LLNL-TR-830560

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Report on Depth-Dependent Q from Frequency-Dependent Lg Q

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January 6, 2022

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Report on depth-dependent Q from frequency-dependent Lg Q

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Background

As a phase that travels through the crustal waveguide, Lg samples the velocity and attenuation structure of the crust. We have developed methods (Pasyanos et al., 2009a; Pasyanos et al., 2009b) to estimate Qp and Qs of the crust and upper mantle from the amplitudes of regional phases, and have applied it to a number of regions around the world, and over a broad frequency band (0.5 - 10 Hz). In prior attenuation modeling, Lg phase amplitudes are able to effectively distinguish the high Q (low attenuation) of old stable cratonic crust from the low Q (high attenuation) of more recently active tectonic regions (**Figure 1**).

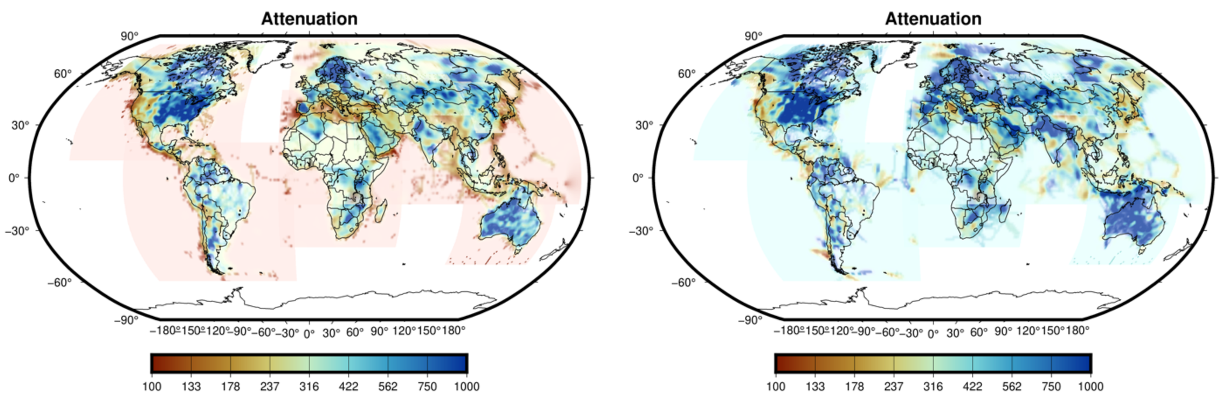

Figure 1. Composite map of shear-wave attenuation (Qs) of the crust (left) and mantle (right) in the 1-2 Hz passband, covering every continent except Antarctica.

For a variety of purposes (e.g. waveform modeling, seismic hazard, etc.), it is useful to have more information on the depth-dependence of the Q structure in the crust. One obvious candidate for doing this is using the frequency-dependence information of Lg Q, in the manner of surface waves. Unfortunately, however, Lg samples the whole of the crust without much differentiation with respect to frequency that is characteristic of fundamental mode surface waves.

Lg is generally thought to be the sum of supercritically reflected S-waves trapped in the crustal waveguide (e.g. Xie and Lay, 1994). The phase can also be modeled as a superposition of surface waves. At lower frequencies, it is primarily composed of fundamental and low-order surface waves, while at higher frequencies, it is comprised purely of many high-order surface waves. The low-order surface waves that comprise Lg in low frequency bands (< 1 Hz) are preferentially sensitive to shallow earth structure, such as sedimentary basins and upper crust, while high-order surface waves have a more homogenized sensitivity to the whole crust.

Furthermore, at the lower frequencies, we might expect to see some differentiation in the sensitivity between early Lg (herein referred to as Lg1) and late Lg (referred to as Lg2) where the latter is comprised of lower-order surface waves and, hence, shallower structure. Therefore, we might expect to see the signature of shallow features, primarily the lower Q of sediments as compared to crystalline crust, at lower frequencies and in later arriving Lg amplitudes.

<u>Amplitude Measurements</u>

In order to test this, we have assembled a dataset of Lg amplitudes for the central and eastern United States (CEUS), where we have measured Lg, Lg1, and Lg2 amplitudes in frequency bands from 0.5 - 10 Hz. The amplitudes were measured for regional events at 47 stations that span the study area (**Figure 2**). The stations are mostly from the U.S. National Seismic Network (network code US), but also included data from the Global Seismographic Network (GSN), International Monitoring System (IMS), and N4 (central and eastern U.S) network. The goal is to provide a large subset of stations from our North American model in order to test the viability of the method.

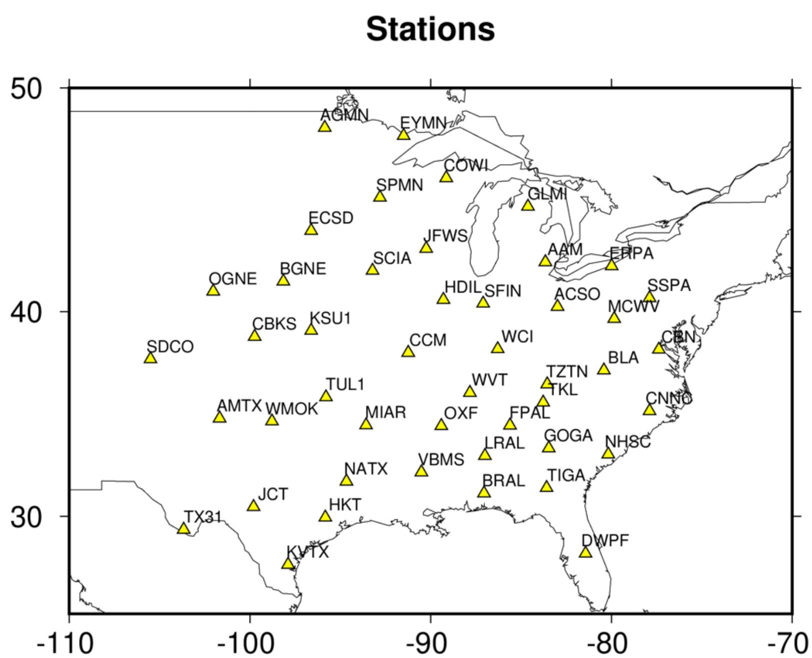

Figure 2. Station used in test for central and eastern United States.

This region was selected for several reasons. First, station coverage is exceptional and, consequently, path coverage is excellent and tomographic features are generally well-resolved. Secondly, there is a well-resolved contrast between the North American craton (encompassing the Canadian Shield and associated platforms) and Cenozoic and Mesozoic aged crustal rock of the coastal plain on the Atlantic and Gulf of Mexico coasts. On the western edge of the model, we observe differences between stable North America of the CEUS and tectonic North America to the west. In the tomographic models, there are hints that some known sedimentary basins have even lower Q structure than adjacent regions. The final reason is that there are known deep sedimentary basins that we can try to identify in any method to test depth isolation of Q structure. **Figure 3** shows estimates of sediment thickness from two different models.

a)

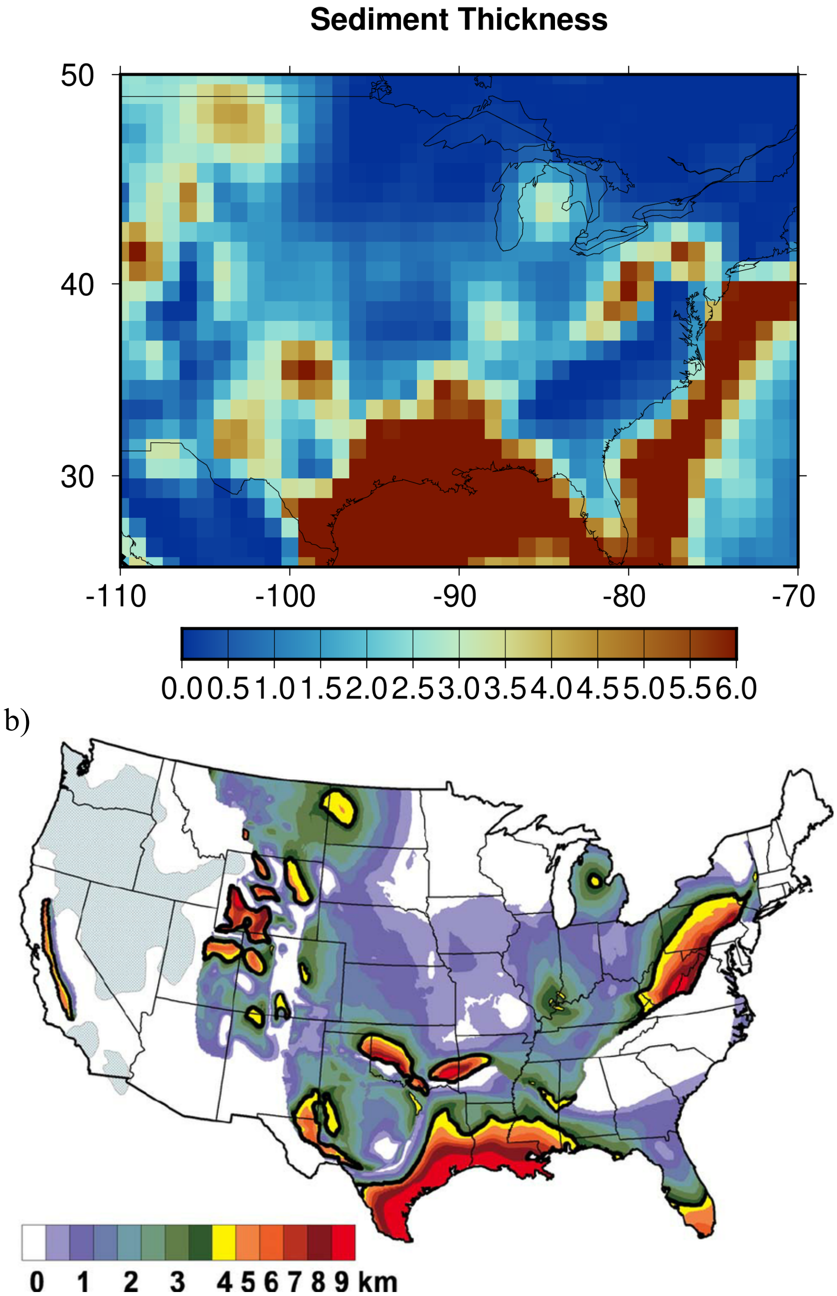

Figure 3. Sediment thickness maps of the study area from a) CRUST1.0 (Laske et al., 2012) and Tester et al. (2006). Crustal thickness is in km.

Amplitude measurements were made on early and late parts of the Lg waveform as shown in **Figure 4**. All amplitudes are made using the Regional Body-wave Amplitude Processor (RBAP), which was developed in-house at LLNL by Doug Dodge. Lg amplitudes are RMS amplitudes for a group velocity window appropriate for Lg in CEUS (~ 3.55 - 3.0 km/s) where the theoretical arrival times can be modified (faster or slower) by picks. Amplitudes for Lg1 are RMS amplitudes for a window from the pick time until 3.4 km/s (modified by changes to the pick time), while Lg2 amplitudes are RMS amplitudes for a window from the end time of Lg1 to 3.0 km/s. Like in our routine processing used for our multi-phase inversion method, amplitudes need to pass both a pre-event and pre-phase signal-to-noise criteria. Amplitude measurements were then assembled and separate inversions were performed for Lg (as a reference), early Lg and late Lg.

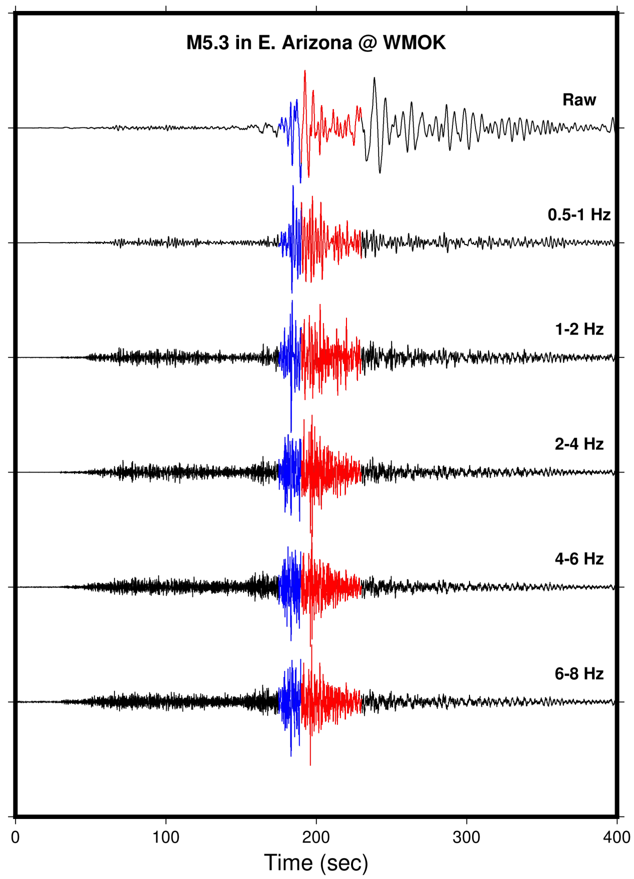

Figure 4. Example of amplitude measurements for early Lg (Lg1) shown in blue and late Lg (Lg2) shown in red on the unfiltered displacement signal and in frequency bands of 0.5-1, 1-2, 2-4, 4-6, and 6-8 Hz. All waveforms are scaled to their maximum.

Inversion Results

A multi-phase attenuation model of the lithosphere in North America was first published in Pasyanos (2013) (**Figure 5**) and has been updated significantly since then (**Figure 6**). Relative to the 2013 model, we have many more amplitude measurements, the resolution of the model has increased, and the fidelity of the model improved substantially. If we focus on the current model, we see much higher Q in the CEUS relative to the western U.S. This is a well-known feature and accounts for the large differences in felt regions for similar sized earthquakes (**Figure 7**) and is due to differences in the age, temperature, and lithosphere between the North

American craton and tectonically-active North America (**Figure 8 and 9**). In addition, in the CEUS, we also note lower Q in the coastal plain to the south.

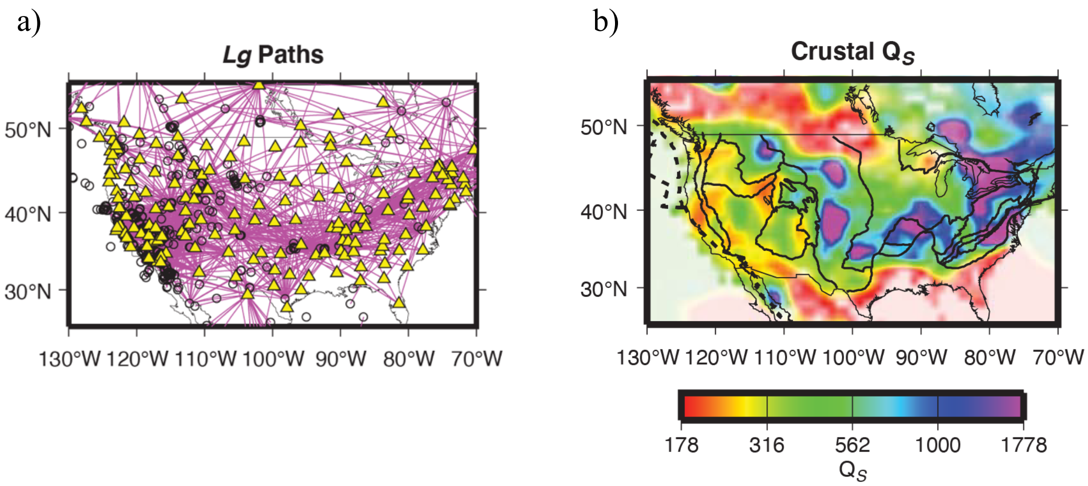

Figure 5. Lg path coverage and crustal Qs of the United States at 1-2 Hz from Pasyanos (2013).

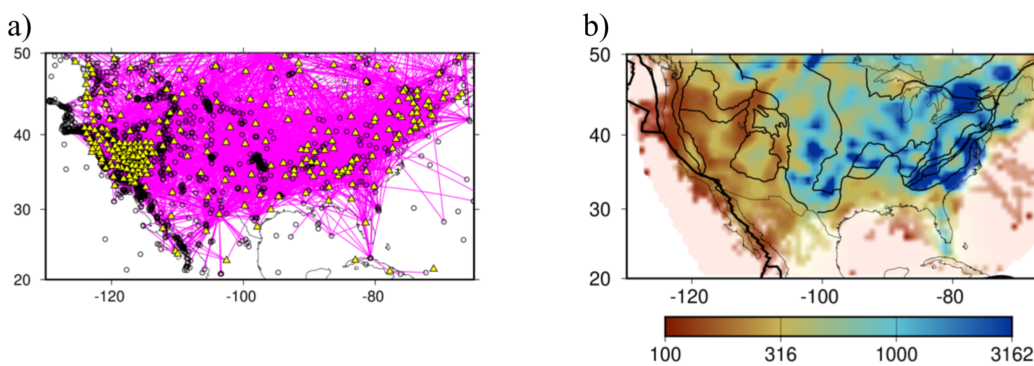

Figure 6. Lg path coverage and crustal Qs of the United States at 1-2 Hz from current model.

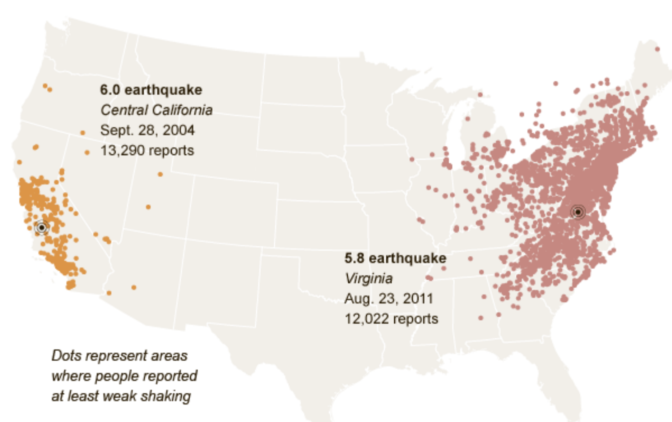

Figure 7. Comparison of felt areas on the east and west coast of the United States for similar sized events. [Source: New York Times] www.nytimes.com/interactive/2011/08/23/us/map-of-damage-reports-from-the-virginia-quake.html

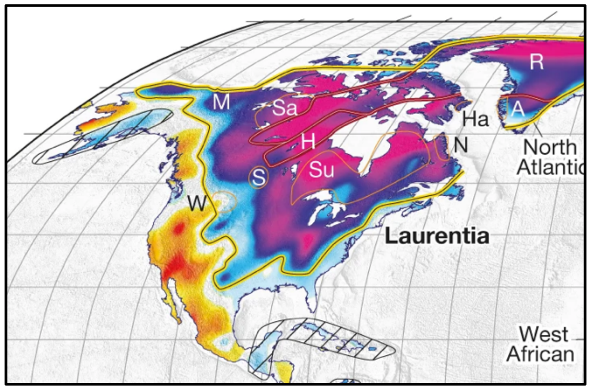

Figure 8. Cratonic regions defined with seismic imaging of continental mantle lithosphere where hot colors represent lower velocities and cool colors represent higher velocities. From Pearson et al. (2021).

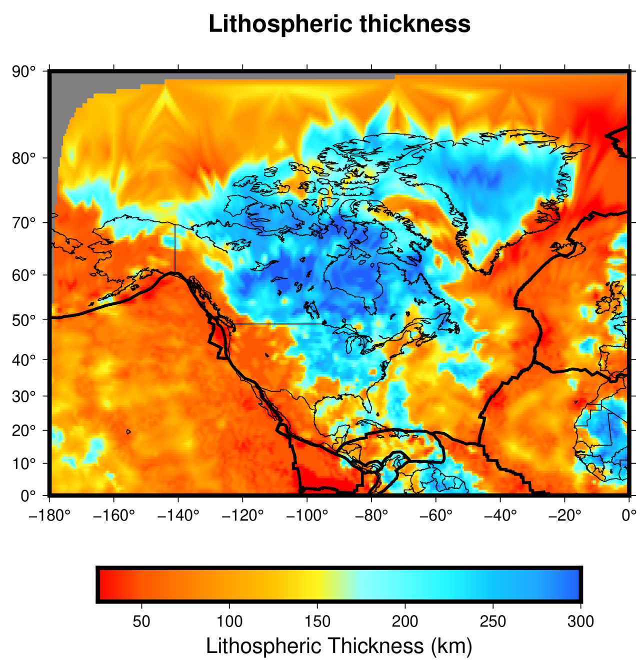

Figure 9. Lithospheric thickness of the northwestern quadrant of the globe from the LITHO1.0 model (Pasyanos et al., 2014).

We have selected a subset of stations (shown in **Figure 2**) and made Lg1 and Lg2 amplitude measurements. **Figure 10** shows a comparison of the path coverage of Lg, Lg1, and Lg2 at 1-2 Hz. Although obviously not as good as the full dataset shown in **Figure 6a**, we still see dense sampling and crossing paths over the study area, albeit for an area with a smaller footprint. Coverage of the Gulf of Mexico (and western Atlantic Ocean) is poor, as Lg does not propagate efficiently in regions of thick sediments and thin crust, where the crustal waveguide is disrupted. In order to enhance coverage, we have included events only recorded by a single station ("singletons"). These are normally removed from our inversion because, for these paths, there is a stronger unresolved tradeoff between station site terms and event source terms. Although minor variations are observed, there is not a substantial difference in coverage among Lg, Lg1, and Lg2.

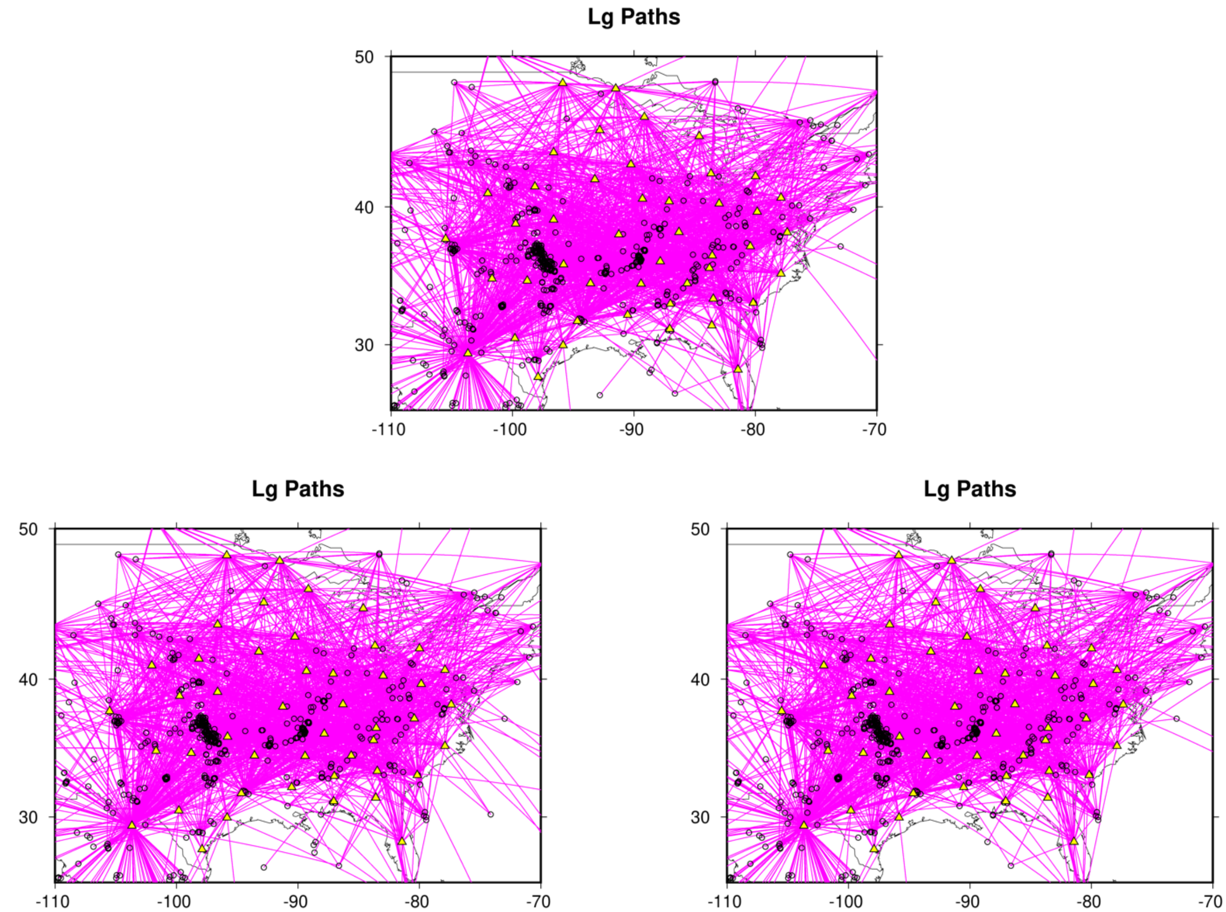

Figure 10. Path coverage of Lg (top), Lg1 (bottom left), and Lg2 (bottom right) at 1-2 Hz.

Figures 11-13 shows the results of our inversions for a number of frequency bands: 0.5-1 Hz, 1-2 Hz, and 2-4 Hz. In each case, we show the results of the normal Lg inversion at the top panel, with the early Lg (Lg1) inversion, and the late Lg (Lg2) inversion shown side-by-side at the bottom. To first order, the attenuation model of Lg, Lg1, and Lg2 at all frequencies show the same features and don't exhibit substantial differences between maps, although there are some minor variations in the results, as we will see later.

At 0.5-1 Hz, we see high Q for most of the CEUS (**Figure 11**). Results of the attenuation inversions are plotted along with the boundaries of physiographic provinces. We see lower Q in the surrounding regions, although it is not clear if this is an edge effect. Compared to the multi-phase tomography, in which we are simultaneously inverting the amplitudes of Pn, Pg, Sn, and Lg (**Figure 6b**), the Lg-only tomography looks significantly noisier, which might be compensated through greater normalization in the inversion. We see much of the same at 1-2 Hz (**Figure 12**). At 2-4 Hz, however, we see larger variations between the Gulf Coast and Mississippi Embayment and the rest of the CEUS.

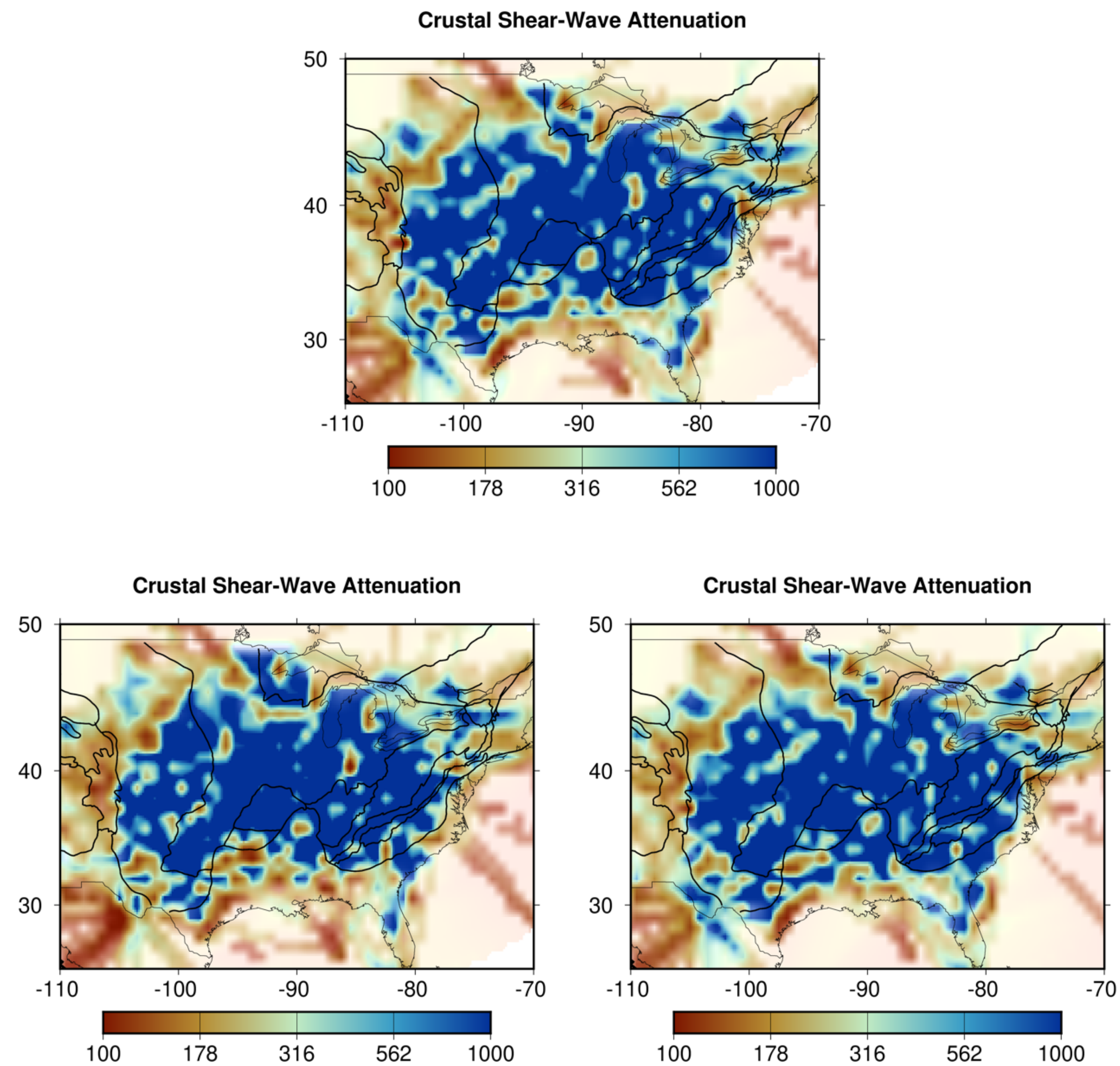

Figure 11. Crustal Qs of Lg (top), Lg1 (bottom left), and Lg2 (bottom right) at 0.5-1 Hz.

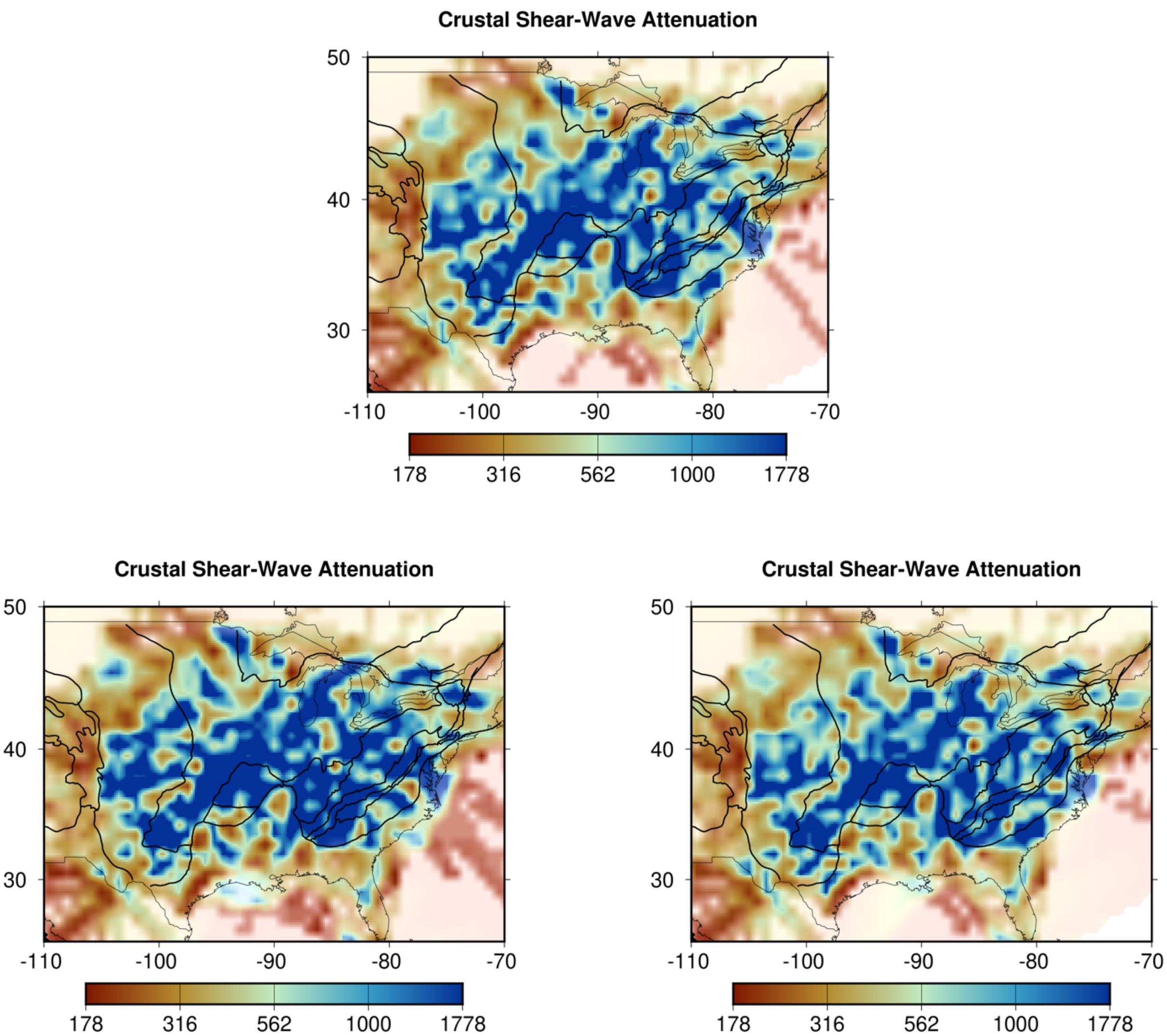

Figure 12. Crustal Qs of Lg (top), Lg1 (bottom left), and Lg2 (bottom right) at 1-2 Hz.

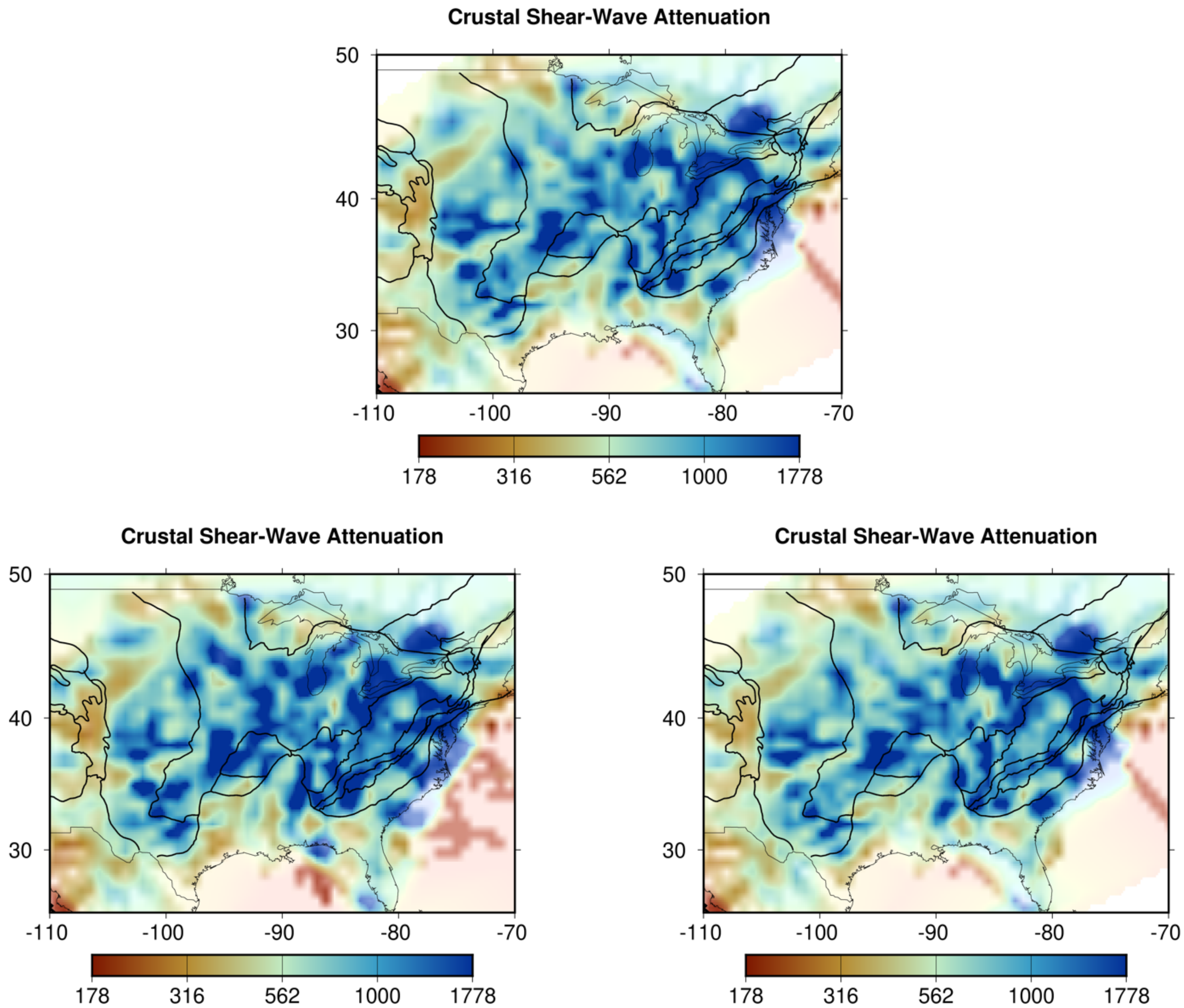

Figure 13. Crustal Qs of Lg (top), Lg1 (bottom left), and Lg2 (bottom right) at 2-4 Hz.

Since we are interested in examining the difference in attenuation between early and late Lg, we calculate and plot Q^{-1}_{Lg1} - Q^{-1}_{Lg2}. Positive values (shown in blue) indicate that Q^{-1} is higher (Q values lower) for early Lg than for later Lg, which will be sensitive to shallower structure than early Lg. Correspondingly, negative values (shown in red) indicate that Q values are higher for early Lg than for later Lg. As an example, if we assume that Q for the whole crust is 500 (Q^{-1}=0.002) and Q for the sediments is 200 (Q^{-1}=0.005) and we further assume that Lg1 is whole crust and Lg2 is sediments only, then the difference in this case would be -0.003.

Figure 14 shows the difference in the three frequency bands. As expected, the differences are larger at lower frequencies. Unexpectedly, at 0.5-1 Hz (**Figure 14a**), we see a positive anomaly in the Gulf Coast, where we were expecting to see a negative feature due to the thick sediments. We do see a negative anomaly in the Superior Upland, which is part of the Canadian Shield. In **Figure 15**, we plot the difference map at 0.5-1 Hz with sediment thickness contours (from CRUST1.0) plotted on top.

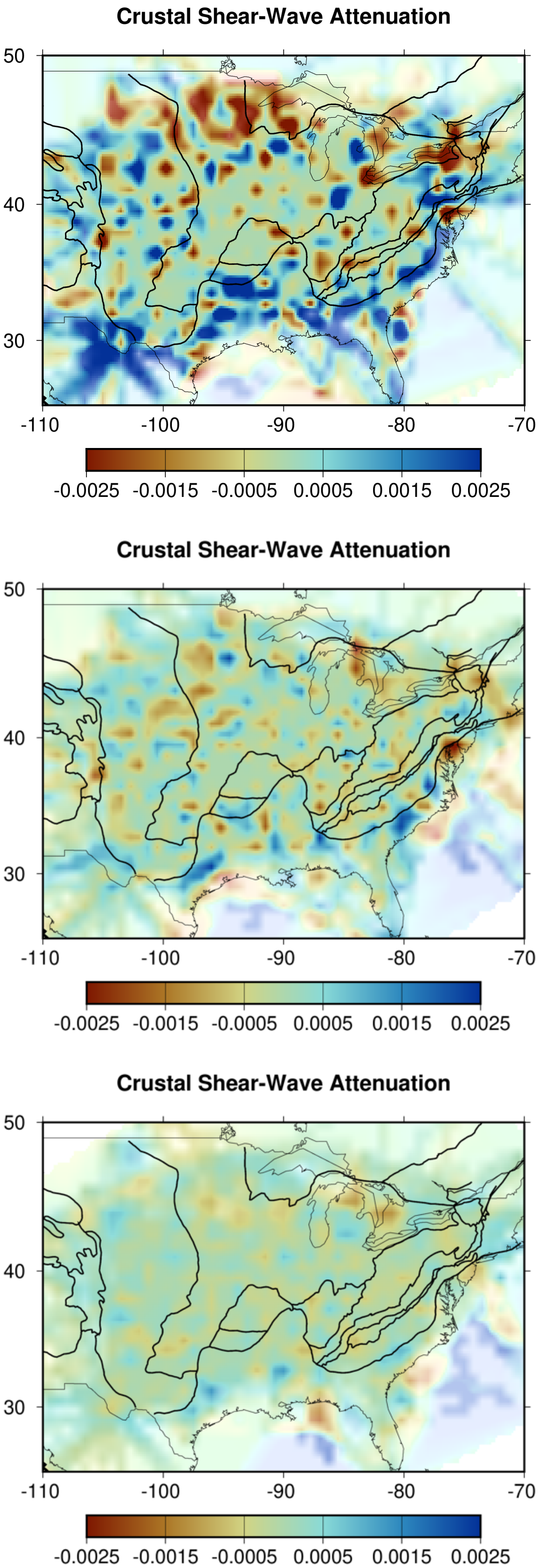

Figure 14. Attenuation difference (Q^{-1}_{Lg1} - Q^{-1}_{Lg2}) at 0.5-1, 1-2, and 2-4 Hz.

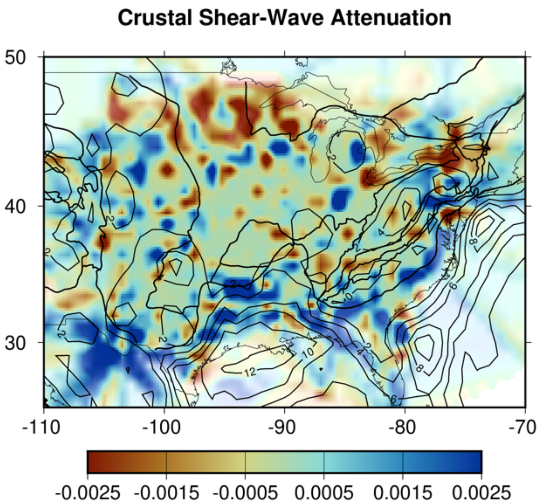

Figure 15. Attenuation difference (Q^{-1}_{Lg1} - Q^{-1}_{Lg2}) at 0.5-1 Hz with contours of sediment thickness from CRUST1.0 plotted on top.

The last thing we try is cross-spectral analysis. This has the potential to enhance the difference in attenuation between shallow structure and the crust as a whole. As an example, we compare early Lg at 2-4 Hz with late Lg at 0.5-1 Hz. Since there is a strong frequency dependence to Q ($Q = Qo f^{\eta}$) we normalize by frequency before making the comparison. Results are shown in **Figure 16**. Here, perhaps, we finally see some differences that may be attributable to lower Q from sediments with negative anomalies in both the lower Gulf Coast and eastern Atlantic seaboard.

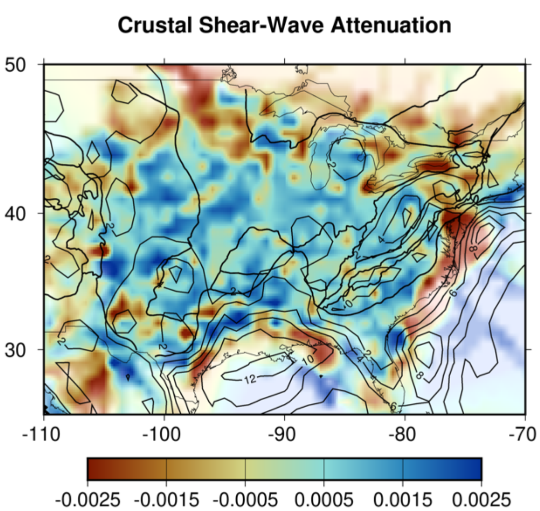

Figure 16. Attenuation difference (Q^{-1}_{Lg1} - Q^{-1}_{Lg2}) where Lg1 is at 2-4 Hz and Lg2 is at 0.5-1 Hz with contours of sediment thickness from CRUST1.0 plotted on top.

Discussion

In this study, we explored the use of frequency-dependent Lg Q to derive depth-dependent Q(z). This is our first effort to systematically test the viability of this method. The expectation is that differences between early and late Lg will be most significant at lower frequencies and negligible at higher frequencies. We also expect that the observed differences will likely be due to regions of thick sediments which have lower Q than crystalline rocks.

While we have made great strides in implementing and testing the method, the results to date are inconclusive. Still, there are at least some indications that the method might be worth exploring more thoroughly. In the short term, there are some details with the method that we would like to more systematically test, which can be categorized into amplitude and inversion changes.

Under the amplitude category, we would like to test: 1) changes to the group velocity boundary between early and late Lg (currently set at 3.4 km/s), and 2) changes to end time for late Lg (currently set at 3.0 km/s), slow enough for low-order surface waves. Under the inversion category, we would like to test: 1) better coverage of the Gulf Coast, 2) testing variations in smoothing in the inversion, 3) the use or non-use of singletons, and 4) running each of the inversions as part of a multi-phase inversion (with Pn, Pg, and Sn).

In order to test the method, however, we needed to hack changes to both the measurement tool (RBAP) and extraction codes in order to measure the Lg1 and Lg2 amplitudes. The difficulty in doing so (much of which required hands-on manipulation of 70 or so RBAP projects) has prevented us from easily testing some of the proposed changes. The next version of RBAP (RBAP2) will be equipped to measure amplitudes for phases beyond the standard regional phases (Pn, Pg, Sn, Lg), including Lg1 and Lg2. Once this version is in place, it should be easier to test differences related to amplitude measurements.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This is document number LLNL-TR-830560.

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