# CALIBRATION OF ATTENUATION STRUCTURE IN EURASIA TO IMPROVE DISCRIMINATION AND YIELD

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## ABSTRACT

It is well known that one-dimensional models do a poor job of predicting both regional amplitudes and travel-times over large and tectonically complicated regions. As a result regional discrimination methods (e.g., high-frequency P/S, $M_s$:$m_b$) and magnitude estimates (e.g. coda magnitude) can perform poorly when applied over broad regions. The careful calibration of the earth's attenuation structure is critical to the universal application of event discrimination and yield estimation methods down to very small magnitudes. We have developed and are continuing to improve methods that use the direct amplitudes of the major regional phases (Pn, Pg, Sn, Lg) to determine the attenuation structure of the lithosphere in the Middle East and East Asia. The amplitudes are inverted simultaneously for attenuation parameters (Qp, Qs) of the crust and upper mantle, event source terms, and station site terms, which ensures that parameters, such as seismic moment and apparent stress, are consistent across each phase. We are using these models to correct observed amplitudes for path-dependent variations due to earth structure. Amplitude corrections can be demonstrated to improve high-frequency regional P/S discriminants (e.g., Pn/Lg, Pg/Lg, Pn/Sn) by reducing scatter in the earthquake population and increasing separation from explosions. Better path corrections allow the extension of discrimination to lower frequencies so long as true source differences between events exist at those frequencies.

We are applying similar methodologies to coda amplitudes with the goal of improving magnitude and yield estimation. While coda waves average over large regions and have less variation than direct phases, they too are subject to path-dependent variations in amplitudes. Furthermore, they can be sensitive to changes in the dominant phase (e.g., Sn vs. Lg) over broad regions. We report on our efforts for the 2-D calibration of coda amplitudes in the Middle East. A similar calibration of attenuation structure can be used to improve surface wave amplitudes used in the $M_s$:$m_b$ discriminant. For small events correcting for attenuation is very important for the regional analog surface wave magnitude $M_s$(VMAX) because amplitude variations are significantly higher at 7 seconds than at 20 seconds.

All of these attenuation models and their associated source models can be used to predict expected signal-to-noise values for all possible source regions for a given station. We are making use of the models and earthquake source spectral models to create magnitude thresholds maps for regional discriminants such as P/S. This is a natural way to incorporate lithospheric structure into better and more realistic capability assessments.

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14. ABSTRACT

**It is well known that one-dimensional models do a poor job of predicting both regional amplitudes and travel-times over large and tectonically complicated regions. As a result regional discrimination methods (e.g., high-frequency P/S, Ms:mb) and magnitude estimates (e.g. coda magnitude) can perform poorly when applied over broad regions. The careful calibration of the earth?s attenuation structure is critical to the universal application of event discrimination and yield estimation methods down to very small magnitudes. We have developed and are continuing to improve methods that use the direct amplitudes of the major regional phases (Pn, Pg, Sn, Lg) to determine the attenuation structure of the lithosphere in the Middle East and East Asia. The amplitudes are inverted simultaneously for attenuation parameters (Qp, Qs) of the crust and upper mantle, event source terms, and station site terms, which ensures that parameters, such as seismic moment and apparent stress, are consistent across each phase. We are using these models to correct observed amplitudes for path-dependent variations due to earth structure. Amplitude corrections can be demonstrated to improve high-frequency regional P/S discriminants (e.g., Pn/Lg, Pg/Lg, Pn/Sn) by reducing scatter in the earthquake population and increasing separation from explosions. Better path corrections allow the extension of discrimination to lower frequencies so long as true source differences between events exist at those frequencies. We are applying similar methodologies to coda amplitudes with the goal of improving magnitude and yield estimation. While coda waves average over large regions and have less variation than direct phases, they too are subject to path-dependent variations in amplitudes. Furthermore, they can be sensitive to changes in the dominant phase (e.g., Sn vs. Lg) over broad regions. We report on our efforts for the 2-D calibration of coda amplitudes in the Middle East. A similar calibration of attenuation structure can be used to improve surface wave amplitudes used in the Ms:mb discriminant. For small events correcting for attenuation is very important for the regional analog surface wave magnitude Ms(VMAX) because amplitude variations are significantly higher at 7 seconds than at 20 seconds. All of these attenuation models and their associated source models can be used to predict expected signalto- noise values for all possible source regions for a given station. We are making use of the models and earthquake source spectral models to create magnitude thresholds maps for regional discriminants such as P/S. This is a natural way to incorporate lithospheric structure into better and more realistic capability assessments.**

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## OBJECTIVES

Our objective is to develop and calibrate methodologies to improve event discrimination and yield estimation down to small magnitudes and for broad regions. Earthquake-explosion discrimination using high-frequency regional P/S amplitude ratios over large and tectonically complicated regions can only be accomplished by properly calibrating the regional attenuation structure. Similar calibration of attenuation structure to coda amplitudes is also necessary to improve the magnitude and yield estimation of smaller events in these complicated regions. Lastly, we will be using the attenuation information in capability assessment.

## RESEARCH ACCOMPLISHED

In the past year, we have accomplished a number of research goals in regional amplitude tomography, regional discrimination, coda tomography, and capability assessment.

### Regional Amplitude Tomography

Lawrence Livermore National Laboratory (LLNL) has developed a four-phase amplitude tomography which allows us to determine a set of attenuation, site, and source corrections for the primary regional phases of Pn, Pg, Sn, and Lg. Our basic methodology, employed in Pasyanos et al. (2009a) for Lg, uses a magnitude and distance amplitude correction (MDAC) source model (Walter and Taylor, 2001), which more explicitly defines the source expression in terms of an earthquake source model formulated in terms of the seismic moment. One of the advantages of this approach is to easily estimate predicted amplitudes for an event of any given location and size.

In a subsequent paper (Pasyanos et al., 2009b), we applied the technique to simultaneously invert amplitudes of Pn, Pg, Sn and Lg in the Middle East to produce P-wave and S-wave attenuation models of the crust and upper mantle for the region (Figure 1). The attenuation is modeled as P-wave and S-wave attenuation surfaces for the crust, and a similar set for the upper mantle. Inverting all of the phases simultaneously allows us to determine consistent attenuation, site, and source terms for all phases, and eliminates non-physical inconsistencies among them.

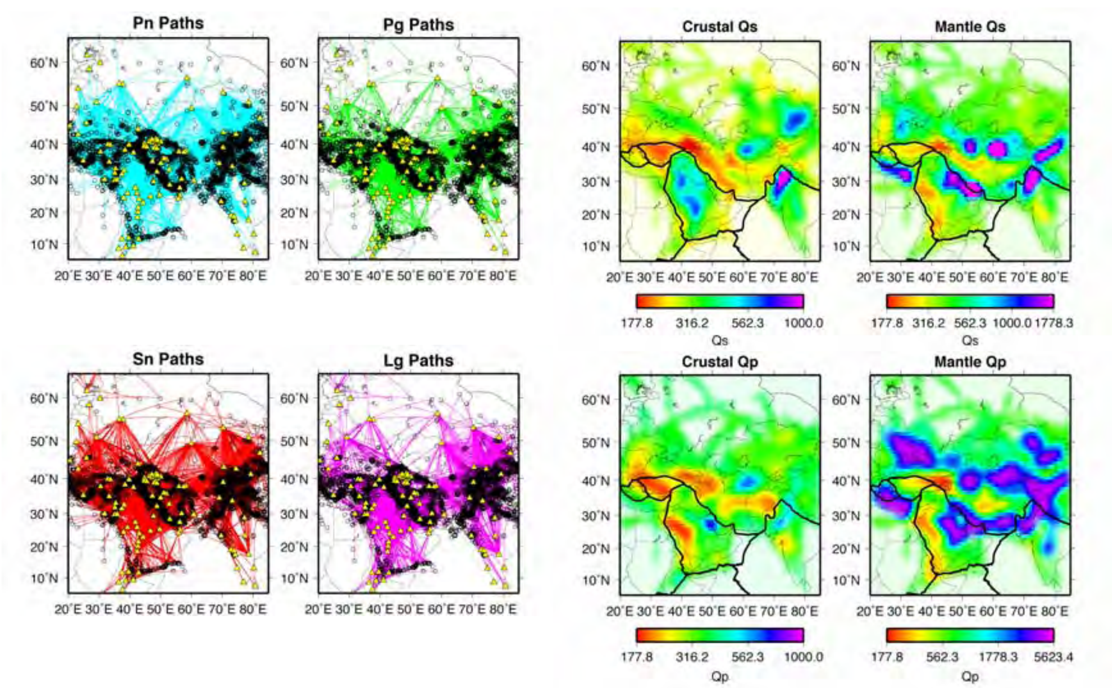


**Figure 1. Path map and attenuation results for the Middle East region in the 1-2 Hz passband. a) Path map of Pn, Pg, Sn, and Lg attenuation measurements. b) Attenuation for crustal Qs, mantle Qs, crustal Qp, and mantle Qp (figure from Pasyanos et al., 2009b).**

In the past year, we have focused on making improvements to our model-based attenuation tomography. This has been accomplished by making more amplitude measurements and improving the physics of the regional raypath. While we continue to make more measurements in the Middle East, the main focus of measurements for the past year was on amplitudes in East Asia. Applying the tomography to this region forced us to focus on the complex tectonics of the region, including an imbedded region of oceanic crust and subducting slabs in the upper mantle.

One thing we have done to improve the physics of the raypath is to introduce a variable crustal thickness into our inversion. This is particularly important in the Sea of Japan and Pacific Ocean, where the crustal thickness is less than 10 km. Figure 2 shows path and attenuation results in East Asia in the 1-2 Hz passband. Notice the small number of Pg and Lg measurements (passing the signal-to-noise criteria) crossing the Sea of Japan, even though we have picked and measured hundreds of these paths (see Pn and Sn path maps). The tomographic inversion shows relatively simple structure in the Yellow Sea and Korean Peninsula, but gets more complicated outside of this region, particularly to the east. We find low Q in the crust for the Sea of Japan. We also see complicated structure in the mantle that seems to be related to slab structure, but mainly for P-wave attenuation.

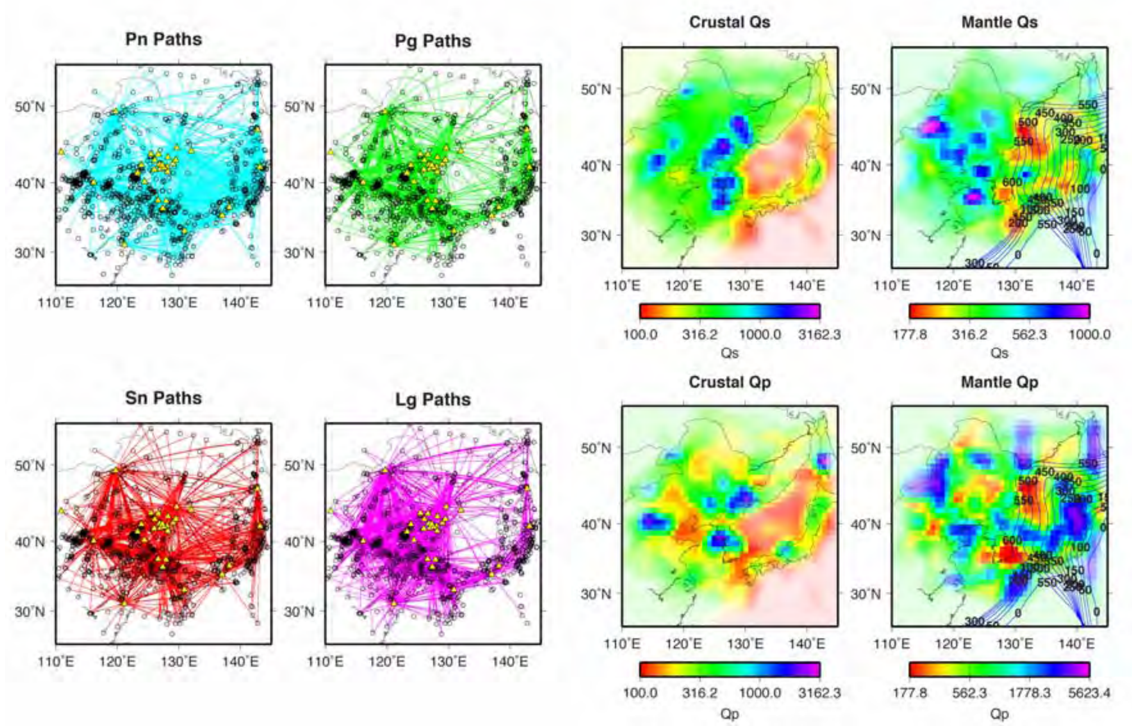


**Figure 2. Path map and attenuation results for East Asia in the 1-2 Hz passband. a) Path map of Pn, Pg, Sn, and Lg attenuation measurements. b) Attenuation for crustal Qs, mantle Qs, crustal Qp, and mantle Qp.**

We have run a series of tests with the same dataset comparing tomography methods using different choices for raypaths and for geometrical spreading. For the former, we compare a phase-based inversion (which uses a specific attenuation surface for each regional phase) to a model-based inversion (where the path propagates through appropriate attenuation layers of the crust and upper mantle). For the latter, we compare standard geometrical spreading (Street et al., 1975) to the 10-parameter geometrical spreading model of Yang et al. (2007). Using our Middle East amplitude dataset, we find comparable amplitude residuals between phase-based and model-based, although the residuals are lowest when the model-based inversion includes variable crustal thickness. This indicates that we might continue to improve as we more completely capture the true raypath. For the geometrical spreading comparison, the residuals are comparable for the whole dataset, but increase significantly for short paths near the cross-over (< 400 km) using the Yang geometrical spreading model. Results are shown in Figure 3.

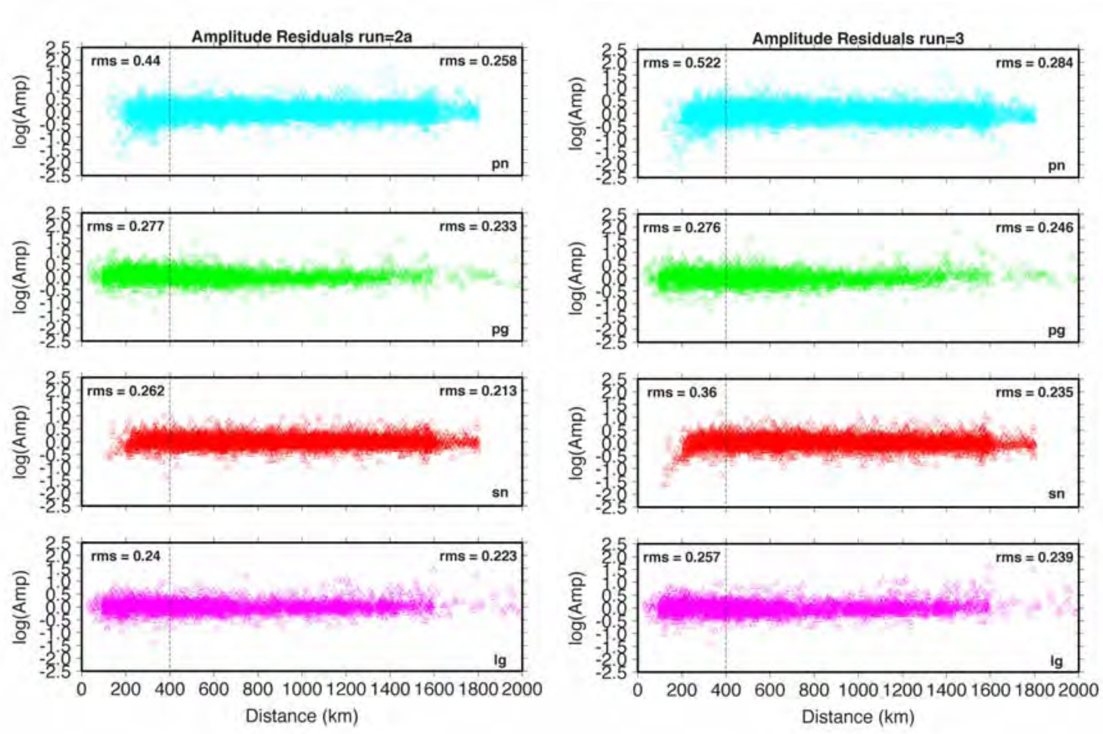


**Figure 3. Residuals as a function of distance for phases Pn, Pg, Sn, and Lg. a) Tests performed using a model-based path and standard geometrical spreading. b) Tests performed using a phase-based path and Yang geometrical spreading. RMS in the upper right hand corner are overall residuals, while those in the upper left-hand corner are those for distances less than 400 km.**

### Regional Discrimination

Applying corrections with the new attenuation models can significantly improve earthquake-explosion discrimination using regional P/S amplitude ratios. P/S discriminants are expressed as the ratio between the P-wave amplitude ($A^P$) and the S-wave amplitude ($A^S$) and, because of the large variations, are usually plotted on a log scale. Figure 3 shows the Pn/Lg discriminant in East Asia, for station MDJ in the 2-4 Hz passband. The series of plots first shows the raw discriminant (as a function of magnitude and in map view), then 1-D and 2-D corrected discriminants. In order to correct the phase ratio for path and source effects, we adjust the individual amplitudes assuming an earthquake source. We then form our discriminant using the ratio of the corrected amplitudes. This is a division of the amplitudes or a subtraction in log-space:

$$\text{discriminant} = \log\left[\frac{(A^P / A_0^P)}{(A^S / A_0^S)}\right] = \log\left[\frac{A^P}{A^S}\right] - \log\left[\frac{A_0^P}{A_0^S}\right] \quad (1)$$

where $A_0$ are the amplitude predictions for an earthquake of that phase and size. As a result, the corrected discriminant should now have a value around 0 (P/S ratio of 1) for earthquakes. We input a best estimate of the earthquake size by using a moment magnitude, if available, or otherwise estimating Mw using other magnitude estimates.

While the P/S discriminant works reasonable well for the portions of the YSKP region with continental crust (including the Yellow Sea), when we start to include earthquakes from the broader region that includes Japan, most of these events have a high P/S ratio, making them look explosion-like (red circles on the middle panel of Figure 4). A 2-D correction is necessary to account for the high attenuation along these paths. The result is that the high P/S ratio of these events can be explained by earth structure and, when corrected, do not look anomalously explosion-like.

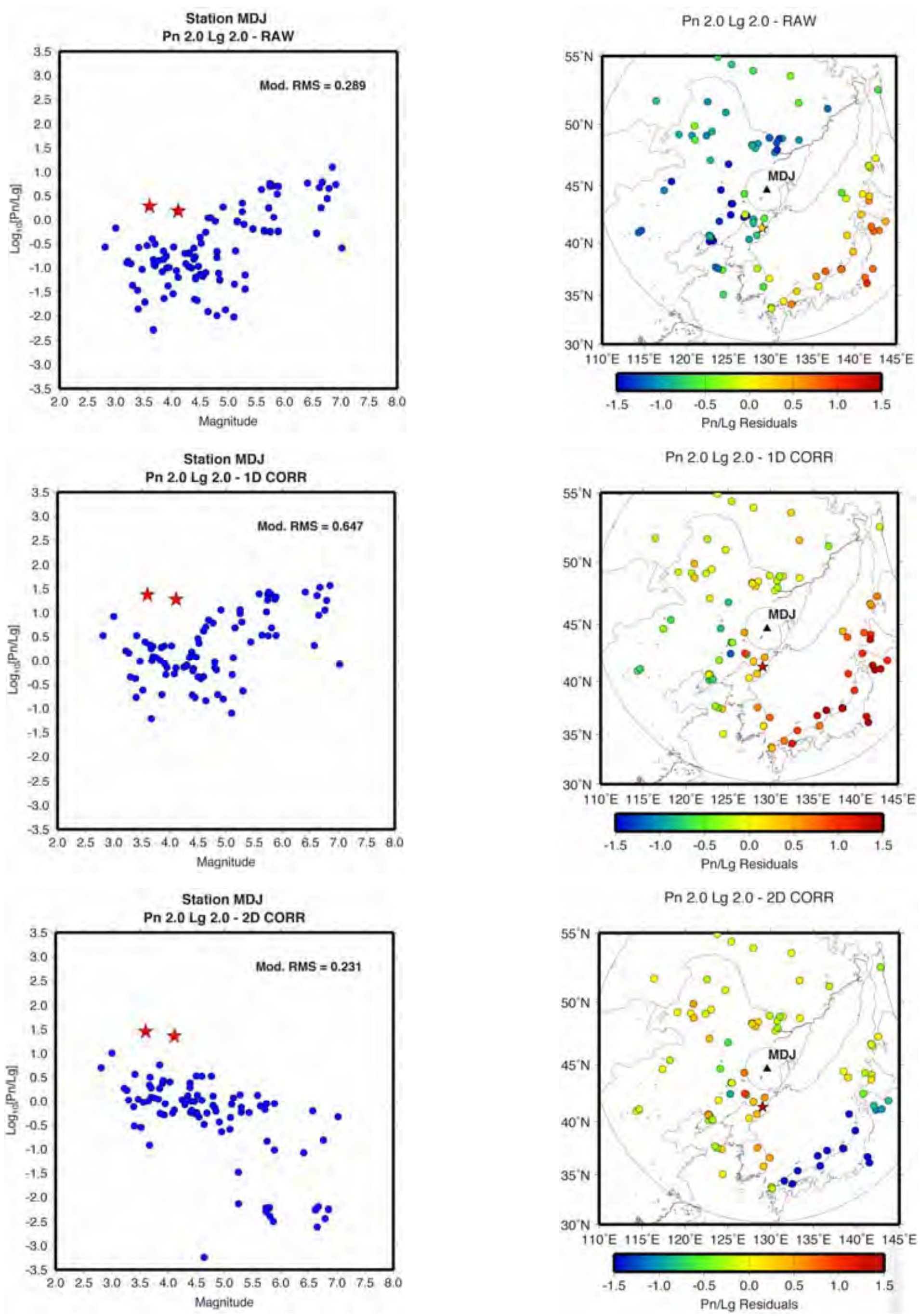


**Figure 4. Pn/Lg discriminant in the 2-4 Hz band at station MDJ. Raw measurements shown as a function of magnitude and in map view (top), 1-D corrected amplitudes using calibrations for the on-shore region (middle), 2-D corrected amplitudes (bottom).**

**Coda Tomography**

We are applying similar methodologies to coda amplitudes with the goal of improving magnitude and yield estimation. We analyzed around 500 events between 1996 and 2008 with magnitudes ranging from 3.4 to 7.4. The large number of events provided an opportunity to calibrate for path (attenuation) and site effects. We limited distances to less than 1500 km to avoid triplications in our coda calibration. After forming coda envelopes in 13 narrow frequency bands (ranging from 0.04 – 7 Hz), we estimated the start of the coda envelope by measuring the peaks of each coda envelope. The coda amplitude is estimated using an exponential decay function, and a conic section (specifically, a hyperbola) is used to fit each narrow frequency band coda amplitude (e.g., Mayeda et al., 2003) and the coda shape parameters were estimated with similar techniques for the early and late part of the coda envelopes. The raw amplitudes were corrected for geometrical spreading using the Extended Street and Herrmann (ESH) method (Morasca et al., 2008). The ESH method allows differences at local and regional coda decays to both be considered. To scale those non-dimensional amplitudes to absolute moment we use independently waveform modeled Mw's (G. Ichinose, personal communication). A constant correction factor at each frequency band is used to correct each event to obtain the moment rate function.

The moment rate functions are then used as input in a tomographic inversion of coda Q. An example of some preliminary results are shown in Figure 5. While the initial region covered is relatively small, the maps bear a great resemblance to the results we see from the direct phases (see crustal Qs map in Figure 1). This argues strongly that, while we can calibrate using the coda amplitudes, we might be able to calibrate regions for coda through the analysis of the direct phases as well. The plan is that, in addition to the moment rate functions, we can also incorporate additional information from the raw spectral ratios (e.g., stress drop, corner frequency) to include in the tomography.

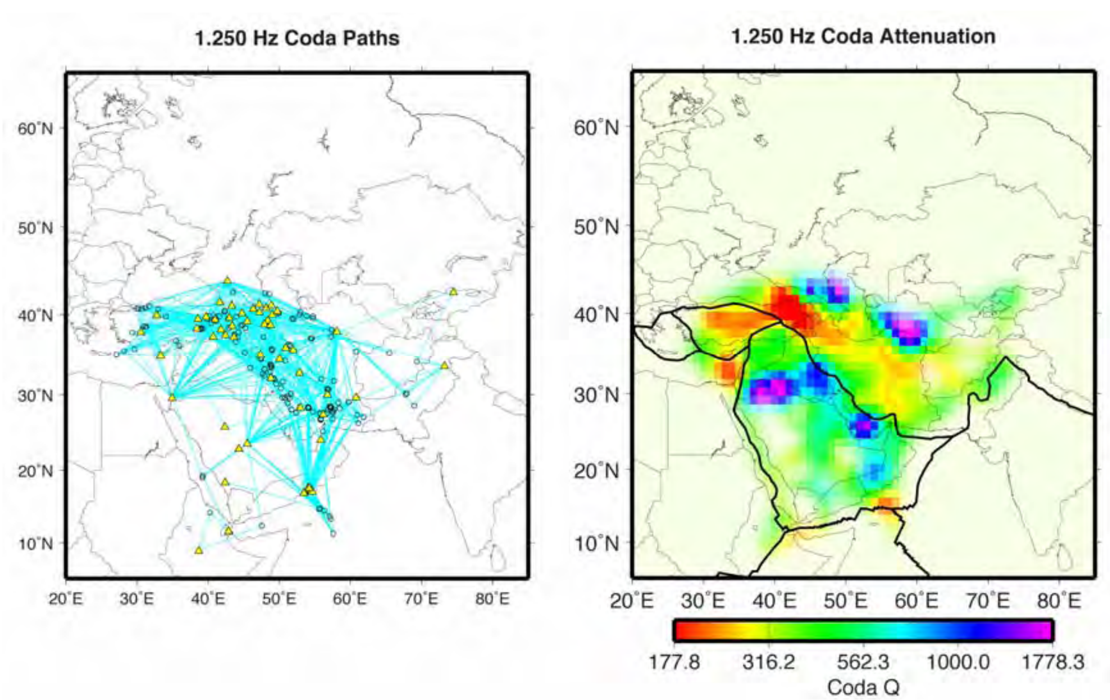


**Figure 5. a) Path map of 1.25 Hz coda amplitude measurements in the Middle East. b) Tomographic map of coda Q in the same frequency band.**

While we see attenuation variations that can affect coda amplitudes, this is a less significant effect at lower frequencies where larger events are recorded. While we are calibrating the 2-D structure, we have calculated coda magnitudes for many events based on a 1-D coda calibration of the region at frequencies below 0.5 Hz. Figure 6 shows 752 events in the Middle East where we have calculated coda magnitudes. The magnitudes range from Mw 3.1 - 6.4. In order to make more precise measurements of smaller events, 2-D corrections (like those described above) will have to be applied.

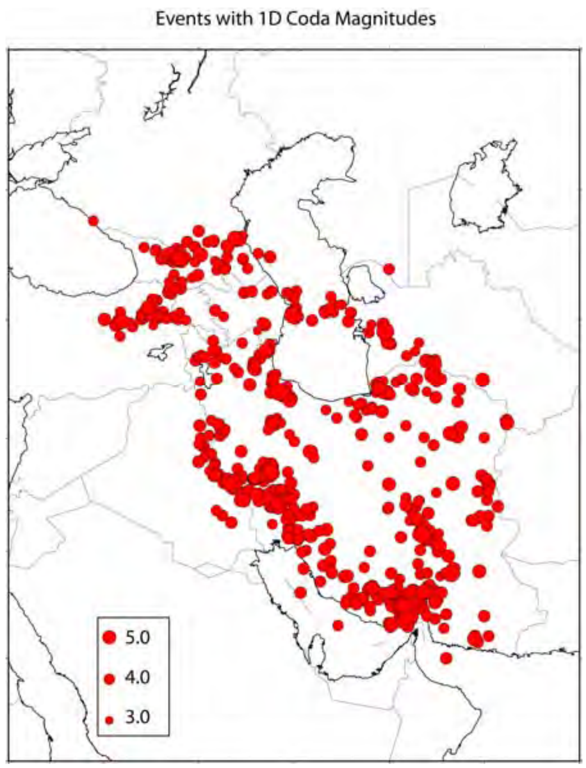


**Figure 6. Events in the Middle East for which we have calculated coda magnitudes based on a 1D coda calibration of the region.**

### Capability Assessment

The ability to detect regional S-waves from earthquakes is key to P/S discrimination capability. Where an explosion would have detectable S-waves, we have a solid P/S discrimination. In situations where an earthquake would have detectable S-waves, but an explosion would not, we have some discrimination. Where even an earthquake would not have a detectable S-wave, we have no ability to discriminate with P/S discriminants.

Techniques like 2D and 3D attenuation methods can map out where and for what magnitude thresholds regional P/S will work as a discriminant and where it does not. Figure 7 shows examples of maps with predicted signal-to-noise recorded at two stations. In the first example, we see the predicted signal-to-noise from a Mw 4.0 event of Lg in the 1-2 Hz passband recorded at station NIL. Where the figure transitions from green to yellow, the expected SNR is dipping below 2.0 and we would not expect to reliably record the signal. The pattern is somewhat symmetric, although we see a clear extension in the SNR to the southwest across the high Q of northern India.

The second example shows a similar map for Lg at station MDJ in the 2-4 Hz passband. We see that station MDJ can record signals well in all directions, except toward the southeast where paths cross the Sea of Japan. We would not expect to see signals from Mw 4.0 events in central Japan, although we might record them from events in the furthest northern and southern portions of the island chain. The reciprocal relationship, i.e. using stations in Japan as discriminants for events near MDJ, would also apply.

Using this information is critical for regional capability assessment. This should help us to determine which stations, bands and phases to use for regional P/S discrimination.

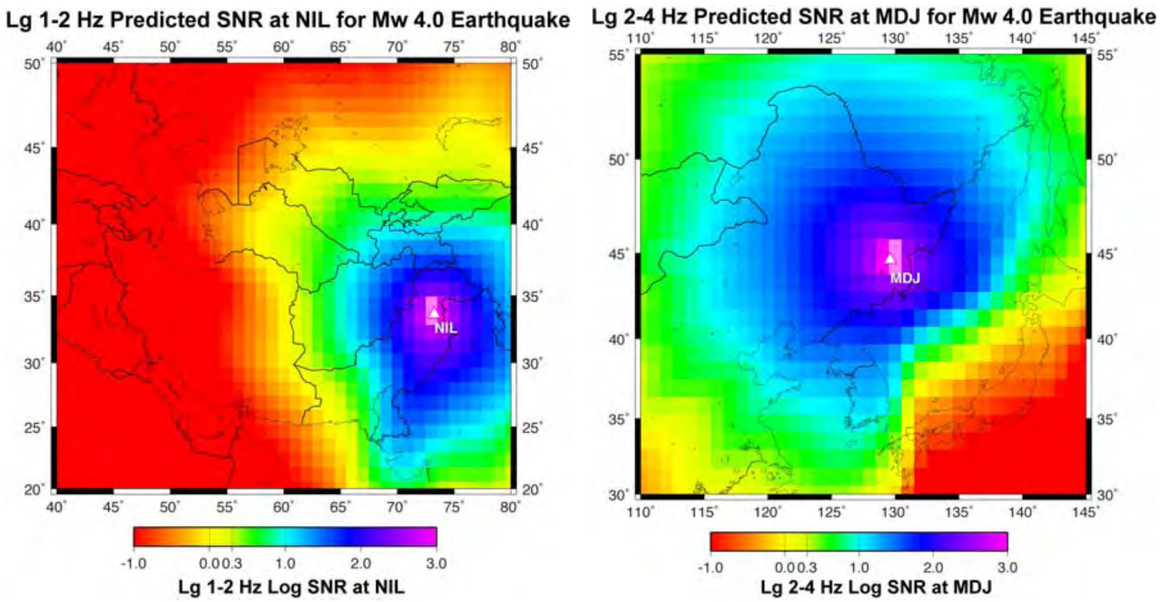


**Figure 7. Predicted signal-to-noise ratios from Mw 4.0 earthquake: a) for 1-2 Hz Lg at station NIL and b) for 2-4 Hz Lg at station MDJ.**

## CONCLUSIONS AND RECOMMENDATIONS

Attenuation tomography can capture the observed variability of regional phase amplitudes (e.g. Phillips and Stead, 2008). The new attenuation tomography method that we have developed allows us to simultaneously invert for the amplitudes of regional phases Pn, Pg, Sn, and Lg (Pasyanos et al., 2009b). We have demonstrated that it is possible to use information about attenuation of the lithosphere to improve regional P/S discriminants. The new attenuation model has the potential to greatly improve earthquake-explosion discrimination across Eurasia. Similarly, we can calibrate the effect of attenuation on coda amplitudes and improve our estimates of magnitude and yield. Finally, we have demonstrated the importance of using amplitude information in regional calibration assessment. Future challenges include calibrating aseismic regions, either using surface waves, or by calibrating attenuation using explosions recorded from these regions.

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