LLNL-CONF-490224

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July 8, 2011

Monitoring Research Review
Tucson, AZ, United States
September 13, 2011 through September 15, 2011

IMPROVED HIGH FREQUENCY DISCRIMINATION: A NEW APPROACH TO CORRECT FOR REGIONAL SOURCE SCALING VARIATIONS

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Sponsored by the Air Force Research Laboratory

Award No. FA8718-09-C-0014

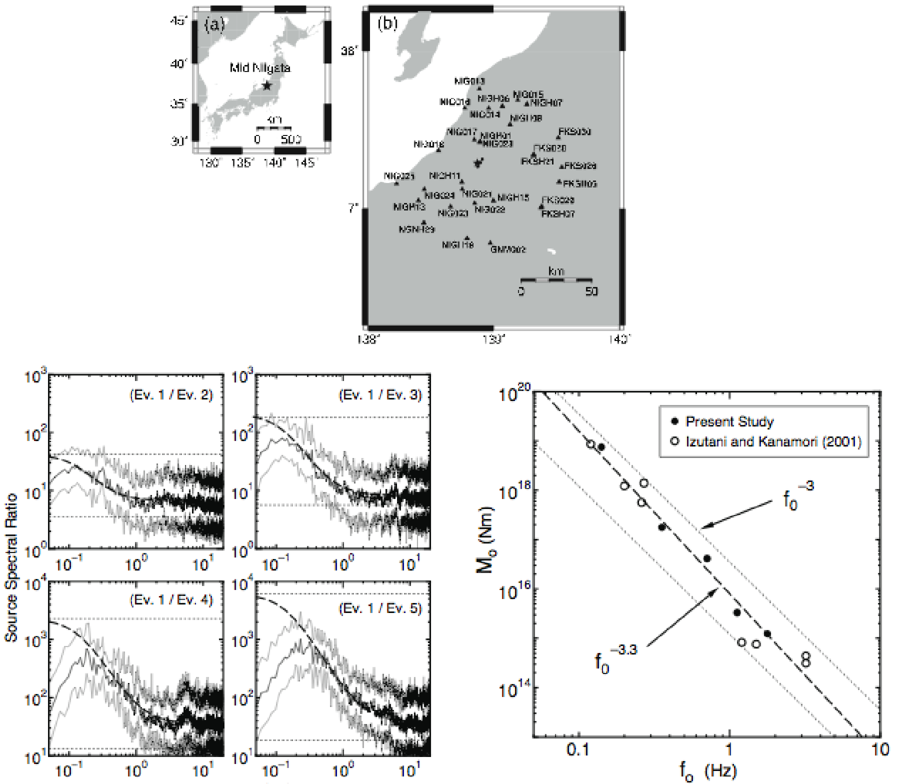
Proposal No. BAA09-74

ABSTRACT

The MDAC methodology of *Walter and Taylor* [2001] corrects ratios of regional phase amplitudes for source, path, and site effects and has proven effective for event identification. The MDAC formulation includes a term that describes the earthquake source scaling as the apparent stress variation with magnitude. In almost all regions we find evidence for non-self similar source scaling. The behavior of earthquake source scaling has been the topic of significant debate in the earthquake source community mainly because current methods require substantial path, site, and source radiation pattern corrections that ultimately yield large variance of the apparent stress. A new, state-of-the-art methodology, the coda ratio technique, was developed by *Mayeda et al*. [2007] and provides unprecedented estimates for corner frequency and apparent stress drop, roughly 3 times less variance than conventional methods using a minimal number of stations and events. Within broad regions it is likely that apparent stress varies with location due to lateral variations in regional stress field, rheology, and degree of tectonic activity. Currently MDAC assumes a single linear apparent stress scaling with moment for a given region, but if we have *a priori* information on lateral variations in apparent stress, then we can use this to lower the amplitude ratio scatter and increase the discrimination capability. The coda ratio methodology has been applied to a variety of tectonic regions and we find clear distinctions between each of them. In this paper, we compare and contrast our findings for a variety of earthquake sequences using the new methodology.

Introduction:

Conventional direct wave methods of estimating apparent and static stress drop have significant errors, so large in fact that the earthquake source community is divided roughly 50-50 on whether or not self-similarity even holds, a fundamental assumption in many earthquake source models that have been used for roughly 4 decades [*i.e., Aki*, 1967, *Brune*, 1970]. One such method involves frequency-dependent path, site, and radiation pattern corrections to get at the source spectra. More often than not, these approaches result in corrections that are so large, the resulting estimates on radiated energy and corner frequency are questionable [see reviews by *Abercrombie et al.,* 2004; *Ide and Beroza*, 2001]. One attempt to alleviate some of the problems is to take source ratios of closely spaced events of different magnitude. These can be either a time-domain deconvolution to extract the source-time function [*e.g.*, *Hough*, 1997] or source spectral ratios [*e.g.*, *Izutani and Kanamori*, 2001]. Figure 1 shows a typical *S*-wave source ratio result from *Izutani* [2005] for the 2004 M_w 6.7 Niigata, Japan earthquake and selected co-located aftershocks. In spite of a plethora of seismic stations that surround the source region, the scatter on the ratio is huge and estimating corner frequency and apparent stress will have large errors.



From Izutani (2005)

Figure 1. From *Izutani* [2005] showing direct *S*-wave spectral ratios (lower left) for the 2004 Niigata earthquake in Japan (Ev. 1) relative to four other smaller aftershocks (Ev. 2,3,4,5). Dashed line shows average ratio and dark lines represent +/- 1 σ from the stations shown in above map. Moment versus corner frequency exhibits non-constant scaling ($f^{-3.3}$) however no error estimates are shown, but are presumably large.

In addition to seismic hazard prediction and fundamental research on faulting dynamics, an *a priori* knowledge of apparent stress drop can have a profound influence on high-frequency seismic discrimination. The Magnitude and Distance Amplitude Correction (MDAC) methodology of *Walter and Taylor* [2001] removes source, path, and site effects from regional phase amplitudes ratios used for regional seismic discrimination (Figure 2).

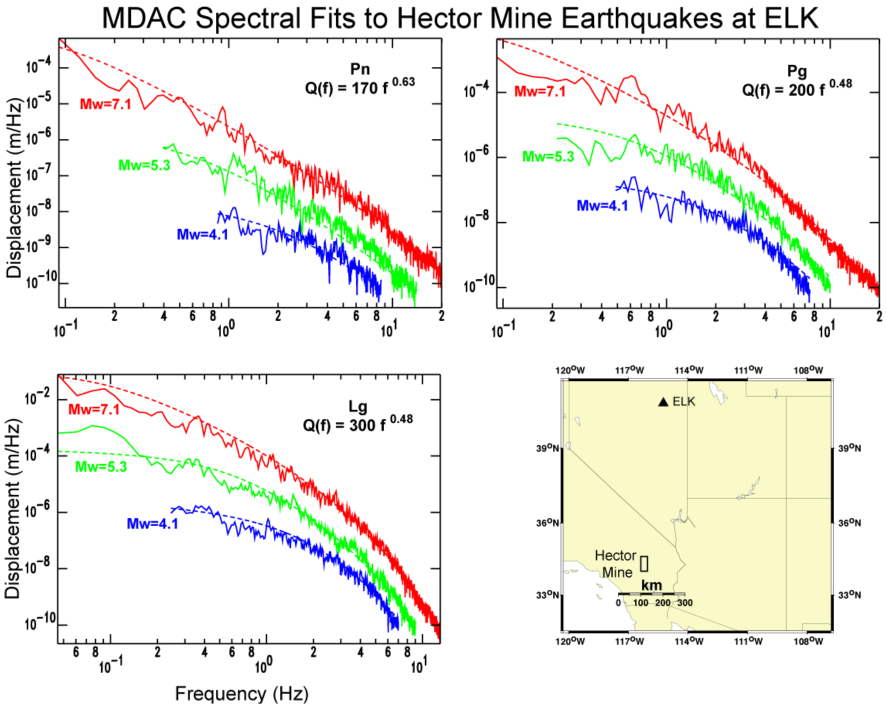


Figure 2. Example of MDAC fits (dashed lines) to observed regional phase amplitude spectra (solid lines) at station ELK for three different size earthquakes in the Hector Mine sequence. MDAC uses an earthquake source spectral model along with path and site corrections to predict amplitudes. In the example shown, part of the path effect is a power law attenuation model that is different for each regional phase type. The MDAC predicted amplitudes are removed from the observed amplitudes leaving residuals that are corrected for source, path and site effects, and ready for use as discriminants, such as in high frequency *P/S* MDAC residual ratios.

MDAC works by correcting observed amplitudes at each frequency by subtracting the predicted earthquake amplitudes based on the distance and magnitude of the source. This requires an independent estimate of the seismic moment, which is usually obtained from regional coda envelopes. Implicit in the MDAC formulation is a term that describes the earthquake source spectra in terms of its apparent stress [*e.g., Wyss*, 1970]. For a given region we usually use either a fixed average apparent stress, or a linear apparent stress relation that increases with seismic moment. We search for the choice that best reduces the earthquake scatter. For example in Figure 3 in the Korea region we use an apparent stress that increases with seismic moment. Despite allowing for this scaling there remains significant scatter in the earthquake population. One source of this scatter may be spatial variations in the apparent stress related to changes in the geology, tectonics and regional stress field.

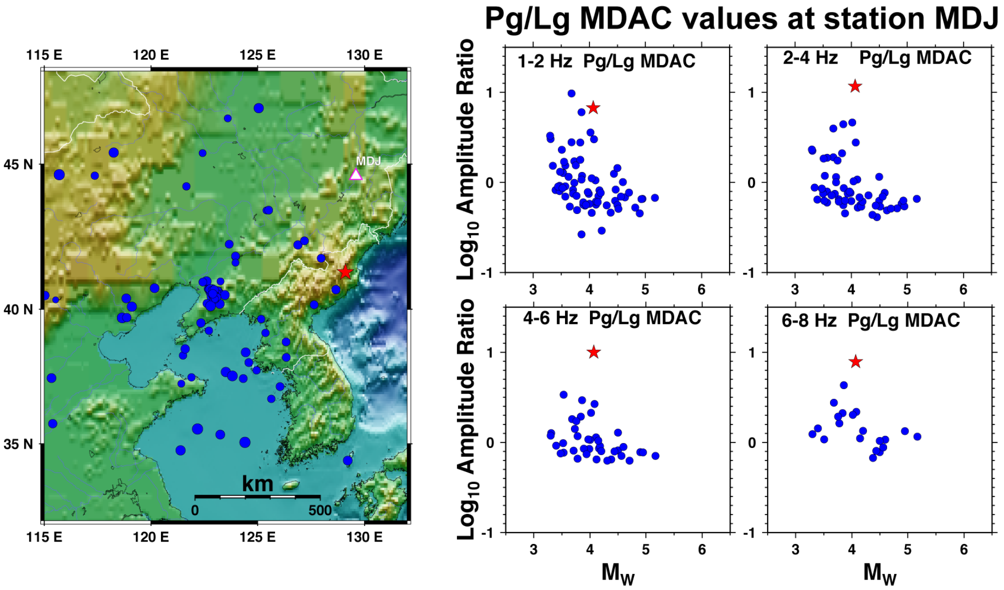


Figure 3. Example of local and regional phase ratios from MDAC for the Yellow Sea/Korean Peninsula for earthquakes (blue circles) and explosions (red star) at station MDJ. Notice the earthquake scatter in all the high frequency discriminants is significant.

To date, in regions of monitoring interest, the apparent stress scaling has been obtained usually through a grid-search or by geophysical analogy (see equation 3). What is found in almost all regions is that apparent stress appears to increase with magnitude, indicating a non-self similar source scaling. The estimation of earthquake source scaling in general, has been the topic of large debate in the earthquake source community mainly because current methods require substantial path, site, and source radiation pattern corrections that ultimately yield large variance in apparent stress. A new, state-of-the-art methodology has been developed by *Mayeda et al.* [2007] which provides unprecedented estimates in static and apparent stress drop, roughly 3 times less variance than conventional methods using a minimal number of stations and events. For the broad area, there is every reason to believe that lateral variations in source scaling exist due to lateral variations in regional stress field, rheology, and degree of tectonic activity.

Methodology:

Assuming the simple single corner frequency source model [*Aki*, 1967; *Brune*, 1970] used in MDAC, the ratio of the moment-rate functions for two events (1 and 2) is given by,

$$\frac{\dot{M}_1(\omega)}{\dot{M}_2(\omega)} = \frac{M_{0_1}\left[1+\left(\omega/\omega_{c_2}\right)^2\right]^{p/2}}{M_{0_2}\left[1+\left(\omega/\omega_{c_1}\right)^2\right]^{p/2}} \qquad (1)$$

where M_0 is the seismic moment and ω_c is the angular corner frequency ($2\pi f_c$) and p is the high frequency decay rate. At the low frequency limit the source ratio shown in equation 1 is proportional to the ratio of the seismic moments $\left[M_{0_1}/M_{0_2}\right]$, whereas at the high frequency limit, equation 1 is asymptotic to $\left[M_{0_1}/M_{0_2}\right]^{\left(1-\frac{p}{3}\right)}$ under self-similarity. If we follow the usual *Brune* [1970] omega-square model and set p=2, the exponent of the high-frequency ratio becomes 1/3. However, it has been proposed by *Kanamori and Rivera* [2004] that the scaling between moment and corner frequency could take on the form,

$$M_o \sim \omega_c^{-(3+\varepsilon)} \qquad (2)$$

where e represents the deviation from self-similarity and is usually thought to be a small positive number. For example, *Walter et al.* [2006] found e to be close to 0.5 for the Hector Mine mainshock and its aftershocks using independent spectral methods. For the current study we use the source spectrum portion of the Magnitude Distance Amplitude Correction (MDAC) methodology of *Walter and Taylor* [2001], which allows for the variation of the corner frequency that does not have to be self-similar. For example,

$$\omega_c = \left(\frac{k\sigma_a}{M_0}\right)^{1/3} \text{ and } \sigma_a = \sigma'_a\left(\frac{M_0}{M'_0}\right)^{\psi} \text{ and } \psi = \frac{\varepsilon}{\varepsilon+3} \qquad (3)$$

where σ_a is the apparent stress [*Wyss*, 1970], σ'_a and M'_0 are the apparent stress and seismic moment of the reference event, and ψ is a scaling parameter. For constant apparent stress, $\psi = 0$ and e =0, however, *Mayeda and Walter* [1996] found ψ=0.25 for moderate to large earthquakes in the western United States. By using the corner frequency defined in (3) into equation 1, we can apply a grid search to find the parameters that best fit the spectral ratio data.

As discussed earlier, the during previous year we processed the following sequences for source scaling as part of our plan to study as many varied geophysical regions as possible: Parkfield, CA; San Simeon, Ca; Wells, NV.

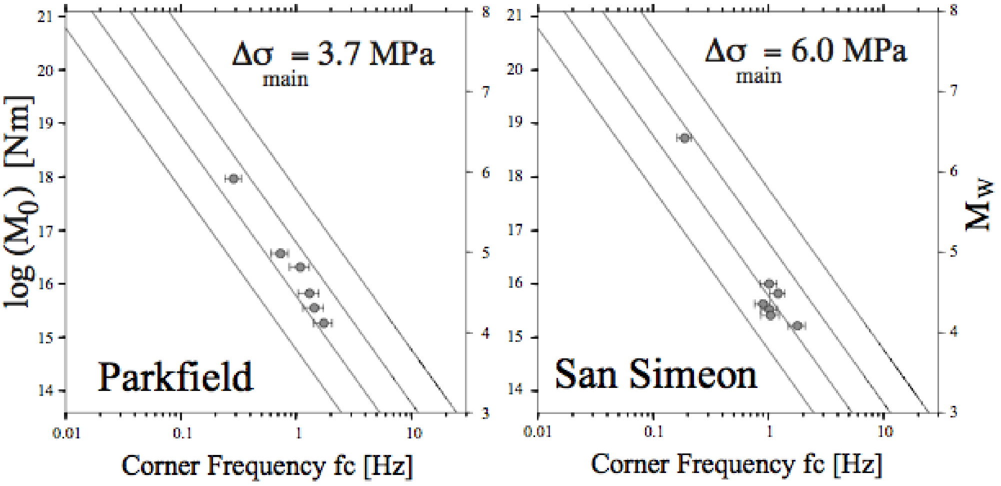


Figure 4a and 4b. Corner frequency vs moment scaling is shown for two sequences in southern California using the coda ratio methodology. The first is the Mw 6.0 2004 Parkfield earthquake and the Mw 6.5 San Simeon earthquake. We see that the Parkfield sequence obeys similarity unlike the San Simeon sequence.

Our results for Parkfield are in some ways a relief since up to this point, virtually all sequences that we have studied were non-self similar. We were wondering if somehow the methodology was biased but this sequence shows that this is not the case. Finally, we completed calibration of the Mw 6.0 2008 Wells, Nevada earthquake and show the results in Figure 5 from Mayeda et al., 2010.

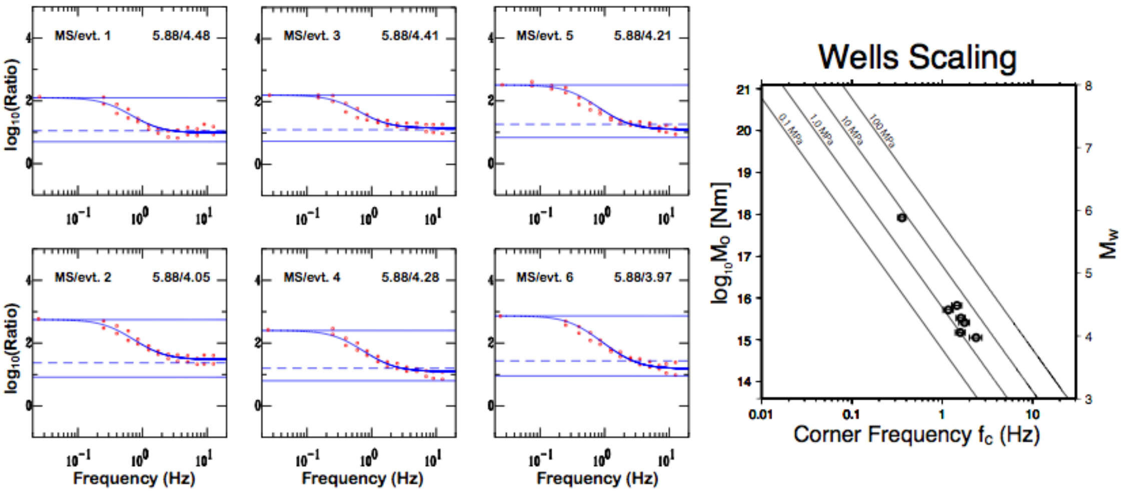


Figure 5. Spectral ratio fits where top horizontal solid line represents the theoretical low-frequency limit based upon the two events' moment estimates, the bottom solid line represents the theoretical high-frequency limit assuming self-similarity, and dashed line is when p=1.5 in equation 1. Estimates of f_c and ± 1 standard deviation error bars for the Wells mainshock and 6 aftershocks. Lines represent constant $\Delta\sigma_B$ in MPa.

<u>Research and Work Completed During this past Year</u>:

This past year we resumed our study on source scaling and considered the April 4, 2010 Baja M_w 7.2 strike-slip event which was well recorded by broadband stations throughout southern California. This sequence along with others in southern California was the focus of a recent SSA talk on April 14, 2011. This sequence was an interesting test because a number of the aftershocks were of mixed focal mechanisms, namely normal and strike-slip. As found with other sequences, the high frequency spectral levels do not reach the theoretically predicted level if the sources obey self-similarity.

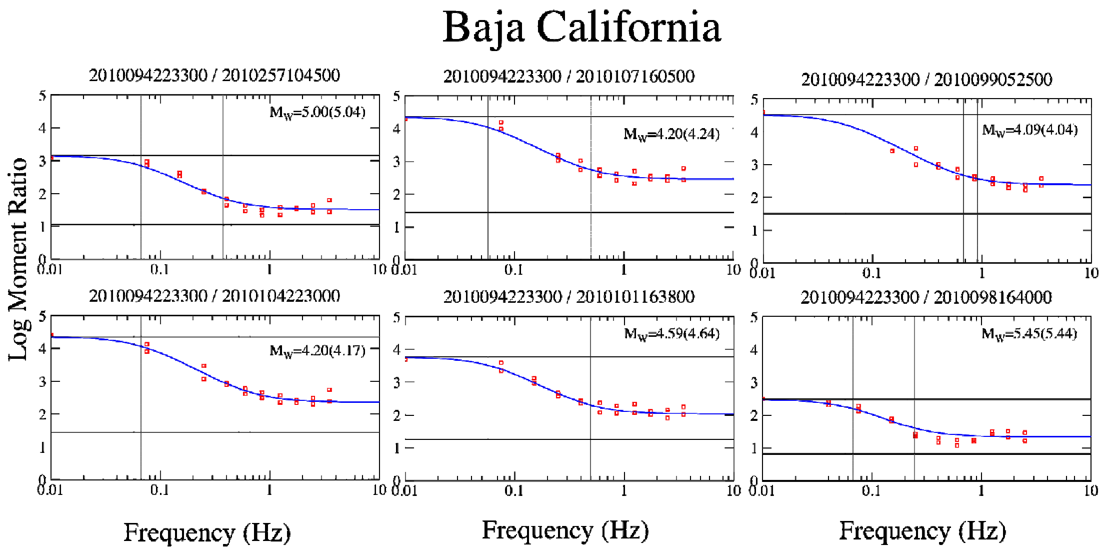


Figure 6. Baja spectral ratio fits where top horizontal solid line represents the theoretical low-frequency limit based upon the two events' moment estimates, the bottom solid line represents the theoretical high-frequency limit assuming self-similarity, and dashed line is when p=1.5 in equation 1. Estimates of f_c and ± 1 standard deviation error bars for the Baja mainshock and 6 aftershocks. Lines represent constant $\Delta\sigma_B$ in MPa.

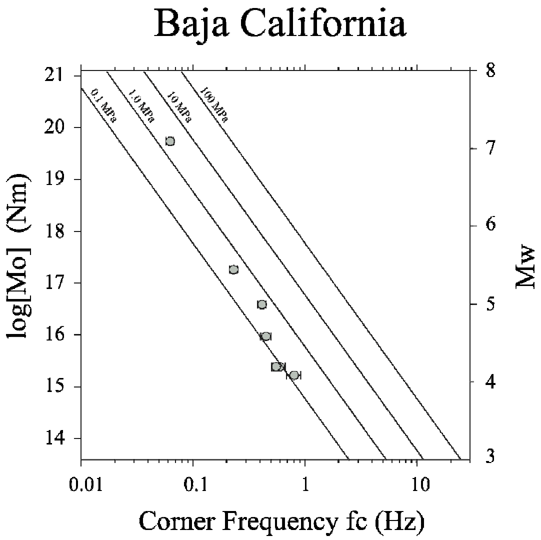


Figure 7. Corner frequency estimates exhibit very low variance for this sequence and also shows a strong decrease in Brune stress drop with decreasing magnitude.

Conclusions and Future Work:

We are now back on track and have collected waveform data from the Christchurch, New Zealand sequence and will start comparing sequences based upon their faulting mechanisms. Other sequences that we will consider are smaller clusters in the middle east region. Again, we highlight the advantages of the methodology below:

- The coda is not sensitive to lateral variations in structure and effectively homogenizes its energy over a broad area
- Directivity and source radiation pattern will not affect the coda envelope amplitude measurement due to azimuthal averaging
- Unlike direct wave methods that require large amounts of data to average, the coda method can use a minimal number of events and stations.
- The methodology does not require path and site corrections.
- Large amounts of data have already been archived by LLNL and Weston in the regions of monitoring interest and coda envelope shape and velocity parameters have already been derived for all the regions.

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