A waveform cluster analysis of 2003 Big-Bear Sequence

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Abstract

With the dense TriNet array in Southern California, the focal mechanism of a Mw ~ 4.0 or larger event can be easily determined using the full waveform data with relatively long periods (usually 5+ sec for Pnls and 10+ sec for surface waves), where imperfections of the velocity models are tolerated. However, the same strategy becomes less effective when applied to smaller events (Mw < 4.0) due to their poor signal to noise ratio (SNR). Better utilizing waveform data of these smaller events has to be pursued over much higher frequency bands for the sake of good SNR. However, any direct use of Green's functions is difficult since the complications caused by the path and site effects are far beyond the current model predictions. In this study, we first determine the focal mechanisms of more than 160 SC events with Mw ~ 3.60 or larger since 1998 following our improved "cut and paste" method. With these well-resolved long period solutions, we are able to study the un-modeled structural distortions on P waves over much higher frequency bands (up to 2 Hz), where the waveforms of an event as small as Mw ~ 2.0 can survive the noise. We found that the azimuthal patterns of P wave amplitude ratios between different events (Mw from 3.60 to 4.50) within a cluster well follow the differences in their various well-known focal mechanisms. This implies that whatever is causing the distortions on the amplitudes of P waves is relatively stationary and can be represented by a single "Amplitude Amplification Factor" (AAF) for the whole cluster at a large fraction of the stations. A detailed investigation is being conducted to learn more about the cause of the AAFs. However, the ratios between the AAFs on the radial component and those on the vertical component imply mainly a site effect. Taking advantage of these AAFs, we develop a new approach using high-frequency waveforms of P waves to determine the focal mechanisms of small events, as long as they occur near well-determined bigger events, which can be used for calibration purpose. We test our new method and check the short-period solutions against the long-period solutions, which shows remarkable consistency.

Source Mechanisms in Southern California

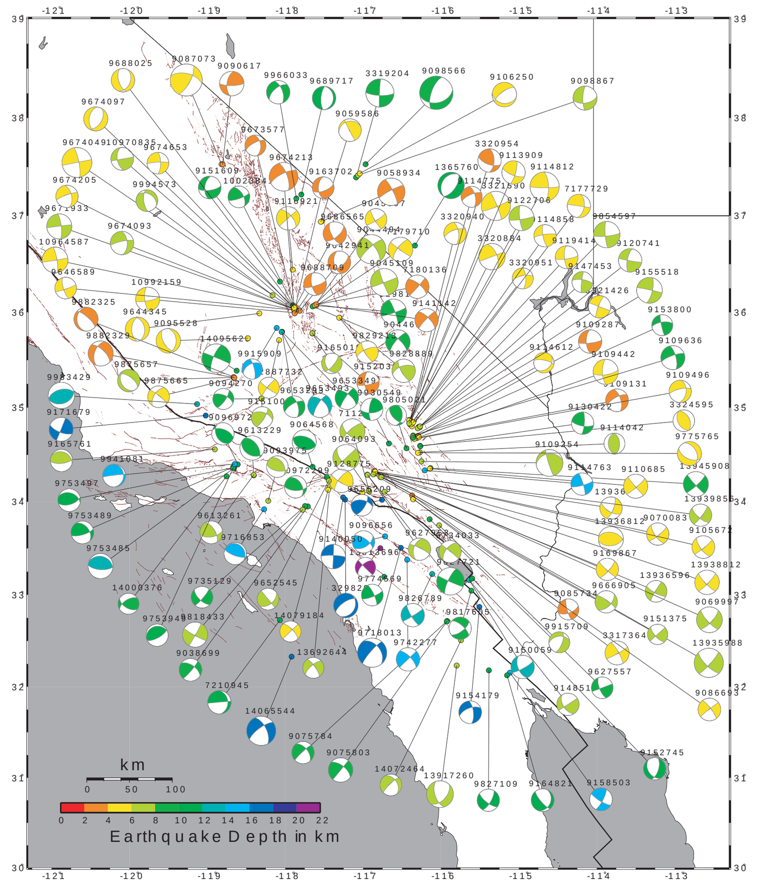

Figure 1

Figure 1 displays focal mechanisms and depths of recent SC events since 1998 with Mw ~ 4.0 and larger determined using full waveform data of relatively long periods. However, the same strategy fails when applied to smaller events. Although the long period signals from these smaller events are easily overwhelmed by noise, they are well recorded at high frequencies as shown in Figure 2, particularly for the early arriving P waves.

Figure 2 compares recordings over different periods at a single station (SBPX) from two clustered events of different sizes. The two events are located within 1 km, and the similarity between the high frequency records indicates their similar mechanisms.

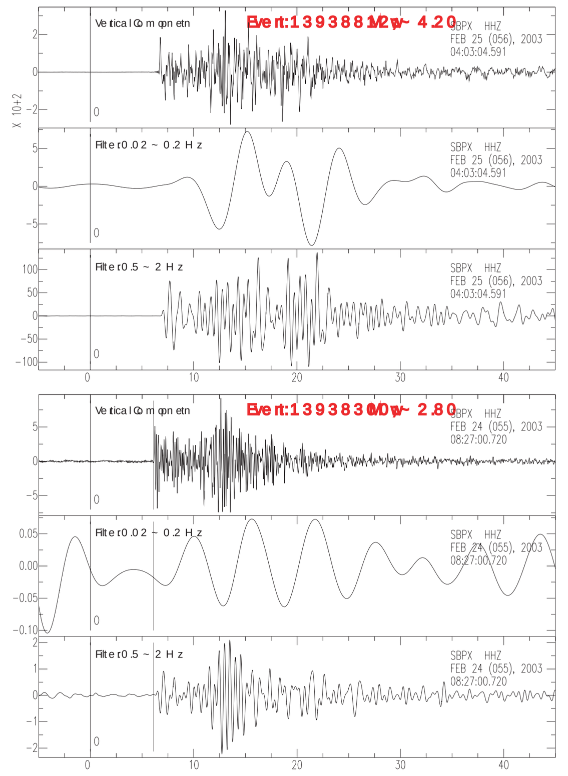

Figure 2

Site Amplification on P Waves

The most difficulty with modeling high frequency P wave is that its amplitude is easily distorted by un-modeled structural effects, mainly the site effects. Forward modeling of P waves from well-determined magnitude 4.0+ events enables us to learn more about this "distortion" on P waves. Figure 3 displays the waveform fits of first P arrivals over two different frequency bands, 0.125 – 0.5 Hz in (a) and 0.5 – 2 Hz in (b). The data are shown in black and the synthetics computed from a "gradient" SC model are in red. Note the comparisons shown here all have good cross-correlation values of 85% or larger, hence the "distortion" on P waves is mainly an amplitude amplification effect and can be well described by an "Amplitude Amplification Factor" (AAF) defined as $\sqrt{|d(t)|^2 / |s(t)|^2}$ where $d(t)$ and $s(t)$ denotes data and synthetics respectively. The AAFs become more significant as the frequency increases.

Meanwhile, comparison of the AAFs at the same stations derived from clustered events reveals remarkable similarity regardless of their different mechanisms. Figure 4 displays the averaged AAFs at each station from eight clustered Mw ~ 4.0 events shown in Figure 5a within the 2003 Big Bear sequence with circles indicating the corresponding variances defined as $\frac{\sqrt{\sum_{i=1,N}(AAF_i - \overline{AAF})^2}}{N\overline{AAF}}$.

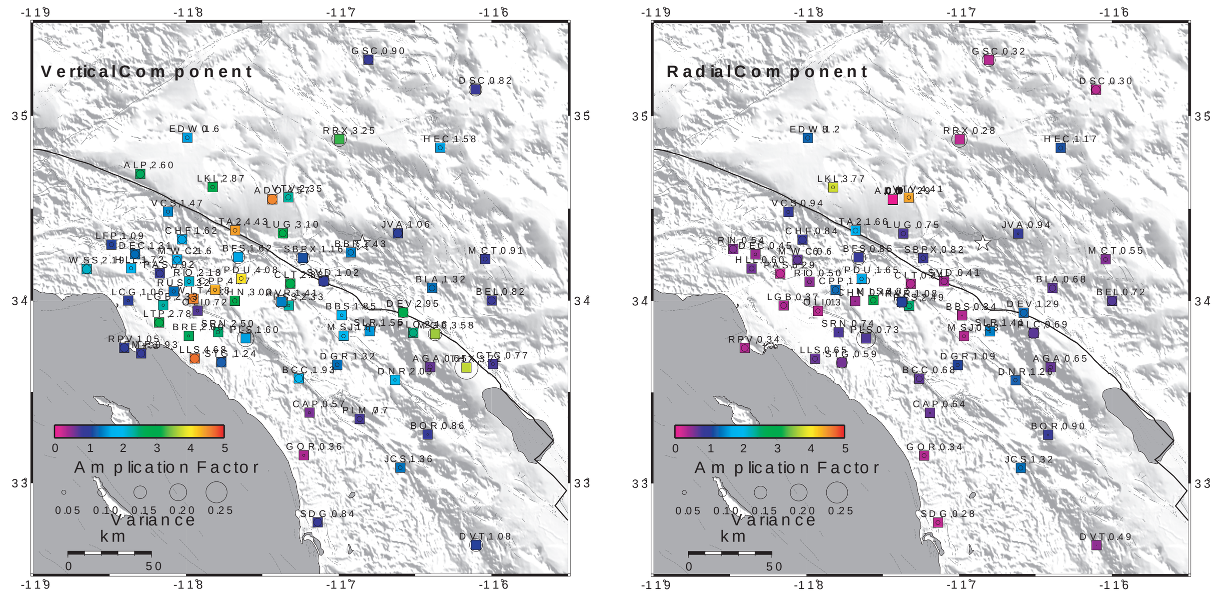

Figure 4

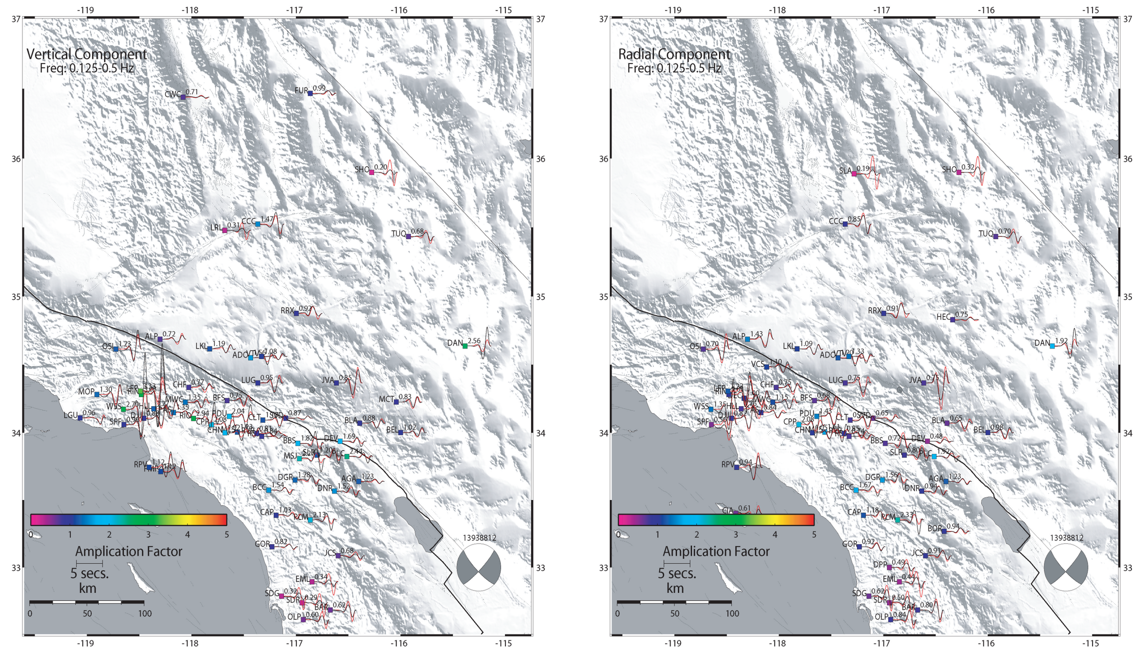

Figure 3a

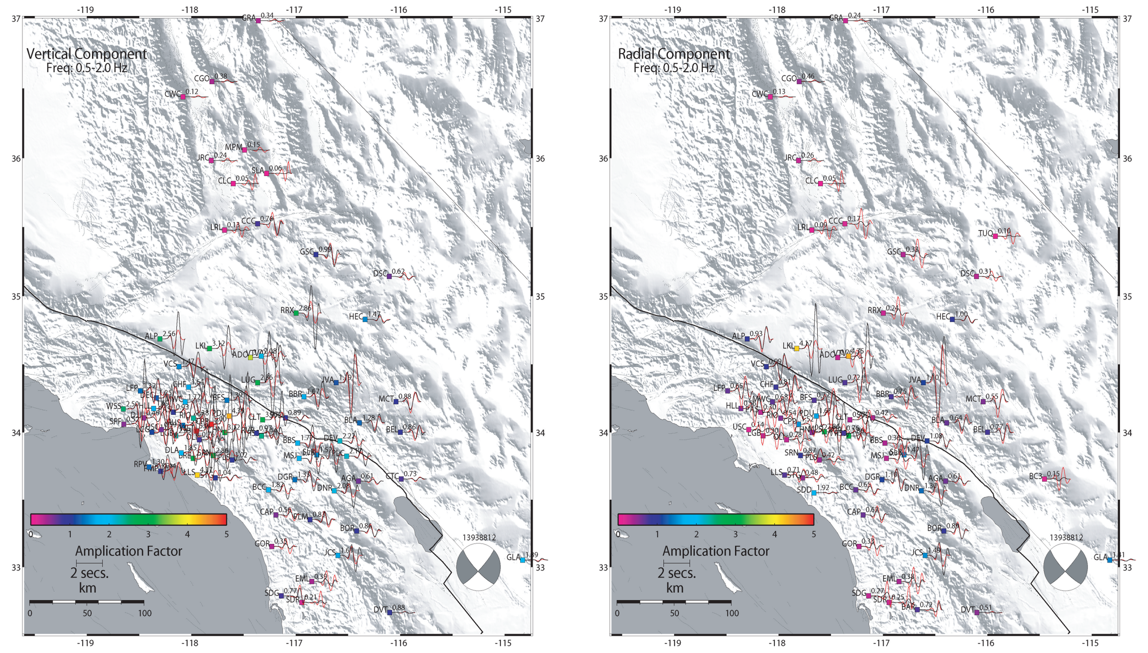

Figure 3b

Retrieving Focal Mechanisms using Corrected P waves

The fact that AAFs at a single station tends to be stable and mechanism independent for a small source region implies the AAFs derived from well-determined bigger events can be applied as empirical P wave amplitude corrections when modeling smaller events nearby. As a first test, we invert for the focal mechanisms of the eight events in Figure 5a by modeling high frequency first arriving P waves. The result is displayed in Figure 5.

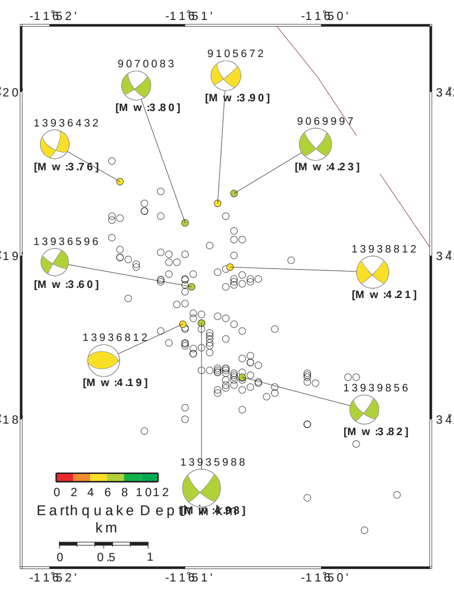

Figure 5a

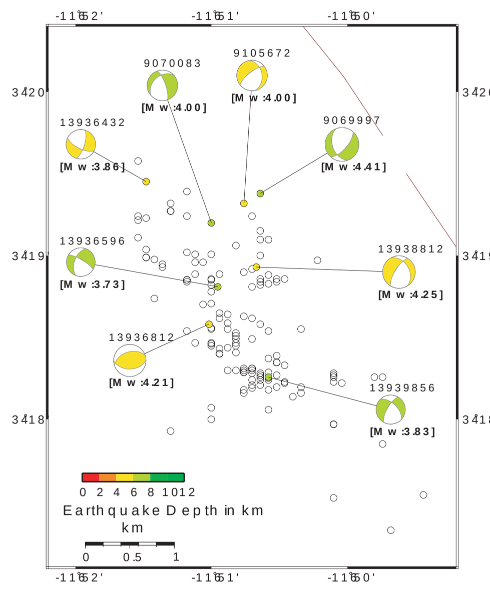

Figure 5b

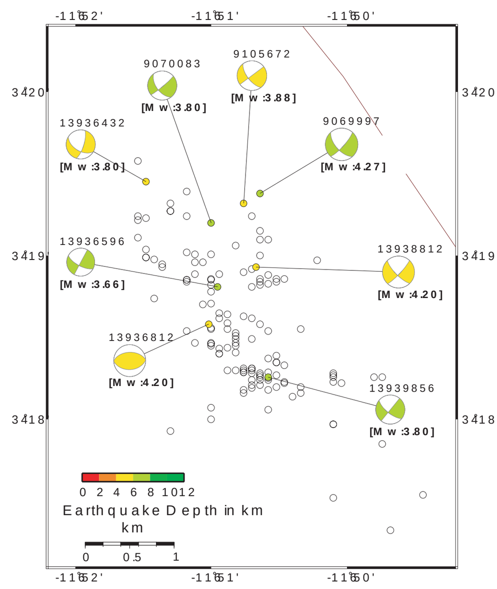

Figure 5c

Figure 5a displays the long period solutions of depths and mechanisms of eight Big Bear events, from which we derive the AAFs shown in Figure 4 for the whole source region.

Figure 5b displays the obtained mechanisms by inverting P waves without the AAFs corrected.

Figure 5c displays the obtained mechanisms by inverting P waves with the AAFs corrected. Comparison between these high frequency solutions with those long period solutions indicates high frequency P waves can be modeled to constrain the source mechanism. Meanwhile, applying amplitude corrections on P waves is crucial for a reliable magnitude estimate and obtaining a well-constrained solution. (more in Figure 6)

Depths and Focal Mechanisms of Events with M_L >2.0

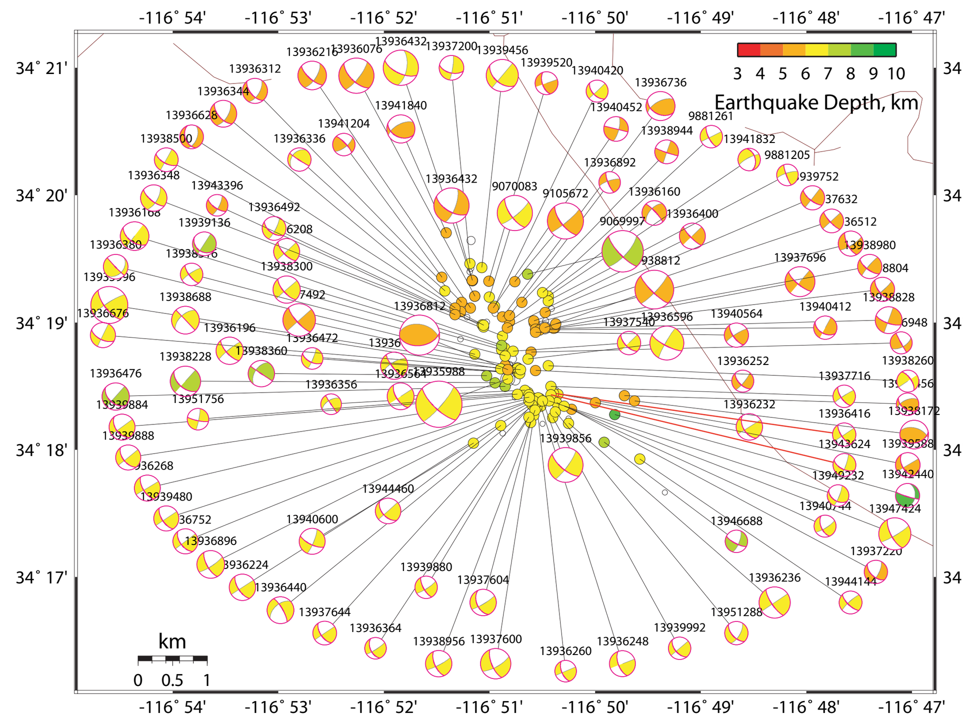

Figure 6a

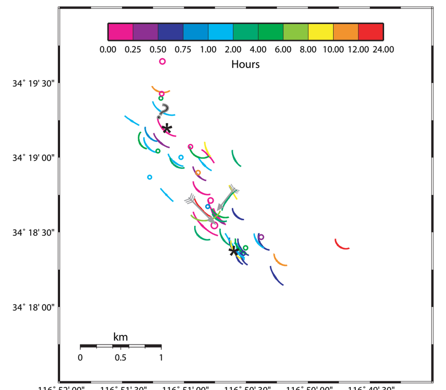

Figure 6b

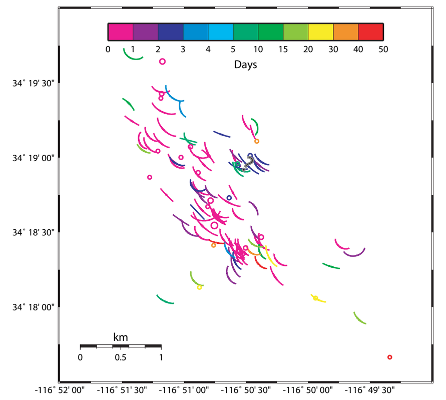

Figure 6c

Figure 6a. Depths and Focal mechanisms retrieved from modeling high frequency P-waves with amplitudes corrected. The events are placed at their double-difference locations by Chi and Hauksson. Figure 6b and c display the time evolution of the events for the first day (6b) and the first 50 days (b). The fault planes outlined in purple in figure 6a are used as plotting symbols. The arrows indicates simple unilatery ruptures (see the next section for details), and a question mark "?" denotes a bi-lateral fault, or simply a circular fault. Some events which are more complicated as doublets, or triplets ... are indicated by "*". Their rupture processes can be retrieved with a deconvolution approach.

Retrieving Rupture Directivity using an EGF Approach

With the first order source parameters recovered for the whole cluster, some second order effect, such as directivity can be examined using an EGF (empiracal Green's function) approach. During the course, the smallest events in the cluster are used as EGF's and the rupture processes of the bigger events can be obtained from a forward modeling approach (shown below) or an inversion approach (deconvolution).

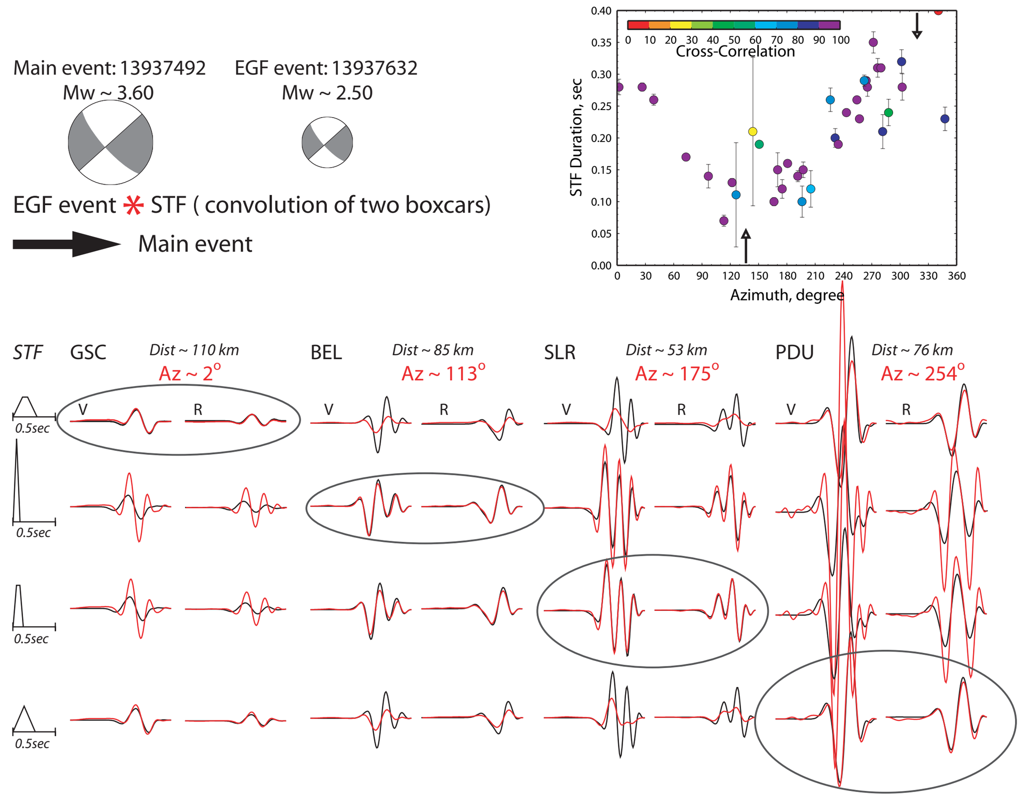

Figure 7

Figure 7. The relative source time functions (STF) of a magnitude ~3.60 event (13937492) were obtained in a grid search manner, which minimized the misfit between the observed P-waves (black) and the "synthetics" (red). The "synthetics" are calculated using the records from a smaller event (13937632) as EGF's. The waveform fits for four stations spanning the whole azimuthal range are shown as examples with the best fits circled corresponding to the optimal STF's. The azimuthal variation of the STF durations implies a unilateral rupture towards southeast.