shaw 2000). Thus estimating the length-scale at which ruptures become unilateral could be a constraint on the stress heterogeneity on real faults. To provide further data for evaluating the potential mechanisms responsible for rupture directivity and to help clarify any potential difference between small and large earthquakes in their directivity I proposed to apply the second moment technique to moderate earthquakes recorded by TRINET with the following primary goals:

1. To determine which areas of TRINET are well suited for determining the 2nd moments of moderate earthquakes.
2. To examine the unilateral/bilateralness of recent Southern California earthquakes in the magnitude 4 – 5.5 range and relate these values to datasets from other regions to examine the scaling of directivity.

Results

Data Issues: In attempting to determine second moments for various earthquakes in Southern California, several data archiving issues arose. In particular, there are several existing datasets that would be useful for source studies that have not made it into the traditional event products at the SCEC DC.

- In general, earthquakes with M_L > about 4.5 that occur within TRINET are sufficiently well recorded (post ~ 2000) to determine the second moments. One of the requirements of my technique is the existence of a suitable EGF event that is at least a factor of 100 smaller in seismic moment than the mainshock but still has a high signal to noise ratio at the important stations. Ideally, the EGF events would be even smaller, but a factor of 100-1000 appears to be sufficient in that any bias from the finite duration of the EGF is small (less than about 15% of the duration) compared to the variations in time function duration caused by directivity (>100%). Only in about ~10% of the events I looked at was finding a suitable EGF (i.e. event at least 2 magnitude units smaller with the same focal mechanism) difficult. Finding a suitable station geometry was much more limiting. As more events of this size occur within the array, similar to say the Yorba Linda earthquake or the 2001 Anza Halloween earthquake, it will be possible to develop a catalog of rupture/auxiliary planes, rupture lengths, and directivity parameters for this size range. This would be a useful dataset to have archived for stress triggering, stress inversion, and earthquake source physics modeling studies.
- The ANZA network provides the best dataset for small earthquake source studies in Southern California owing to the dense station coverage relative to typical source depths and low attenuation sites. Second moments are clearly resolvable down to at least M_L 4.0 with smaller events also exhibiting measurable finite source effects. While it's known to be a difficult area to work in, extending the ANZA network southeast by another 10-20 km would have considerable usefulness for studying rupture propagation of M4-5 earthquakes. This would be a worthy SCEC-seismology infrastructure target.
- The ANZA data for small events before about 2000 does not make it into the scecdc triggered event datasets (i.e. what can be accessed by STP). While this data is available from IRIS (except currently for 1999), it would be more convenient for EGF studies to have the ANZA data at the scecdc for all events with Caltech ids.
- Similarly, the temporary deployment Landers aftershock dataset would be useful for directivity studies if the small (EGF) events were included in the scecdc datasets, not just the large events.

2nd Moment Estimates and Rupture Directivity Scaling: So far, we have been able to estimate the second moments for the six earthquakes in Table 1. For all of these events, there was a clear distinction between the two nodal planes of the event's focal mechanism in terms of the variance reduction produced in the second moments inversion, allowing us to identify the actual rupture plane. One surprising result is that two of the events with standard Southern California strike-slip focal mechanisms (i.e. vertical nodal planes striking to the NW and NE) that were located very close to major fault systems actually occurred on the NE striking nodal plane and hence represent slip on some local conjugate or fault jog structure rather than the through going fault. The September 3rd, 2002 Yorba Linda Earthquake (Figures 1 and 2) had clear directivity to the NE, consistent with the orientation of its aftershock zone, indicating that it did not rupture the near by Whittier Fault. This result has also been found by Chen and Jordan (USC) as well as Clinton and Heaton (Caltech). Moreover, our estimate of characteristic rupture length (1.3 km) is roughly consistent with the aftershock distribution. Similarly, the October 31, 2001 Anza earthquake (Figures 3 and 4) shows clear directivity to the NE indicating that it did not rupture one of the primary strands of the San Jacinto fault system, and instead likely occurred on a fault-jog structure.

The second moments are interesting quantities to evaluate in scaling relations because they can be estimated directly over almost the entire range of earthquake sizes (M2-8). While our dataset is still limited for events smaller than M 6, we compare the scaling of directivity with previous datasets (McGuire et al., 2002) for moderate and large earthquakes in Figure 5. In particular, our small earthquake datasets thus far, from California and Japan, indicate that the majority of small events have a directivity ratio less than .5 indicating a symmetric rupture. In contrast, the majority of large events have a directivity ratio > .7 indicating a predominately unilateral rupture. While there are clear counter examples (i.e. unilateral small quakes and bilateral big ones) it appears at this preliminary stage, that a transition in the predominate behavior occurs in the magnitude 4.5-5.5 range when ruptures reach length scales larger than about 1-2 km (Figure 5). Expanding the catalog of second moment estimates for moderate earthquakes in Southern California will enable us to flesh out the transition region in Figure 5 and to examine in detail the events where unilateral rupture first begins to dominate. There are several mechanisms that may cause unilateral rupture to predominate for large earthquakes. For instance, Shaw's [2000] numerical simulations of events on a simple single fault indicate that "large" events nucleate near the end of a previous rupture on the fault and then propagate primarily in the direction away from this previous rupture owing to the stress shadow left by the previous event. Additionally, large earthquakes may also tend to occur on faults with sufficient cumulative offset to juxtapose rocks with significantly different elastic properties. A contrast in material properties across a fault may also favor enhanced rupture propagation in one direction over the other (Ben-Zion and Andrews 1998), though the details of this phenomenon in 3 dimensions and whether it is significant for real faults are still being examined. Clearly a more precise resolution of the length scale and fault types at which unilateral rupture becomes predominant will aid in the mechanical interpretation of Figure 5.

Event	Magnitude	Rupture Strike	Plane Dip	τ_c (s)	L_c (km)	v_0 (km/s)	L_0/L_c
2003 03/11	4.6	320	80	.10	.34	1.4	0.4
2003 02/22	5.4	320	80	.40	1.2	2.0	.70
2002 09/03	4.8	60	90	.15	1.3	4.5	0.77
2002 01/02	4.2	313	87	.09	.69	1.4	.19
2001 10/31	4.9	225	78	.22	1.4	2.4	.37
2001 02/10	5.1	25	90	.35	2.2	1.1	0.17

Table 1. Characteristic rupture dimensions derived from the second moment estimates for recent moderate earthquakes in Southern California. Several of the focal mechanisms used are preliminary and hence the exact values of strike and dip could change when final solutions are available. τ_c is the characteristic duration, L_c is the characteristic rupture length, v_0 is the "average velocity of the instantaneous centroid", and L_0/L_c is the directivity ratio, see (McGuire, Zhao et al. 2002) for definitions.

Communication of Results

Two of the earthquakes that were studied as part of this proposal were included in a paper describing the second moments estimation technique for small earthquakes that is currently submitted to BSSA (McGuire 2003). Additionally, the results will be part of an upcoming paper on differences in directivity between small and large ruptures. The results were also presented at the SCEC annual meeting and at the SCEC workshop on "seismic networks and earthquake science" at Caltech in September. Hopefully, these second moment estimates and rupture plane determinations will become part of a web accessible database in the next year or two.

Figure Captions:

Figure 1: Map of the Yorba Linda earthquake region. The earthquake location is shown by the focal mechanism. Each of the stations used in the second moment inversion is labeled with two times the square root of the variance of the time function, in units of seconds, resulting from either a P (red) or S (blue) wave EGF deconvolution. Stations to the NE have relatively short time functions while stations to the SE have relatively long time functions. The red contours denote the peak ground acceleration values resulting from the USGS shakemap procedure. The elongation of these contours to the NE appears to be a result of rupture directivity. The inset shows a blow up of the aftershock locations which are aligned NE-SW.

Figure 2. Examples of the EGF deconvolution procedure for the Yorba Linda Earthquake. The top panel for each station compares the mainshock (blue) and EGF (red) seismograms (scale adjusted to match the mainshock). The lower panel for each station shows the time function resulting from the deconvolution. Each time function is labeled with two times the square root of its variance (units of seconds).

Figure 3. Similar to Figure 1, but for the 10/31/2001 Anza earthquake. The mainshock location (red dot) and aftershock locations (black dots) appear to indicate a NE-SW orientation which would be coincident with one of the nodal planes of the mainshock focal mechanism (inset) but not with slip on a primary strand of the San Jacinto Fault zone. Stations to the NE show relatively short time functions while stations to the SW show relatively long time functions indicating rupture directivity to the NE.

Figure 4. Similar to Figure 2, but for the Anza earthquake.

Figure 5. Comparison of the directivity ratio with seismic moment for a number of datasets: Large global earthquakes from McGuire et al. (2002) (black triangles), various strong motion inversions primarily in California and Japan (open circles, see McGuire et al 2002), Southern California earthquakes from Table 1 (black stars), an Intraplate swarm from Japan (open squares, see (Ide 2001)), and magnitude ~3 events from the creeping section of the San Andreas (open diamonds) recorded by a temporary PASSCAL deployment. A directivity ratio of 0 indicates a symmetric bilateral rupture while a ratio of 1.0 indicates a unilateral rupture.

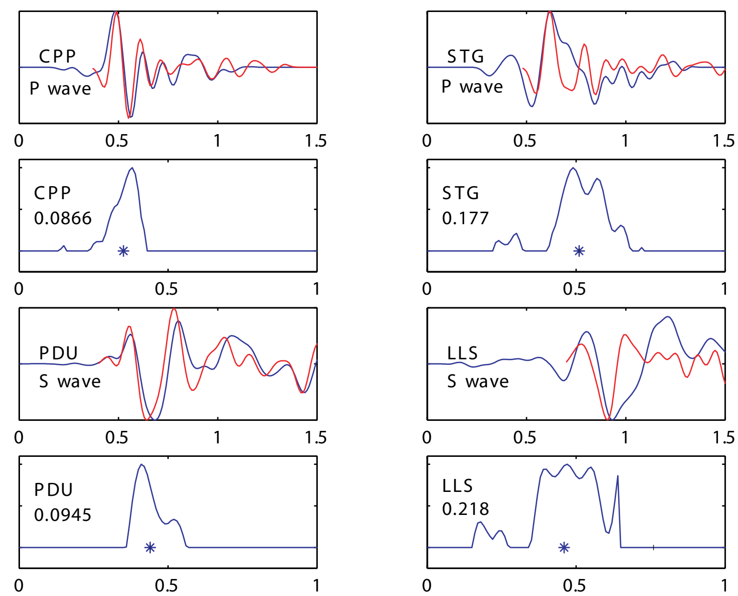

Figure 2

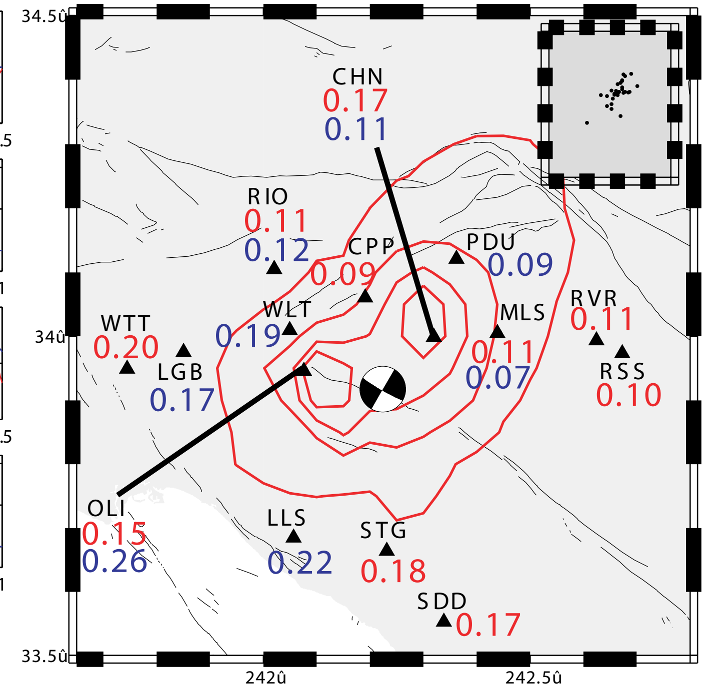

Figure 1

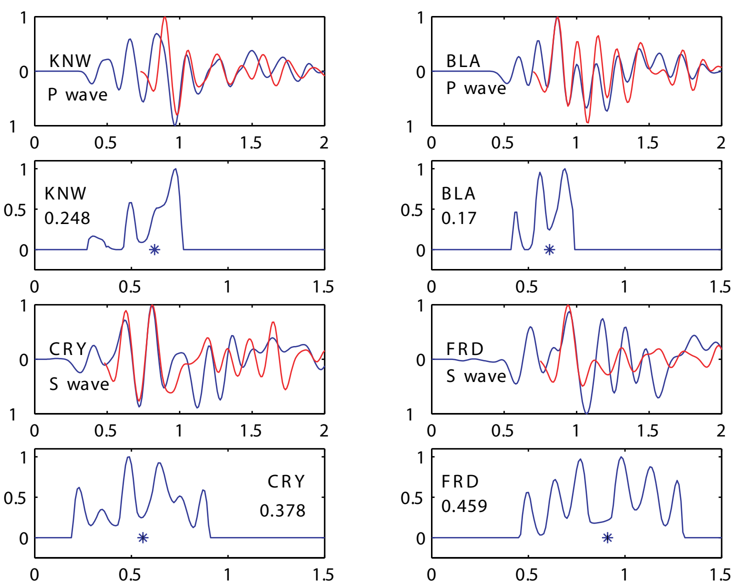

Figure 4

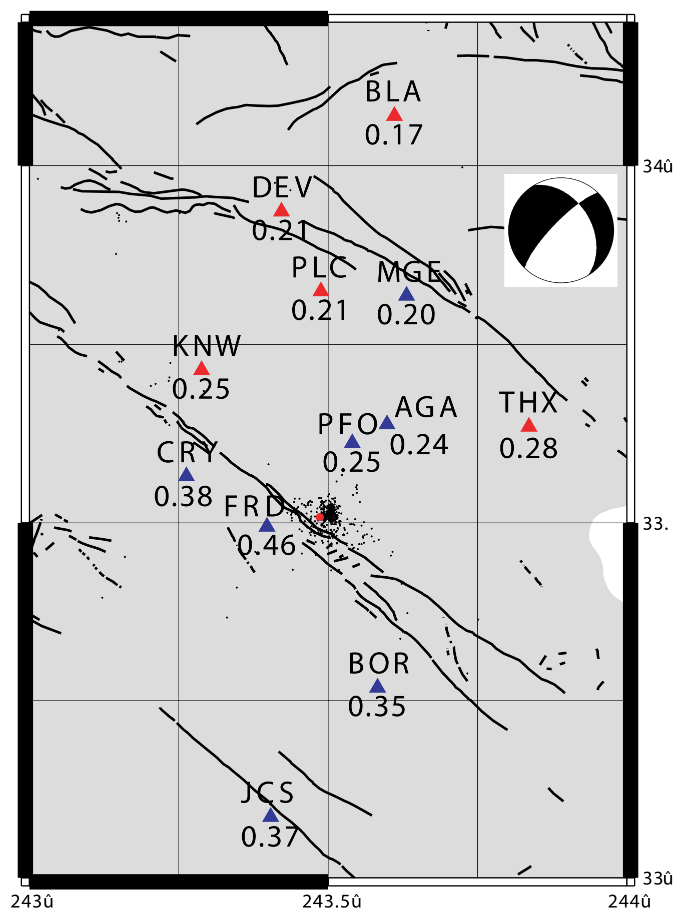

Figure 3

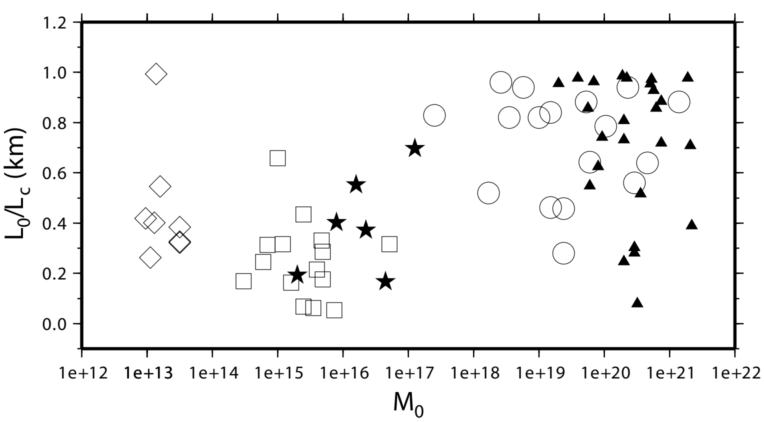

Figure 5

References

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