2016 SCEC Final Report –Project 16104
Detailed analysis of earthquake directivity in the San Jacinto Fault Zone

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Summary

Several studies of the San Jacinto Fault Zone (SJFZ) over the last few years have found evidence for contrasts of seismic velocities along with asymmetric fault-zone damage patterns and additional observables that may result from a preferred rupture propagation direction (time domain signatures of directivity, along-strike asymmetry of aftershocks, reversed polarity secondary deformation structures near step overs). We proposed to perform a systematic seismological analysis of rupture velocity and directivity for M > 3 SJFZ earthquakes that can be compared to and augment the existing results. In 2016 we had two primary accomplishments. First, the fundamental EGF technique and MATLAB inversion toolbox were published in the SRL Electronic Seismologist section making them available to anyone who wants to use them. Second, we have made considerable progress in automating the EGF deconvolution based measurements of directivity effects for earthquakes in Southern California. We developed both an multi-EGF stacking method and routines for automatically choosing the duration of the source time function at each station. These improvements have resulted in roughly a factor of two increase in the number of available measurements for a given earthquake and the possibility of automating the technique for large datasets.

SCEC priorities:

The development of our automated directivity method is relevant for SCEC priorities 2a, 3c. The simplest representation of an earthquake that goes beyond a point source but is general enough to describe the length, width, directivity and duration of the rupture is termed the second moments. Methods for solving the inverse problem are well developed. This year we have made considerable progress in automating the measurement process. We are developing a catalog of 2nd moment estimates for moderate earthquakes on the San Jacinto Fault to connect with observations of asymmetric damage across the fault and 3D estimates of fault-zone rock types. Our results are also relevant to the 2016 FARM priority to asses the predictability of rupture directivity.

Intellectual Merit: Moderate earthquakes are not well suited for finite fault inversions because of a lack of geodetic data to help improve the uniqueness of the solution. However, their finite source properties are still well resolved from seismic data in a gross sense. The second moments inversion procedure is a relatively novel approach that quantifies the length, width, duration, and propagation velocity of a rupture in a well constrained (6 parameter) inverse problem. Our formulation is general, e.g. applicable to any earthquake without bias. The SJFZ dataset is unique in Southern California in terms of the density of on-scale recordings of magnitude 4-5 earthquakes. We are developing the first real catalog of rupture velocity estimates for earthquakes in this magnitude range.

Broader Impacts: A USC graduate student is being trained in the second moment inversion approach to carry this work forward. The MATLAB toolbox and inversion scheme have been made publicly available via SRL for any interested users.

Technical Report

Our goal is to estimate rupture directivity and velocity for a suite of moderate earthquakes on different fault segments of the SJFZ that have been well characterized in terms of their velocity structures, fault damage zones, and large earthquake rupture histories based on past geological and seismic studies. Our main approach for determining rupture directivity and velocity involves estimating the higher-order moments of the slip distribution as detailed in McGuire [2004a]. Unlike finite fault inversions with dozens to hundreds of parameters and assumptions, this approach estimates integral quantities that are well posed (only 5-6 independent parameters) and are free of assumptions like uniform rupture velocity and damping parameters. The analysis utilizes pairs of seismograms at a given station consisting of those for the target mainshock and data of a nearby smaller earthquake that serves an Empirical Green's Function (EGF) to correct for wave propagation effects between the source and station. The SJFZ PASSCAL deployment led by Frank Vernon and Yehuda Ben-Zion started in roughly late 2011. Since that time, there have been approximately 20 well recorded M>=3.0 earthquakes that are suitable for EGF deconvolutions. A second complementary approach will utilize more standard spectral methods combined with EGF to derive rupture directivities [e.g. [*Calderoni et al.*, 2013; *Calderoni et al.*, 2015; *Kane et al.*, 2013]].

The analysis with higher-order moments involves measuring the azimuthal variations in the apparent source duration of earthquakes using the EGF technique. The seismogram of the EGF event's P or S wave at a particular station is deconvolved from the same component seismogram from the mainshock. The function that results, termed the Apparent Source Time Function (ASTF), is a distorted version of the mainshock's moment rate function (Figure 1). If the rupture propagated towards the station, the ASTF will be compressed relative to the true moment-rate function. The extent of this distortion depends on the slowness vector of the particular phase as it leaves the source region. By deconvolving the EGF waveform, we hope to remove all propagation effects and image the azimuthal variation in the ASTFs for different station-phase pairs. See McGuire (2004, 2017) for more details of the technique.

The key obstacle to automating this method is in automating the EGF deconvolution. In 2016, USC student Haoran Meng worked on two improvements in this direction. First, he developed a procedure for automatically selecting, aligning, and stacking a number of M1-2 events as EGFs to produce a lower-noise EGF. For small EGFs, noise at low frequencies is often a key problem in having a stable deconvolution and the multi-EGF stacking approach appears to have improved our results. Secondly, he worked on automating the picking of the ASTF duration which is the key manual decision in the EGF deconvolution algorithm that we use. Figure 2 shows an example of an automatic pick of the duration based on the first derivative of the misfit curve.

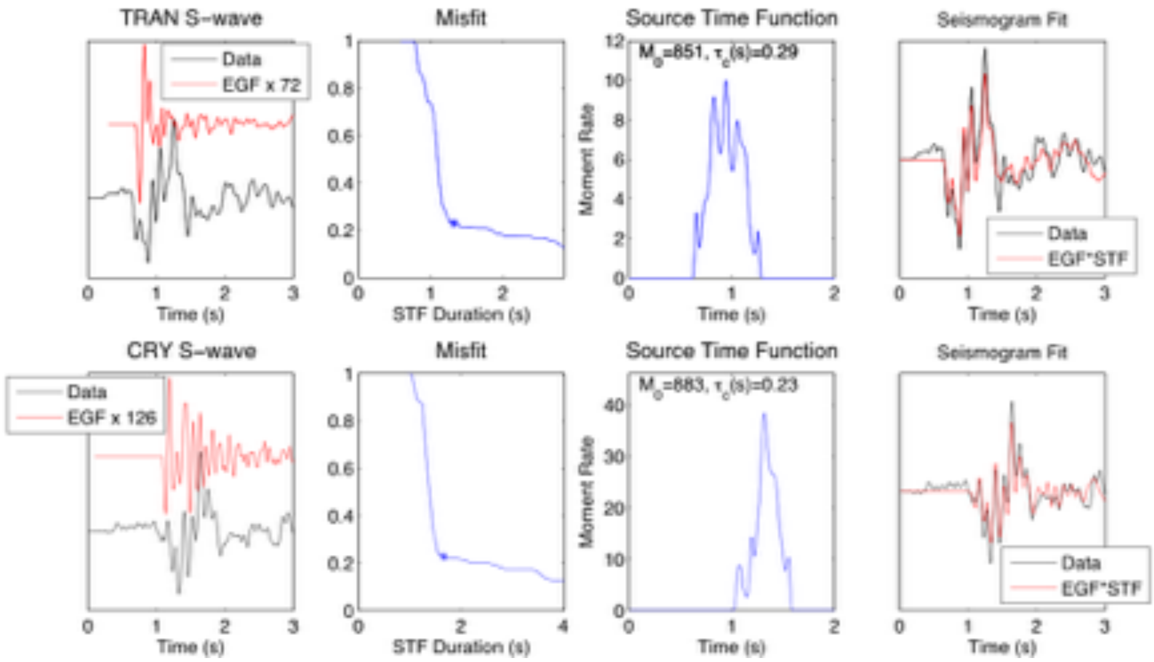

Figure 1. Examples of the EGF deconvolution measurements from the M5.1 March 2013 earthquake on the San Jacinto Fault for the S-waves recorded at stations TRAN (top row) and CRY (bottom row). The left panels show the raw velocity seismograms for the M5.1 and an EGF event. The next panel shows the tradeoff curve for waveform misfit versus source time function duration with the asterisks denoting our pick for the duration of the moment-rate function as seen by that S-wave. The third panels show the resulting moment-rate function (in units of the EGF event's moment). The fourth panels show the fit to the mainshock seismograms. Station TRAN sees a slightly longer ASTF (characteristic duration of 0.29 s) than CRY (0.23 seconds).

Figure 3 shows the results of applying the automated measurement technique to the data from a Mw 5.2 event in 2016. The combination of the stacking and automated picking resulted in approximately 30 measurements of the apparent duration. This is more than enough for a good second moments inversion (six parameters). The azimuthal variation in the durations is very coherent demonstrating the reliability of the automated measurements.

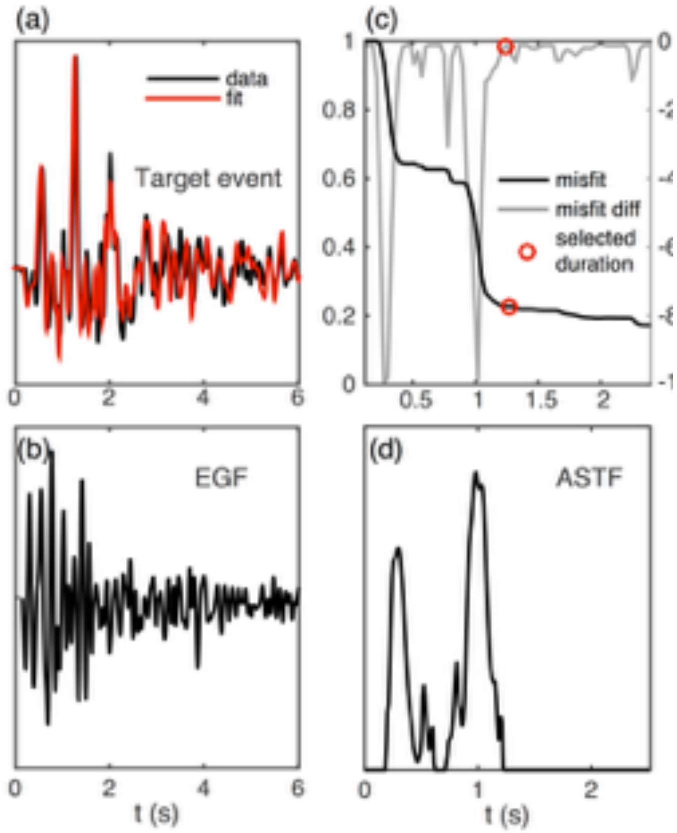

Figure 2. (a) Data and fit of the 2016 Mw 5.2 event at a particular station. (b) The stacked EGF. (c) The trade-off curve waveform of misfit versus source time function duration (black line) with the red circles denoting our pick for the duration of the moment-rate function as seen by that S wave. The gray curve denotes the first derivative of the misfit function. The picked duration (red circle) corresponds to a local maximum of this curve. (d) the resulting apparent source time function.

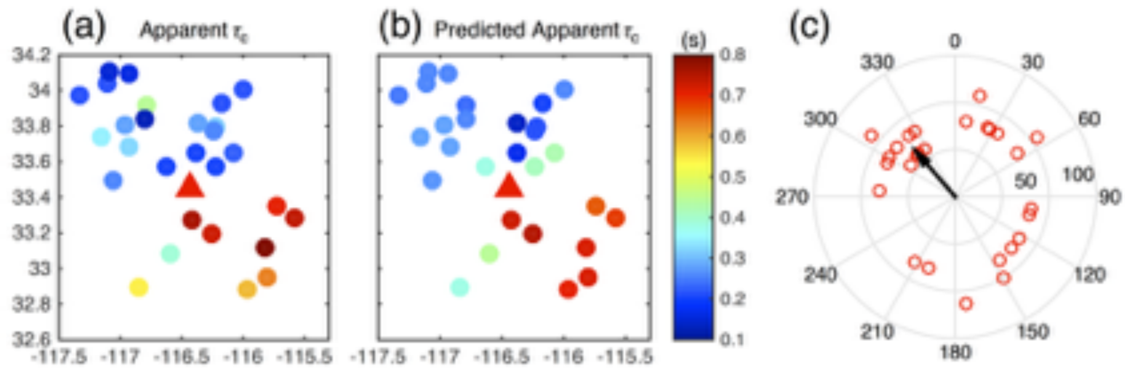

Figure 3. A) Automated measurements of the apparent duration at stations (circle) near the San Jacinto Fault zone for the 2013 M5.1 earthquake (triangle) Short durations (~0.2 s) at stations to the NW indicate the forward directivity direction. B) shows the fit to the measurements from the second moments inversion result which corresponds to unilateral rupture to the NW along the SJF with a rupture length of about 1.1 km.

Products supported by this SCEC funding

Papers:

McGuire, J. J., A MATLAB Toolbox for Estimating the Second Moments of Earthquake Ruptures, Seismological Research Letters, 88, 371-378, doi:10.1785/0220160170, 2017.

Abstracts:

Meng, Ben-Zion, McGuire, Estimating directivity and related source properties of moderate earthquakes in Southern California with second seismic moments utilizing stacked empirical Green's Functions, Abstract to the annual SSA meeting, 2016.

Meng, Ben-Zion, McGuire, Towards automated estimates of directivity and related source properties of small to moderate earthquakes in Southern California with second seismic moments, Abstract to the annual SCEC meeting, 2016.

Meng, Ben-Zion, McGuire, Towards automated estimates of directivity and related source properties of small to moderate earthquakes with second seismic moments, Abstract to the annual SSA meeting, 2017.

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