Quantifying the remote triggering capabilities of 400 teleseismic earthquakes (M>6) using 22 years of data from the ANZA seismic network catalog (Southern California)

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1.0 Investigations undertaken

We search the 22-year ANZA (southern California) network catalog for evidence of remote triggering. We assume aftershock triggering occurs when a given threshold condition (i.e., seismic wave amplitude or frequency) is exceeded in the region of the aftershock. This is based on the idea that a triggered earthquake should be influenced only by what happens at its location. Consequently triggering conditions produced by a local mainshock and matched by a remote mainshock should result in the same local effect. We therefore use the same method for analyzing local triggering and as we do for evaluating remote triggering. Using three statistical tests (Binomial, Wilcoxon Ranksum and Kolmogorov-Smirnov) we determine the significance of quantity and timing of events in southern California before and after large teleseismic events (Figure 1a). To validate the use of our statistical tests, we identify local mainshocks (M>3.2) with obvious aftershock sequences and local mainshocks (M>3.0) that lack an obvious aftershock sequence. Using our statistical tests, we quantitatively confirm the triggering (non-triggering) nature of these local mainshocks and estimate a threshold required for triggering (non-triggering). Similar tests are applied to our teleseismic catalog to help bound the frequency/amplitude thresholds for remote earthquake triggering.

Our goals include: (1) Testing a set of methods for determining if remote triggering occurs in Southern California. (2) Validating these methods by testing them on local mainshocks and aftershock sequences. (3) Providing insight to the triggering mechanism debate.

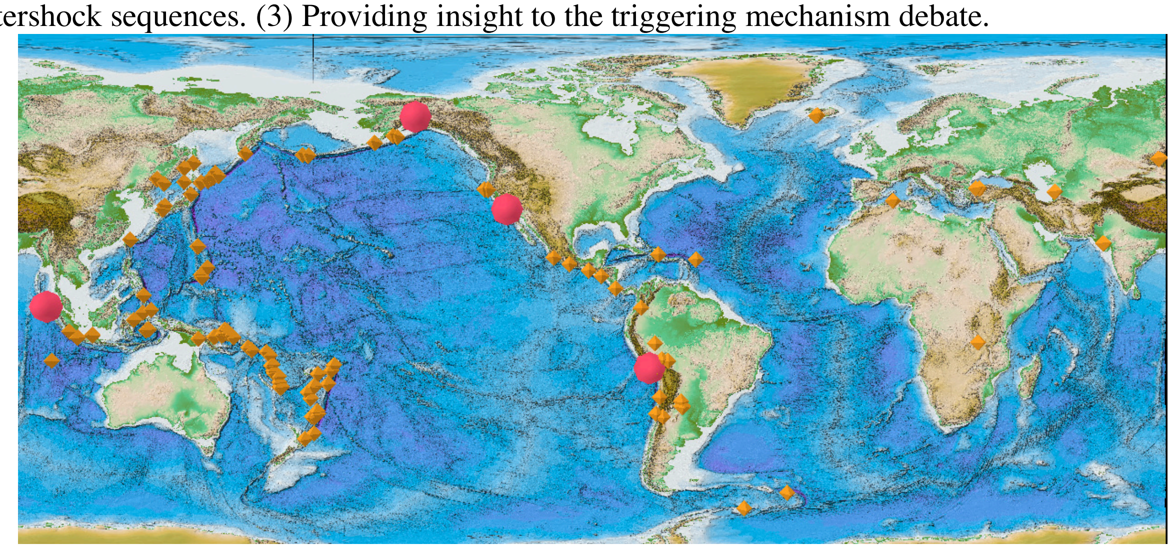

Figure 1a. Distribution of large earthquakes recorded by the ANZA seismic network (orange diamonds). After testing these events we chose a subset of 4 of the largest and closest earthquakes (red spheres) to focus on in this study, these include the: (1) Mw 6.7 Northridge, California, earthquake on 17 January, 1994; (2) M9 Sumatra-Andaman Islands, 24 December 2004; (3) M8.4 23 near the coast of Peru on June 2001; and (4) M7.9 Denali, Alaska, earthquake on 3 November, 2002.

Data & Definitions. We use data recorded by the Anza seismic network in southern California (Figures 1a-b). The Anza network is a permanent array of twenty-four three-component broadband stations that primarily surrounds the Anza seismic gap and span the San Jacinto transform fault. From yearly histograms of earthquake magnitudes, we estimate the ANZA catalog completeness level is approximately magnitude 2 (for events after 1991 this is reduced to ~1.5). Since the network was installed in 1984, there have been relatively few earthquakes over magnitude 4 in our study region, and typically local earthquakes in the ANZA region are less than magnitude 3.5. In comparison with, for example, the seismicity distribution along the San Andreas Fault near the town of Parkfield, where the seismicity is primarily localized along a single fault trace, the seismicity in the southern California region is very diffuse.

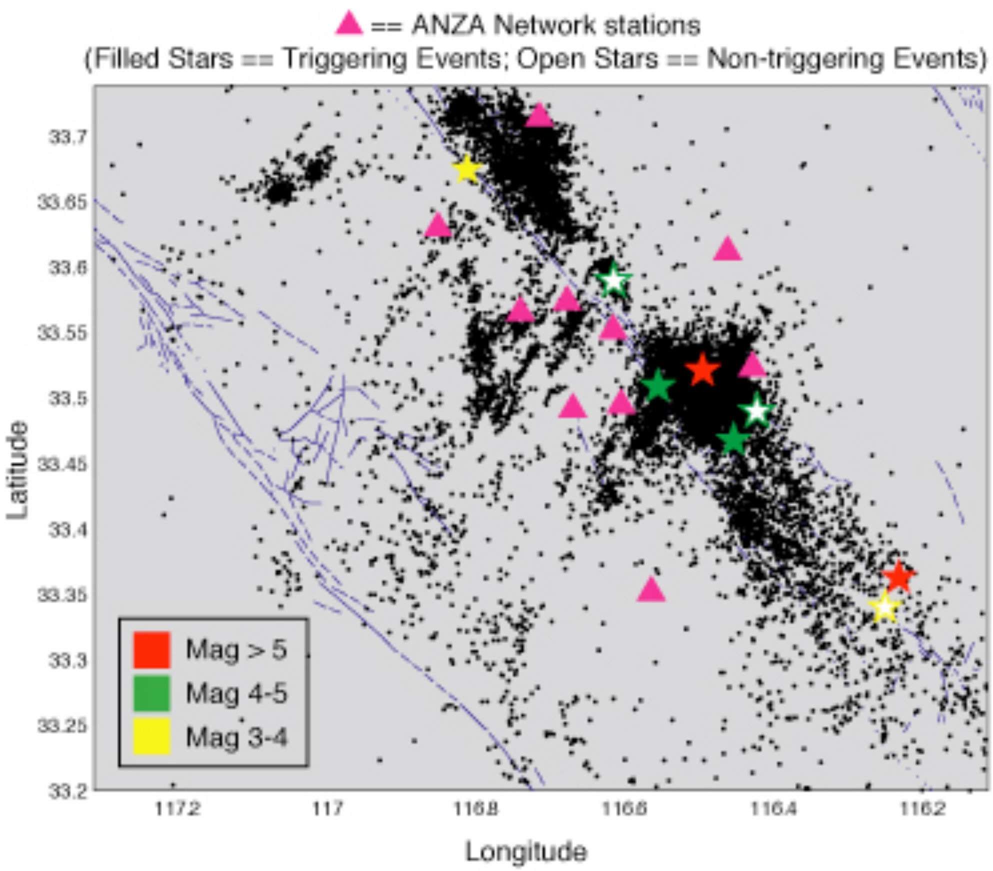

Figure 1b: ANZA network stations in southern California (triangles) and local seismicty recorded by this network (points). Also shown are large magnitude earthquakes (stars) color-coded by magnitude. Filled stars represent mainshocks with an obvious aftershock sequence, open stars represent mainshocks with no obvious aftershock sequence.

We divide the Anza data into three groups based on epicentral distance to the Anza network centroid (33.5, -116.6): (1) Local events are those within 0.5°; (2) Regional events are those between 0.5° and 5°; and (3) Remote events at distances greater than 5°. Within the local, regional and remote groups we also define 'mainshocks' to be events greater than magnitude 3.0, 5.0 and 7.0, respectively. We define an 'aftershock' to be any local earthquake occurring in southern California that could potentially be related to a local, regional or remote mainshock. To avoid complications from local mainshock/aftershock sequences, our aftershock catalog contains no events that are obviously associated with a local mainshock.

Statistical Tests. To quantify earthquake triggering, we use three different statistical tests to analyze the temporal changes in the local seismicity. These tests include: (1) The Binary test. (2) The Kolmogorov-Smirnov test; and (3) The Wilcoxon RankSum test. Both the Kolmogrov-Smirnov test and the Wilcoxon RankSum tests analyze changes in the temporal distribution of seismicity prior to and following a mainshock, where as the Binary test examines only the variation in the number of earthquakes prior to and following a mainshock. Each of these tests produces a statistical significance P-value that ranges between 0 and 1, where a low value indicates a change in the temporal distribution after the mainshock (i.e., triggering) and a high value indicates minimal change (i.e., no triggering).

Spectral Characteristics: We compute the spectra of mainshock seismograms using a multitaper method based on the MATLAB© routine PMTM, which estimates the Power Spectral Density via the Thomson multitaper method. We also enforce a normalization factor to the multitaper result that is consistent with Parseval's theorem. Uniformity in our spectral computations allows us to compare the spectra of one event with that of another, allowing us to test for triggering thresholds in both amplitude and frequency.

2.0 Results

We test the hypothesis that regional and remote mainshock earthquakes trigger aftershocks in Southern California by searching for evidence of seismicity rate changes in the ANZA catalog. We first visually examine the temporal behavior of the local seismicity (33.20° < Lat < 33.74°; -117.31° < Lon < -116.11°) dividing the larger events (M_L>3) into two categories: those that exhibit obvious triggering and those that show no triggering (Figure 2a-b).

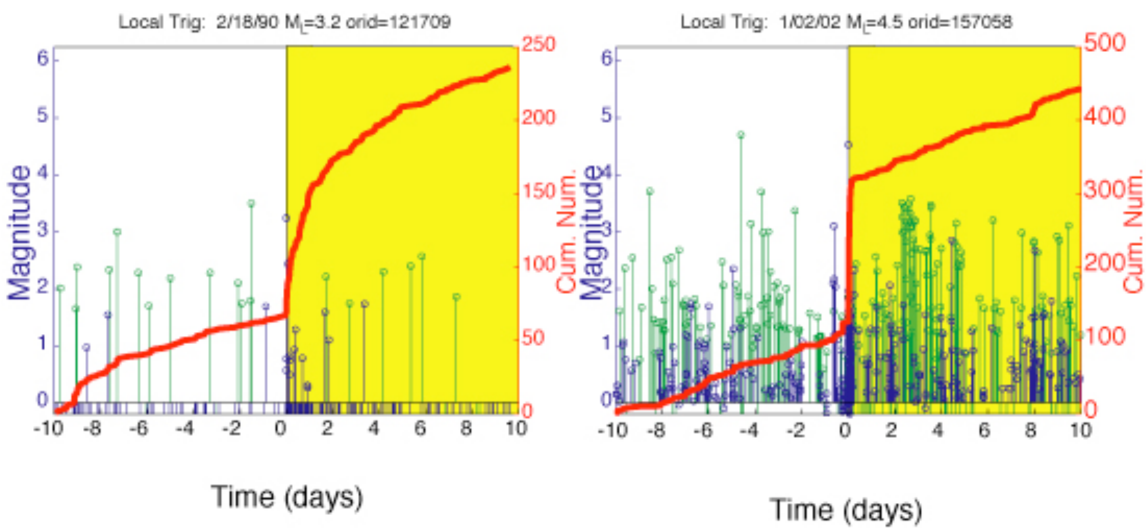

Figure 2a: Examples of local triggering mainshocks (the mainshock occurs at t=0). As a function of time and magnitude (left axis) blue stems represent local events and green stems represent background global seismicity. Also shown is the cumulative number of local events (red line, right axis).

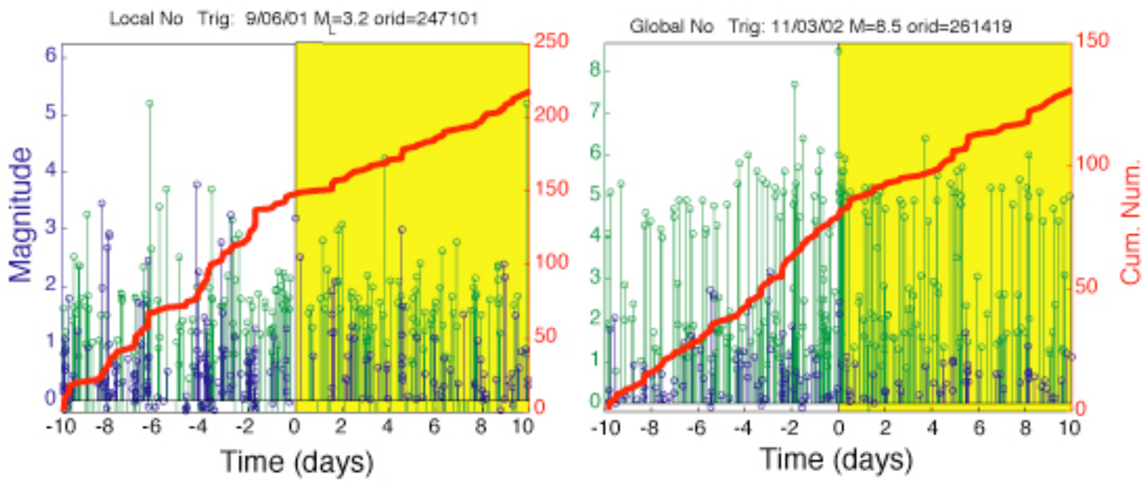

Figure 2b: As in Figure 2a, but for (left) a local event with no obvious aftershock sequence and (right) a global event with no visual appearance of triggering. The lack of triggering for these events is confirmed with our statistical tests.

We apply our three statistical tests to all local earthquakes over magnitude 2 (the level of catalog completeness), using catalog subsets that span 1 day on either side of the earthquake of interest (Figure 3). For the largest events (M>4), which we expect generate local aftershocks, our results show the significance values for the Kolmogorov-Smirnov test, the Binary test and the Wilcoxon RankSum tests are, with the exception of one event, always less than 0.05. We therefore assume that for each of our statistical tests it is reasonable to consider significance values less than 0.05 (the 95% confidence level) to be an indication of earthquake triggering.

We next assess our qualitative estimates of the set of 38 local triggering (non-triggering) mainshocks using our three statistical tests. P-values for the statistical tests are calculated for 2-day windows around the mainshock. We find the statistical results agree well with our qualitative estimates: the triggering group returns significant values for 13 out of 15 events, and the non-triggering returns significant values 22 out of 23 events. Although our tests are likely not foolproof, we conclude that for our purposes, the qualitative and the statistical tests adequately identify local mainshock triggering and local mainshock non-triggering events.

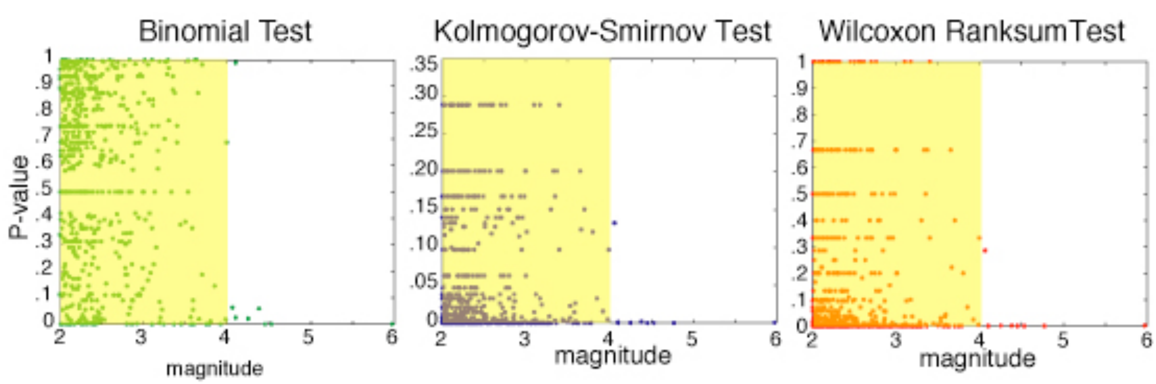

Figure 3: Statistical results for each of three statistical tests (see title) applied to all local earthquakes M>2.0 in the ANZA catalog. For local earthquakes above magnitude 4 (i.e., outside of yellow shaded region) almost all tests show significantly low values (indicating trigging and that aftershocks are expected).

Examining the spectra of our local mainshocks, we find that triggering events generally reach higher spectral amplitudes than non-triggering events, particularly for frequencies in the range of 0.1 to 10 Hz (Figure 4). Assuming that the same mechanism of triggering (i.e., seismic wave amplitude, frequency or duration) applies to both local and remote mainshocks, we apply the same tests, and assumed triggering thresholds, to assess the ability of 40 remote mainshocks (M>7.0) to trigger seismicity in southern California. We find no obvious signature of remote triggering.

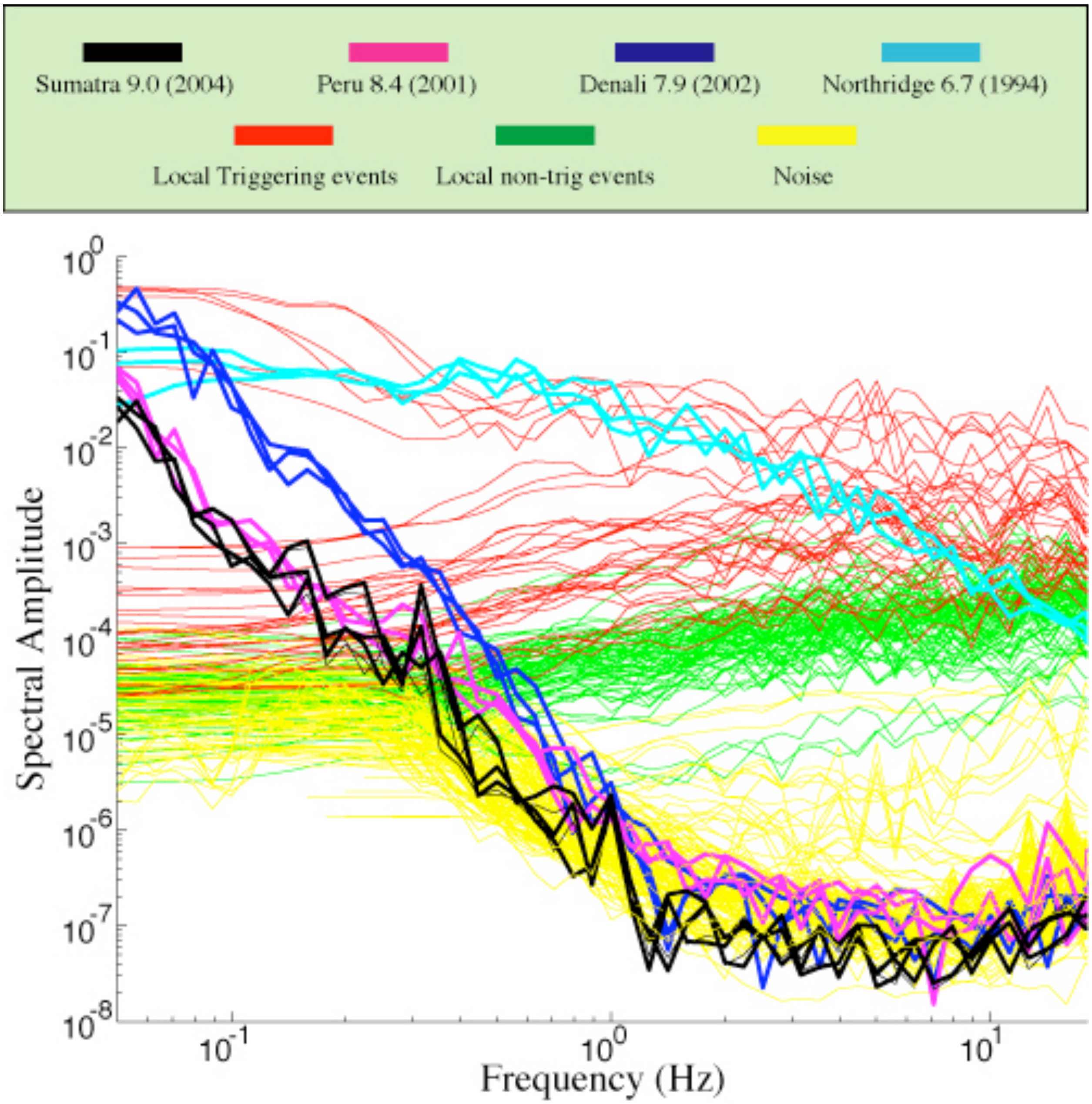

Figure 4: Earthquake spectra color-coded with respect to mainshock location and triggering ability based on statistical P-values from our three statistical tests (see legend).

We focus on a select four remote large earthquakes for our spectral characteristics study. These earthquakes include the: (1) Mw 6.7 Northridge, California, earthquake on 17 January, 1994; (2) M9 Sumatra-Andaman Islands, 24 December 2004; (3) M8.4 near the coast of Peru on 23 June 2001; (4) M7.9 Denali, Alaska, earthquake on 3 November, 2002. Comparing the spectral characteristics of local triggering mainshocks, local non-triggering mainshocks, and remote non-triggering mainshocks we reassess our threshold estimates. The results are complex, indicating that either: (1) the threshold triggering level is a combination of amplitude, frequency and duration; and/or (2) there is a time-to-failure component that we have not accounted for; and/or (3) remote and local events have different triggering mechanisms.

Conclusions. Our statistics have proven to be a valid tool in finding local mainshocks that trigger aftershock sequences. However, based on ANZA catalog data, we find no obvious signature of remote aftershock triggering in southern California. It is possible that remote does exist in the region, but it is difficult to detect. For local mainshocks, we find that triggering events generally reach higher spectral amplitudes than non-triggering events, particularly for frequencies in the range of 0.1 to 10 Hz. We conclude that are results are complex and several possibilities are likely:

(1) The threshold of triggering is a complex combination of amplitude, frequency, and duration.
(2) There is a time-to-failure component that we have not accounted for.
(3) Different triggering mechanisms apply for local and remote mainshocks.

3.0 Non-technical Summary

We hypothesize that large remote earthquakes trigger earthquakes in southern California. We assume the same mechanism of triggering applies to both local and remote mainshocks. We quantitatively estimate a triggering (non-triggering) threshold using local mainshocks, and find triggering events generally reach higher spectral amplitudes in the range of 0.1-10 Hz. Assessing ~40 remote mainshocks (M>7.0) we find no obvious signature of remote triggering. Comparing spectral characteristics, we conclude: (1) triggering is a complex combination of amplitude and frequency; and/or (2) there is a time-to-failure component we have not accounted for; and/or (3) remote and local events have different triggering mechanisms.

4.0 Reports published

Kane, D. L., D. Kilb, A. Berg and V. G. Martynov, Quantifying The Remote Triggering Capabilities Of Large Teleseismic Earthquakes Using 22 Years Of Data From The Anza Seismic Network Catalog (Southern California), JGR, Manuscript in preparation, 2006.

Kane, D.L., D. Kilb, A. Berg and V. Martynov, Quantifying The Remote Triggering Capabilities Of Large Teleseismic Earthquakes Using 22 Years Of Data From The Anza Seismic Network Catalog (Southern California), SSA, April 2005.

Kane, D., D. Kilb, A. Berg, and V. Martynov, What Components of the Mainshock Seismic Waves (Frequency, Amplitude, Duration) Triggers Aftershocks?, SCEC, September, 2005.

Kane, D., D. Kilb, A. Berg, and V. Martynov, Quantifying Properties Of Triggering (Non-Triggering) Local Mainshock/Aftershock Sequences: Establishing Thresholds That Can Be

Applied To Remote Mainshock/Aftershock Triggering Studies. EOS Trans. AGU, 86, Fall Meet. Suppl., Abstract S13B-0196.

5.0 Availability of seismic data

There is a world-wide-web home-page for the ANZA network, http://eqinfo.ucsd.edu, which provides maps and information about the database, stations, hardware configurations, including all network metadata in dataless seed volumes. We make special event web pages (http://eqinfo.ucsd.edu/special_events/index.html) for significant local, regional, and teleseismic events and maintain our *dbrecenteqs* webpages showing the latest seismicity on local, regional, and global scales (e.g., http://eqinfo.ucsd.edu/dbrecenteqs/anza/AZ_R2_map.html). The complete waveform data set of the ANZA network data consists of over 119,000 events. These data are stored in the standard CSS 3.0 format complete with instrument responses and they are accessible over the Internet. Additional information can be obtained by sending email to anzanet@epicenter.ucsd.edu. At present we provide data in the following formats: CSS 3.0, SAC, or SEED. The IRIS Data Management Center is maintaining a complete copy of our data archive (updated in real-time) and ANZA data is integrated into their standard FARM database and BUD real-time data distributions. Researchers from academia and industry have complete access to all ANZA data and results directly through UCSD or can access data through the SCEC Datacenter or the IRIS DMC.

Additional information can be found at:
http://eqinfo.ucsd.edu/~dkilb/dynamic.html