LG AND PG ATTENUATION IN THE MIDDLE EAST

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ABSTRACT

In order to construct reliable frequency-dependent Q models for both Lg and Pg, we have used approximately 8000 waveforms from approximately 500 events recorded by 11 permanent and temporary networks throughout the Middle East. Using these waveforms, we have developed a tomographic model with frequency-dependent Q using direct Lg waves in this region. We have also measured Pg across the Middle East including the Arabian platform and the Arabian shield. In general, we found lower Pg Q within the Arabian platform and less Pg attenuation for much of the Arabian Shield. Not surprisingly we found that the Pg Q does not vary as much as Lg Q; however, the general trend is the same: low Q within the plateau and high Q within the stable Arabian plate. The frequency dependence, however, is different from what we have found for Lg. We have found a higher average eta (~0.4) for Pg as compared with Lg. Resolution tests of 2x2 cell size for our Pg Q tomography indicate that we have very good resolution throughout much of the Anatolian Plateau and resolution of anomalies larger than 200 km in much of the northern Arabian plate.

We have begun work on validating our Lg and Pg attenuation models. We are developing a catalog of "amplitude ground truth" seismic events. We will use these events to test whether path corrections from our attenuation models can successfully predict the source spectra (i.e., moment and corner frequency). In order to develop a catalog of events with reliable event spectra, a search was performed on 373 events at 89 stations in the Middle East to look for doublets or repeating earthquakes. Exactly the same procedures and parameters were employed as those by Schaff and Richards (2004) who found 9% of the events in and near China. Only two events or one pair met the same criteria for repeating events as were used in China. This is 1% of the seismicity, as compared to 9% from all the currently available waveforms in China (1,301 events out of ~14,000). This difference may be due to the absence of magnitude 3.0s from the Middle East data set; these events would probably have a greater chance of having similar waveforms due to simpler rupture areas and closer proximity to one another. This catalog of similar waveforms will also allow us to calibrate and adjust our model to better predict a reliable source spectra.

OBJECTIVES

The objective of this study is to obtain laterally varying Q models for multiple regional waves, including Sn, Lg and Pg for the Middle East. We are developing Q models that have the highest possible lateral resolution. For some waves such as Lg and Pg, the resulting Q model will be in the form of a tomographic Q map; for other waves such as Sn, the resulting models will consist of blockage maps. Blockage effects will be represented by low effective Q values in the models.

Challenges Associated with Regional Phase Q Measurements

It is well known that the attenuation rate of regional waves, including the high-frequency Lg, Pg, Sn and Pn and the lower-frequency surface waves, is highly variable over major continents. Reliable knowledge of the lateral variation in regional wave attenuation rate, or its inverse, Q, is extremely important for event detection and identification in the nuclear monitoring program. The preferred way to acquire this knowledge is to conduct tomographic mapping of regional wave Q. However, in contrast to the wide success in seismic velocity tomography since the 1970s, there has been relatively little progress in Q tomography. The main obstacle is the difficulty in obtaining reliable measurements of Q: the observed amplitude of high-frequency waveforms is affected by a number of factors, including (1) possible non-isotropic source radiation patterns, (2) source spectra that may be only grossly described by a seismic moment and a corner frequency; (3) geometrical spreading terms caused by the wave front expansion which, in complex 3D Earth structures, may cause focusing and defocusing; and (4) potential site responses caused by local structural complications under the seismic stations. Effects of these factors are difficult to correct, causing biases in Q measurement. We have assembled a unique waveform database of waveforms with reliable instrument response information for both short period and broadband stations.

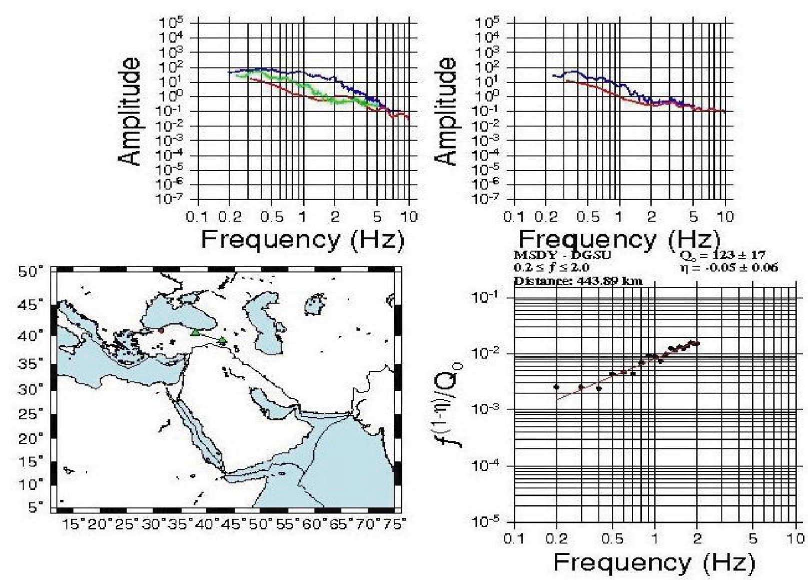


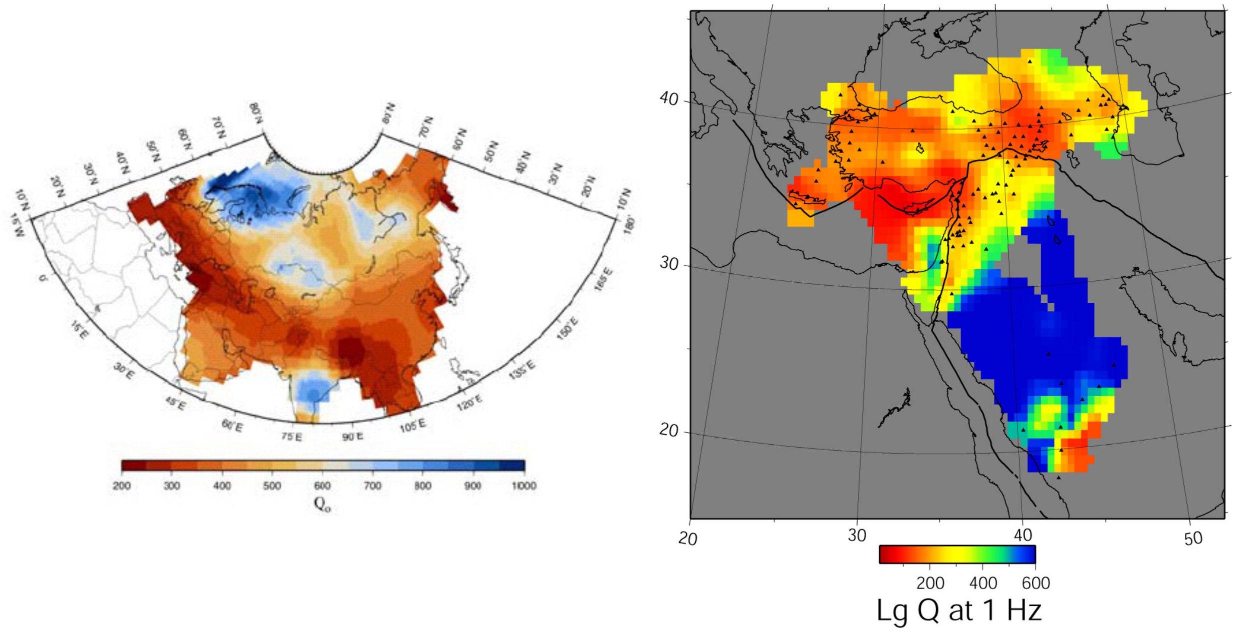
Figure 1. **Examples of Lg spectra analysis and calculation for Q via the 2-station method. We used a group velocity window length of 1 km/s and calculated smoothed spectra.**

RESEARCH ACCOMPLISHED

Using a two station approach we have determined the direct wave Q for both Pg and Lg phases traveling across a large portion of the Middle East. An example of the processing we used to determine the two-station Q for Lg is shown in Figure 1. To define the alignment we use an angle $\delta\theta$, which is the difference between the azimuths from the source and the two stations. Q_o and η values may contain errors because of the effects of Pg and *Lg* attenuation outside the path and a non-isotropic source radiation pattern using non-zero $\delta\theta$. In order to minimize this error, we chose to set $\delta\theta_{max}$ to 15º for both phases as explained by Xie et al. (2004) based on results of Der et al. (1984). The second important parameter in this method is the inter-station distance. The potential error caused by inter-station distance is strongly related to the estimated Q_o value for the corresponding path and can be estimated by using the method given by Xie et al. (2004).

In order to keep our errors lower than 35% with a given modeling error value (δx=0.2), the inter-station ratio between Q_o (Q at 1 Hz) and Δ_{ij} (the inter-station distance) should not be greater than 1.6. By applying the criterion of $\delta\theta_{max}$= ±15° and the inter-station ratio = 1.6 to the ~2300 Lg spectra, we have found 1,383 two-station paths from approximately 140 regional events (Figure 1). When calculating Lg Q_o and η, we did not fix the Lg window on the waveform because Lg velocity typically varies by 20% from one region to another as emphasized by Nuttli (1973).

We have compared our results for Lg with coda methods and found that at the longer wavelengths, the relative attenuation structures agree quite well (Figure 2). The excellent ray path coverage and the nature of our tomography accounts for smaller scale fluctuations in the direct wave Q model (e.g., Figure 2b) that is not present in the coda Q maps (Figure 2a). In general, the smallest Q values are found throughout western and central Anatolia, with much higher Q values in the Saudi Arabian shield. In terms of the frequency dependence of the coda and direct Lg Q measurements, the coda measurements of η are consistently larger. This has been true not just for the Middle East but also for measurements throughout Eurasia. However, we do observe consistent spatial variations of η. This includes the finding of smaller values for the Arabian Shield (-0.1 for the direct phase and 0.4 for the coda measurements) and larger values for the Anatolian Plateau (0.5 for direct phase and 1.0 for coda).



(a) (b)

Figure 2. A comparison of Lg Q_0 using the (a) direct wave two station methods and (b) coda (Cong and Mitchell, 2005).

Mapping Variations in η

We also finalized our model for the frequency dependence for both Pg and Lg frequency dependent Q. Figure 3 shows our map of η for the northern Middle East for both Pg and Lg. We found an anomalously low average η for the Middle East (0.22) for Lg including large regions of negative η. We found a correlation between large Q-values and small η values that is consistent with frequency dependent coda-Q measurements. The spatial variation in η also suggests that these anomalously low Q measurements might be, to some extent, a function of Sn-to-Lg converted energy. Not surprisingly, we found that the Pg Q does not vary as much as Lg Q; however, the general trend is the same: low Q within the plateau and high Q within the stable Arabian plate. Our estimated η value, however, is higher (~0.4) for Pg than for Lg (Figure 3). This observation is consistent with the idea that some of the anomalously low-frequency dependence for Lg is caused by high-frequency energy leaking into the crust because this effect might be different for Pn-to-Pg converted energy.

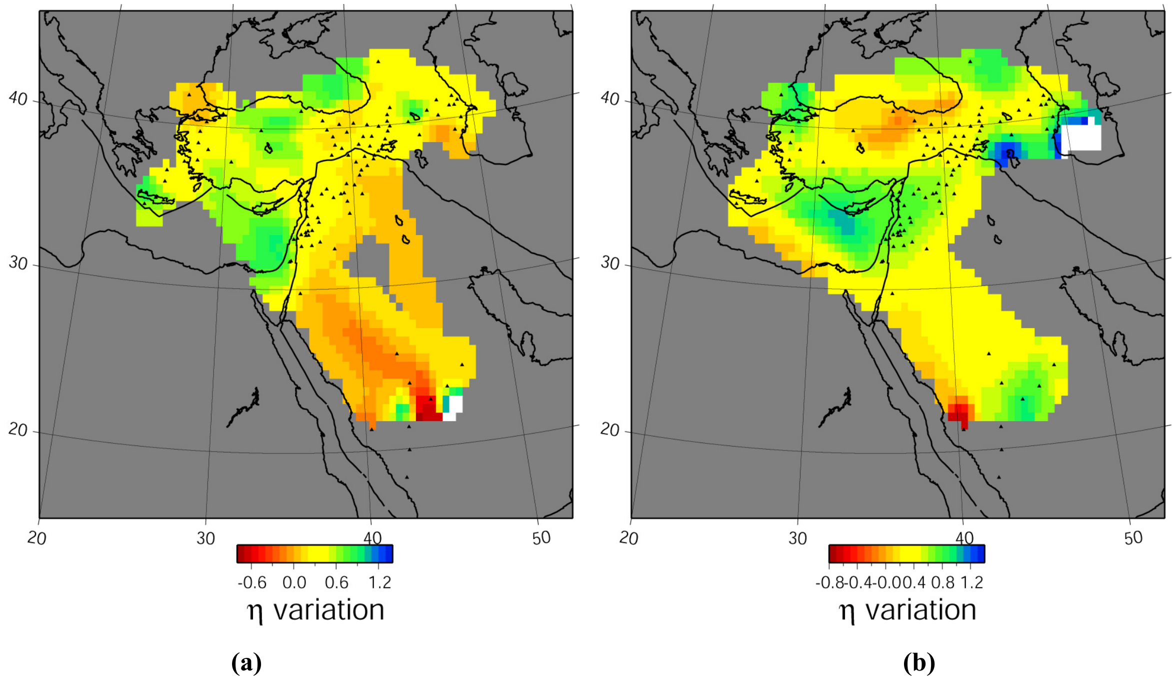


Figure 3. A comparison of η values for (a) direct wave Lg model and (b) direct wave Pg model. The mean η values for Pg is substantially larger (0.4) than for Lg (0.2).

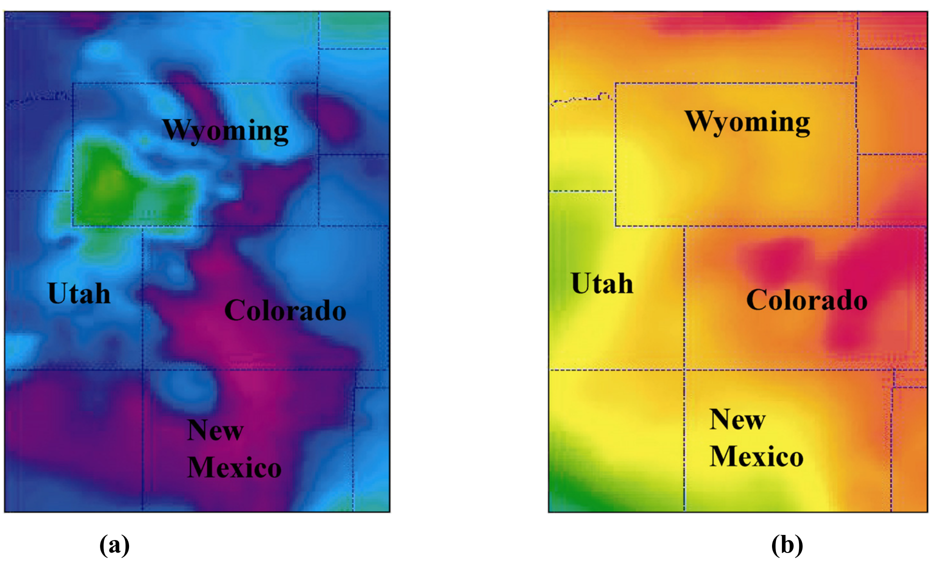


Figure 4. (a) A map of the depth of sediments for the Rocky Mountains and surrounding regions. Colder colors indicate less sediment thickness. (b) A Moho map used for the calculation of synthetic regional seismograms. Hotter colors indicate thicker crust.

Investigating Pg Behavior using Synthetic Seismograms

In order to better understand the behavior of Pg propagation we calculated a fairly large number of synthetic waveforms to neglect the influence of instrument response and intrinsic attenuation terms by initialization of Q. We calculated these synthetic regional waveforms using the GEON-SYNSEIS tool that utilizes the E3D finite difference codes for a series of source receiver geometries. The model is from the GEON database for crustal and sediment thickness data for North America (Figure 4). Using this model and the SYNSEIS module we calculated approximately 100 synthetic waveforms to investigate the behavior of Pg waveforms in a complex two-dimensional velocity model. In order to isolate the effects of scattering attenuation, we created a model with a uniform Qp and Qs (Figure 5). We found some correspondence between changes in sedimentary cover and Pg Q, which agrees with some of our observations that we have made for Pg propagation in the Middle East.

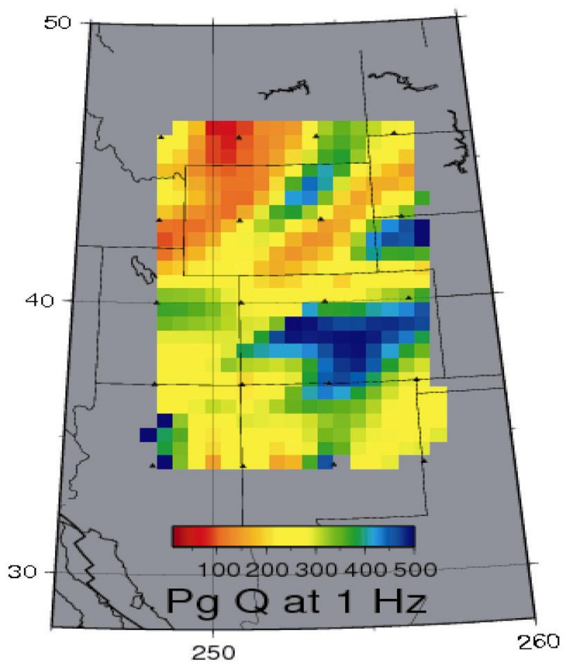


Figure 5. **Pg Q estimates for a tomographic model using finite difference synthetics created from a model with a uniform intrinsic attenuation for the entire crust. We are using these synthetics to investigate the sensitivity of Pg waveforms to crustal structure.**

In order to solve for the Pg Q values we assumed a geometric spreading term very similar to that of Lg. Because this is not necessarily a good assumption, we have begun to work on determining a reliable geometrical spreading term for Pg propagation in the Middle East. In order to measure the Pg geometric spreading, we estimated the Pg amplitudes at 1 Hz and then normalized the Pg amplitudes in order to determine the average distance relationship. We have found evidence of Pg propagation well beyond 12 degrees. Much of the scatter in Figure 1 can be attributed to lateral variations in the Pg attenuation structure.

Validation of Q Models

We have also begun work on validating our Lg and Pg attenuation models. We have developed a catalog of "amplitude ground truth" seismic events. We will use these events to test whether path corrections from our attenuation models can successfully predict the source spectra (i.e., moment and corner frequency). In order to develop a catalog of events with reliable event spectra, a search was performed on 373 events at 89 stations in the Middle East to look for doublets or repeating earthquakes. Exactly the same procedures and parameters were employed as were used by Schaff and Richards (2004) that found 9% of the events in and near China were repeating with cross-correlation coefficients (CC) above 0.8 and separation distances of no more than 1 km. Windows started 5 s before the P-wave and ended 40 s after the Lg-wave. The waveforms were filtered from 0.5 to 5 Hz. Only two events or one pair met the same criteria for repeating events as were used in China. This is 1% of the seismicity as compared to 9% in China (1,301 events out of ~14,000). However, the correlations are intended to find similar events that are close enough to use as empirical Greens functions for Q tomography.

Figure 6d shows the separation distance of the pairs that met the CC > 0.5 criteria, revealing that most of them indeed are close to each other within location errors. One explanation of why there is a smaller percentage of similar events in the Middle East as compared to China is the separation distance. 110 out of 373 total events (29%) have at least one other event occurring within 10 km based on the catalog locations in the Middle East, whereas in China, 5,152 out of 14,214 events (36%) have at least one other event within 10 km based on the locations in the Annual Bulletin of Chinese Earthquakes (ABCE). The magnitude distributions for the two regions are similar (Figures 6a and 6b) for magnitude 4 and larger, so greater source complexity for larger magnitudes doesn't seem to be the reason for the smaller percentage of high correlations. Although magnitude 3.0s are missing from the Middle East dataset which in general probably have a greater chance of having similar waveforms. This is because these smaller events have simpler rupture areas and are very often in close proximity to one another. The other reason that the waveforms could be less similar in the Middle East would be if there were greater variability in focal mechanisms between nearby events. We are attempting to solve this problem by extracting many more waveforms with smaller magnitudes than we previously used in our two-station approach. The catalog of events for which we have collected waveforms is shown in Figure 7. We expanded our two-station waveform database by a factor of 10 in order to find more highly correlative waveforms from which we can create a reliable catalog of known source spectra.

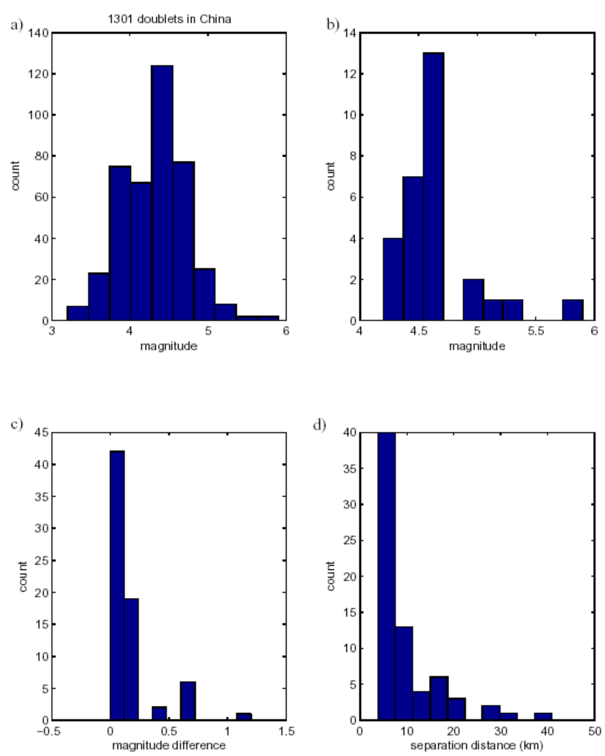


Figure 6. Comparison of magnitude distribution for doublets in China (a) and the Middle East (b). Distribution of magnitude difference (c) and separation distance (d) for pairs meeting the CC > 0.5 criteria.

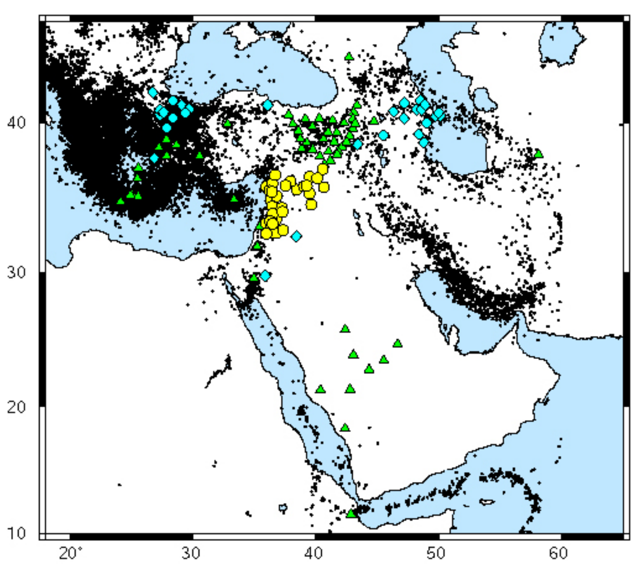


Figure 7. A map showing all seismic stations (colored symbols grouped by network) and seismic events from which we have collected seismic waveforms. We are in the process of searching this database to find event pairs with large cross-correlation coefficients.

CONCLUSIONS AND RECOMMENDATIONS

In this study, we processed a large set of new broadband waveform data to obtain both a Pg and Lg Q model for much of the Middle East. The resulting tomographic model in Figure 2b clearly shows the variation in Lg Q across the boundary between the Arabian Plate and the Turkish Plateau portion of the Eurasian Plate. The Lg Q_o values are generally higher within the Arabian Plate than beneath the Turkish Plateau. Other studies have similarly concluded that Lg propagation in the Turkish-Iranian Plateau is usually blocked or highly attenuated (Sandvol et al., 2001; Al-Damegh et al., 2004, Cong and Mitchell, 2005). We also observe substantial variation in Pg and Lg Q_o values within the Arabian Plate itself; we observe higher values beneath the Arabian shield than beneath the Arabian and northern Arabian Platform.

High Pg and Lg attenuation values within the Anatolian plateau (Q_o ~100–200) may be caused by a combination of scattering and intrinsic attenuation. Scattering attenuation is due to the tectonic complexity and the intrinsic attenuation could be due to the widespread crustal melting. However, the low Q_o values in eastern Anatolian plateau (~70–100) and portions of western Turkey (~60 to150) are probably due to the widespread Quaternary volcanism. In western Turkey, there is a correlation with the location of the young volcanism and the geothermal activity (İlkışık, 1995; Göktürkler et al., 2003). Zhu et al. (2006) have shown that the crustal thickness of western Turkey probably does not change rapidly enough to reduce or block the Lg phases and or affect Pg propagation. Beneath the western Taurus Mountains in southern Anatolia, relatively normal Pg and Lg Q_o values (~200–300) have been found. These relatively higher values may be related to the root of the mountain that would comprise a stable continental crustal waveguide like that in southernmost Tibet in the general region of the high Himalayas (>300) (Xie et al., 2004). Furthermore, the sedimentary cover is limited in this region, which might also improve the efficiency of Lg propagation in this region and attenuate the Pg waveforms. This would help to explain the very high Lg/Pg ratios that were found by Sandvol et al., (2001). For northeastern Turkey, the Caucasus and Azerbaijan, we also found some low to normal Lg Q_o values (~170–180) as well as some blocked two-station paths.

We found large variations in Pg and Lg Q_o for paths crossing the Arabian Peninsula (~300-800). The northern Arabian platform crust has low to normal Lg Q_o values (~300–350). In addition, we observe high Q_o values (~670–800) for the southern Arabian Plate where previous Lg/Pg studies show little attenuation. This is probably due to the lack of any substantial sedimentary cover in the Arabian shield. We also observe lower Q values (~550) for paths crossing the northern and southern Arabian platform where the sedimentary layer is thicker than the western Arabian plate. Additionally, we have found a dramatic decrease in Lg Q_o across the Arabian-Eurasian plate boundary. This is mostly due to a fundamental difference in the rheology of the Anatolian crust compared with the Arabian crust. Paths to the south of the Bitlis suture have Lg Q_o values of ~350–550 but the paths crossing the Bitlis suture have an Lg Q_o of ~200. This decrease may be related to the higher intrinsic attenuation due to partial melt in the eastern Anatolian Plateau. In contrast, the Pg Q values are uniformly low throughout the northernmost Arabian plate and into the Anatolian plateau.

Our primary focus for the remainder of our project is to attempt to validate both our final Pg and Lg Q models. We have finalized these models; however, it is important to verify that they can be used to extract information about the source spectra before they can be helpful in extracting reliable source spectra information (i.e., corner frequency and stress drop). Thus we are continuing our work on developing a method to validate our Lg and Pg attenuation models. In order to accomplish this validation we must create a catalog of calibration seismic events in which we have reliable earthquake source spectra. In order to obtain these events we are going to use earthquake event pairs with from which we can obtain the earthquake source spectra parameters. The resulting catalog can be used to both validate and to calibrate our existing Pg and Lg models. We are planning to adjust our tomographic models to successfully extract the source spectra in order to help create transportable discriminants for the Middle East.

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