Improving Earthquake Stress drop Measurements – The Earthquakes Targeted by SAFOD

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Measuring the stress drop during an earthquake is fundamental to understanding the physics of the rupture process, in calculating seismic hazard, and to monitoring seismology. Although it is superficially simple to calculate an estimate of stress drop from the corner frequency of the radiated spectrum, it is much harder to be certain that measurements are reliable and accurate. The large number of seismological studies of earthquake stress drop, the high variability in results (~0.1-100 MPa), the large uncertainties, and the ongoing controversy of whether stress drop changes with earthquake magnitude are evidence for this. I use earthquakes in the 3 sequences targeted by the San Andreas Observatory at Depth (SAFOD), Parkfield, California to investigate resolution and uncertainties of earthquake stress drops calculated using an empirical Green's function (EGF) approach. The earthquakes are recorded by multiple borehole stations (some by SAFOD) and have abundant smaller earthquakes to use as EGFs.

The source spectra of earthquakes in cluster T1 (M~2.1) are well-fit by a circular source model. The corner frequencies correlate with those from previous studies implying that the inter-event variability is resolvable. The earthquakes have stress drops between 25 and 65 MPa, with a gradual increase before the 2004 M6 earthquake, followed by an immediate decrease, then a rapid return to previous levels. The spectra of the cluster T2 (M~1.9) include high frequency energy not fit by simple source models and so stress drops are unreliable, and probably under-estimated (1-20 MPa). The wide-bandwidth of the SAFOD recordings confirms this (see Figure). There is no correlation with previous studies, and inter-event variation is not resolvable. The earthquakes in the smallest magnitude cluster (M~1.8, T3) have the highest corner frequencies, but similar stress drops (4-120 MPa). The stress drops exhibit the same temporal variation as the first cluster, but there is poor correlation with surface measurement, probably because the frequency bandwidth of the latter is too limited.

I use earthquakes in cluster T1, to quantify the likely uncertainties to arise in less optimal settings. I use EGF earthquakes with a range of cross-correlation values and separation distances from the main earthquakes. The stress drop measurements decrease by a factor of three as the quality of the EGF assumption decreases; a good EGF must be located within about one source dimension of the large earthquake, with high cross-correlation. I sub-sample measurements of stress drop to investigate the uncertainties in studies where fewer stations or EGFs are available. I find that using multiple EGFs is a good alternative to multiple stations. To investigate the effects of limited frequency bandwidth, I re-calculate the corner frequencies after progressively decimating the sample rate. Decreasing the high-frequency limit of the bandwidth decreases the estimate of the corner frequency (and stress drop). The corner frequency may be underestimated if it is within a factor of three of the maximum signal frequency.

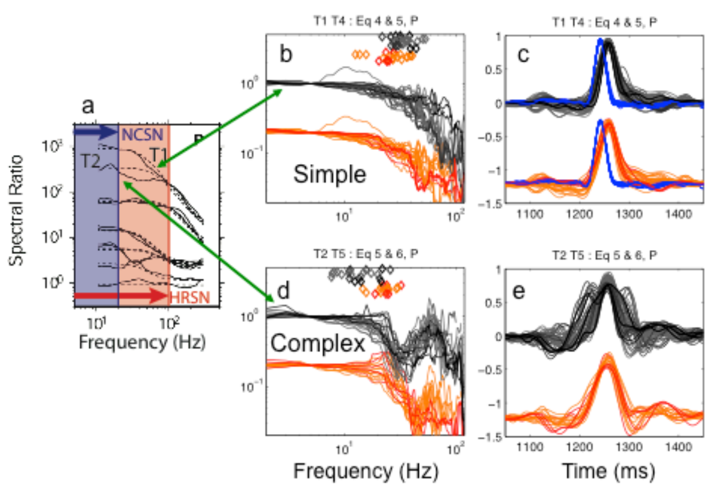

Figure: Simple and complex sources recorded in different frequency bandwidths. (a) Source spectra of a group of earthquakes recorded at depth by SAFOD, after Imanishi and Ellsworth (2006). The largest earthquake is in cluster T1, and the second largest in T2, of Abercrombie (2014). The blue shading and arrow represent the frequency range of the surface stations, the red shading and arrow those of the borehole HRSN, Abercrombie (2014). The green arrows link these to the same events in (b) & (d). (b) & (d) show source spectra, and (c) & (e) show source time functions, for two events from each of cluster T1 and T2, respectively. For the simple sources in cluster T1, all studies obtain consistent results. For the complex sources in cluster T2 (high frequency bump in spectra, complex source time function) different studies obtain inconsistent measurements of corner frequency because of the inadequate model and different frequency ranges.

Abercrombie, R. E. (2014), *Geophys. Res. Lett.*, doi:10.1002/2014GL062079.
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