

## Measurements of Regional Phase Q in the Middle East

Eric Sandvol<sup>1</sup>, Ekrem Zor<sup>2</sup>, Bao Xueyang<sup>1</sup>, Jiakang Xie<sup>3</sup>, Brian Mitchell<sup>4</sup>, Arif H. Gasanov<sup>5</sup>, and Gurban Yetirmishli<sup>5</sup>

University of Missouri<sup>1</sup>, TUBITAK Marmara Research Center<sup>2</sup>,  
Air Force Research Laboratory<sup>3</sup>, St. Louis University<sup>4</sup>, and Azerbaijan National Academy of Science<sup>5</sup>

Sponsored by National Nuclear Security Administration  
Office of Nonproliferation Research and Development  
Office of Defense Nuclear Nonproliferation

Contract Nos. DE-FC52-03NA99518<sup>1</sup>, DE-FC52-03NA99519<sup>3</sup>, and DE-FC52-03NA99520<sup>4</sup>

### **ABSTRACT**

In order to construct reliable frequency-dependent Q models for both Lg and Pg, we have used approximately 5,000 waveforms from approximately 200 events recorded by 10 permanent and temporary networks throughout the Middle East. Waveforms with unstable values that had higher standards were separated from the final data file used in our model. Using these waveforms, we have developed a tomographic model with frequency-dependent Q using direct Lg waves in this region. Our tomographic model of Lg  $Q_0$  is consistent with previous, more-qualitative Lg attenuation models that showed inefficient or blocked Lg across the Eurasian-Arabian plate boundary. We have also found, similar to the previous models, efficient Lg propagation throughout much of the Arabian Plate. The lowest  $Q_0$  values found were located in the East Anatolian Plateau (~70 to 100) and East Anatolian Fault Zone (~80 to 120). The systematic variations appear to correlate with regions where there is evidence of Sn-to-Lg converted energy leaking into the Lg group velocity window.

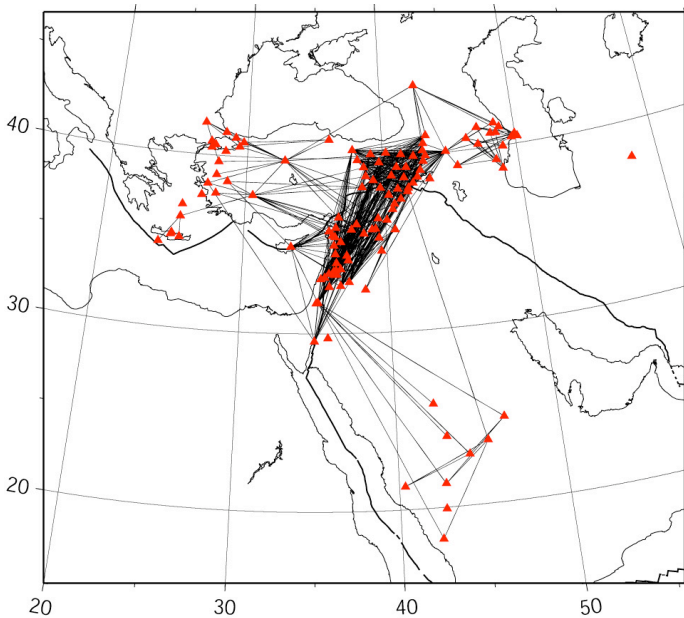
We have also measured Pg across the Middle East, including the Arabian Platform and the Arabian Shield. We have manually picked the Pg group velocity window for the seismograms used in the Q-calculations. We also used this process to identify the seismic waveforms where there was a clear Pg phase. In 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 than what we have found for Lg. We have found a higher eta ( $\eta \sim 0.4$ ) for Pg as compared with Lg. Resolution tests of 2 x 2 cell size for our Pg-Q tomography indicate that we have very good resolution throughout much of the Anatolian plateau. Currently, we cannot resolve details within much of the northern Arabian Plate or the Dead Sea Fault System (DSFS). We still expect to improve on our existing coverage by including waveform data from the Syrian National Seismic Network (SNSN). The SNSN is currently installing several broadband seismometers that will be very important because they are located along key regions of the northern DSFS, and they have reliable instrument response information.

## OBJECTIVES

The objective of this study is to obtain laterally varying Q models for multiple regional waves, including Lg, Pg, and Pn, 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 Q models may be region specific. We will divide the Middle East into several sub-regions of constant Q. 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 waves 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 with reliable instrument response information for both the short period and broadband stations (Figure 1).



**Figure 1.** The current two station paths for Turkey and surrounding regions that we have used for both Pg and Lg. We have determined reliable Q measurements for all existing paths.

## RESEARCH ACCOMPLISHED

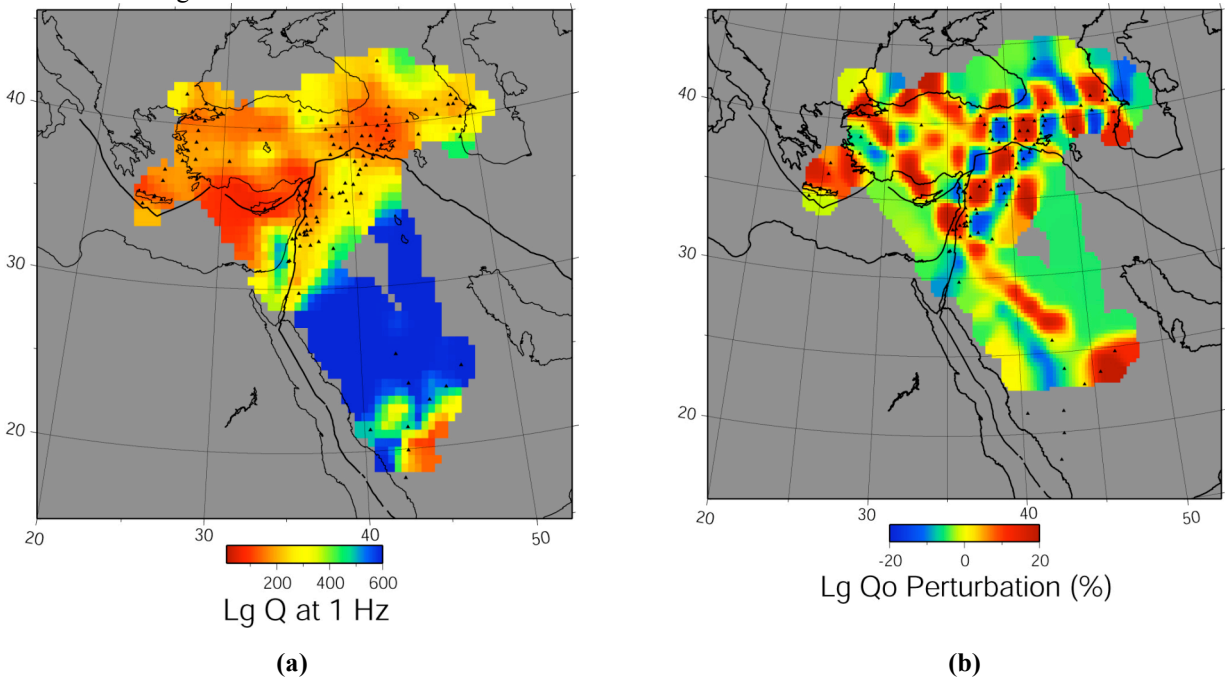
We determined the possible two-station paths aligned with every source. To define the alignment we use an angle  $\delta\theta$ , which is the difference between the azimuths from the source and the two stations. The choice of  $\delta\theta_{max}$  is less restrictive for Lg than for many other phases. The  $Q_0$  and  $\eta$  values may contain errors because of the effects of 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 15°, 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 ( $\Delta_{ij}$ ). The potential error caused by  $\Delta_{ij}$  is strongly related to the estimated  $Q_0$  value for the corresponding path and can be estimated by using the equation given by Xie et al. (2004):

$$\frac{\delta Q_0}{Q_0} \approx 1.1 \left( \frac{Q_0}{\Delta_{ij}} \right) \quad (1)$$

In order to keep this error lower than 35% with a given modeling error value ( $\delta x$ ) as 0.2, the inter-station ratio between  $Q_0$  and  $\Delta_{ij}$  should not be greater than 1.6. By applying the criterion of  $\delta\theta_{max} = \pm 15^\circ$  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  $Q_0$  and  $\eta$ , 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 define our frequency dependent Q model using  $Q_0$  and  $\eta$  using the following relation:

$$Q(f) = f^{\eta-1} Q_0 \quad (2)$$

We also show two interesting inter-station paths crossing the western Taurus Mountains in southern Anatolia and the eastern Mediterranean. Exceptionally low to normal Lg  $Q_0$  values have also been found for stations ISP-MALT (~150-315) and CSS-EIL (~300). The relatively higher values beneath the western Taurus Mountains may be related to the root of the mountain. In the eastern Mediterranean, we observe what appears to be a relatively fast (3.9 km/s group velocity) phase for the inter-station path between Israel and Cyprus (Figure 1). It is not classified as Sn because it arrives much later than a typical Sn. The usual Sn window is plotted in the figure using the upper mantle velocity between 4.5 and 4.7 km/s. With its relatively fast group velocity and its path through oceanic crust, this is probably energy converted from Sn to Lg. The conversion is probably occurring along the northern coast of the Sinai, west of the southern DSFS. This conversion will bias our Q measurements upward along the eastern Mediterranean. It is interesting to note, however, that the Lg Q values are consistent with the number we obtained from the DSFS region.



**Figure 2.** (a) Our current Lg Q tomography for the Middle East and surrounding regions. (b) Resolution checkerboard test using the two-station paths shown in Figure 1.

### Mapping Variations in Lg $Q_0$ and $\eta$

Of the 1,383 two-station pairs, those paths with standard deviations greater than 50% from the linear regression were excluded from the tomography. This model is a significant improvement for the Dead Sea Fault region, where we have added approximately 600 new two-station paths using data from the SNSN. Even though this is primarily a short period network, we were able to verify that we have accurate instrument response data for all 26 short period stations in the SNSN using reverse two-station paths.

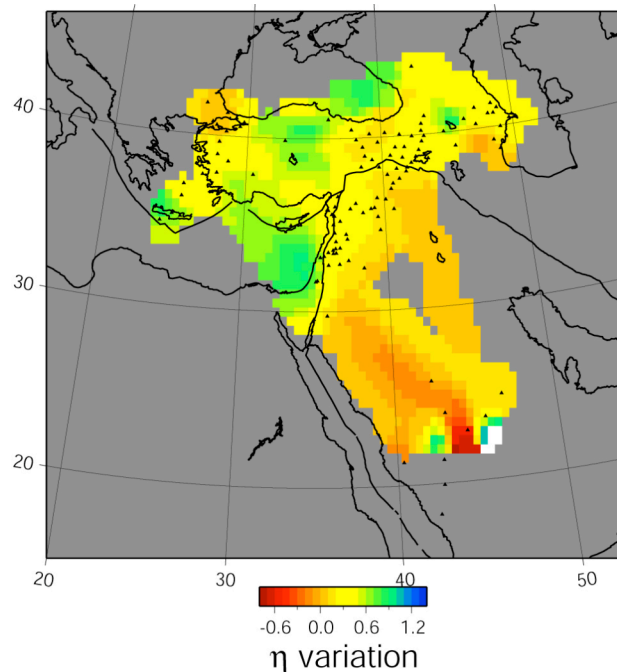
We have defined a two-station blocked Lg path as a two-station pair, where Lg is observed at the closest station and then not observed at the more-distant station. Hence, we know that the Lg blockage is occurring between the two

stations. After averaging repeated observations from 296 unblocked two-station paths, the resulting Lg  $Q_0$  values were used to obtain a laterally varying  $Q_0$  model, as shown in Figure 2a, using a  $1^\circ \times 1^\circ$  cell size. We used the average Lg  $Q_0$  of 148 for the initial constant  $Q_0$  model for the study area. From the total of 720 cells, 198 were sampled and used. The variance reduction is 43% over an initial constant  $Q$  model, corresponding to 70% variance reduction in predicted amplitudes. Although stable measurements of inter-station  $\eta$  values are much more difficult to obtain than those of  $Q_0$  values, as stated by Xie et al. (2004), an attempt has been made to invert for laterally varying  $\eta$  values and their deviation from the linear regression.

In order to increase path coverage and resolution, we supplemented the 296 unblocked paths with 154 blocked paths in our tomographic model. In order to estimate the  $Q$  values for these blocked paths, we used the equation below:

$$\frac{V_{Lg}}{\pi\Delta_{ij}} \ln \left( \left( \frac{\Delta_i}{\Delta_j} \right) A_{loss} \right) = f^{1-\eta} Q_0^{-1} \quad (3)$$

We have assumed a  $V_{Lg} = 3.5 \text{ km/s}$  and  $A_{loss} = 99.0$ . This represents a 99% amplitude loss from the first ( $i^{\text{th}}$ ) station to the second ( $j^{\text{th}}$ ) for  $f = 1 \text{ Hz}$ . We term this value the maximum allowable Lg  $Q_0$ . Of course the actual  $Q_0$  value is probably less than this value. Attenuation perturbations of  $\pm 20\%$  were used to calculate a synthetic data set. By using a series of checkerboards with different cell sizes, we estimated that the smallest easily distinguished cell size is  $2^\circ \times 2^\circ$ . The checkerboard test for the tomographic inversion is shown in Figure 2b. As can be seen from this figure, we have excellent resolution for the areas where we have good coverage in terms of crossing rays. In the areas where we do not have enough crossing rays, such as in the Arabian Plate, smearing reduces the resolution.



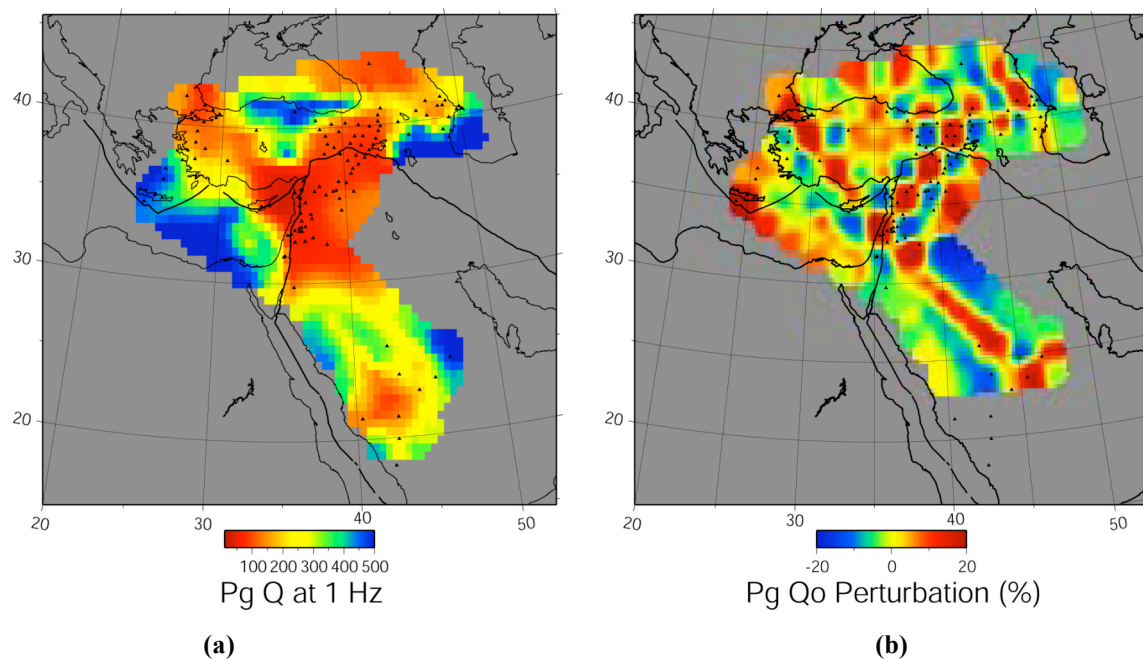
**Figure 3.** Frequency dependence for Lg attenuation in the Middle East. In general, we observe lower  $\eta$  values where we have higher  $Q$  values.

We also finalized our model for the frequency dependence of Lg  $Q$ . Figure 3 shows our map of  $\eta$  for the northern Middle East. We found an anomalously low average  $\eta$  for the Middle East (0.22). We also found large regions of negative  $\eta$ . We found a correlation between large  $Q$  values and small  $\eta$  values that is consistent with frequency-dependent coda- $Q$  measurements. The spatial variation in  $\eta$  also suggests that these anomalously low  $Q$  measurements might be, to some extent, a function of Sn-to-Lg converted energy.

**Comparison with Coda Measurements (e.g., Cong and Mitchell, 1998)**

Given the larger number of available coda-Q measurements, it is important to compare frequency dependent Q models for the Middle East. The most comprehensive Lg coda-Q model for the Middle East is Cong and Mitchell (1998). The comparison of the two Lg Q models reveals a number of important consistencies and some interesting differences. Overall, the direct phase and coda measurements demonstrate a strong and relatively rapid increase in attenuation across the Arabian-Eurasian plate boundary and relatively small attenuation across the Arabian Shield. The direct phase methods have some further complexity that must be verified but suggest that much of the Lg attenuation in the Middle East is concentrated within the fault zones.

In terms of the frequency dependence of the coda and direct Lg Q measurements, the coda measurements of  $\eta$  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  $\eta$ . This includes the finding of smaller values for the Arabian Shield (-0.1 for the direct phase and 0.4 for coda) and larger values for the Anatolian plateau (0.5 for direct phase and 1.0 for the coda measurements).



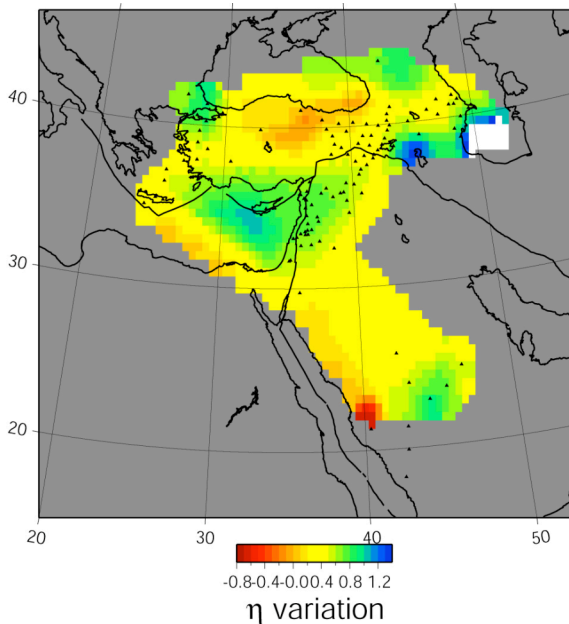
**Figure 4.** (a) Our current Pg Q tomography for the Middle East and surrounding regions. (b) Resolution checkerboard test using Pg two-station paths. This model suggests that we have good resolution for most of the northern Arabian-African-Eurasian plate boundaries but are still lacking data resolution within much of the Arabian plate.

**Mapping Variations in Pg Q<sub>o</sub> and  $\eta$**

We have also created a Pg-Q model for the Middle East. We measured Pg across the Arabian platform and the Arabian shield. We manually picked the Pg group velocity window for the seismograms used in the Q calculations. We also used this process to identify the seismic waveforms where there was a clear Pg phase. In general, we found Pg-Q values between 100-200 for northern Arabian Plate and Anatolian Plateau and between 200 and 300 for the Arabian Shield (Figure 4). Similar to our Lg Q model, this model has very good resolution for most of the northern Middle East, including the DSFS, Anatolian Plateau, and Lesser Caucasus. It is important to note that we have assumed an “Lg-like” geometrical spreading function for Pg; however, this assumed function should not greatly affect relative variations in Pg attenuation. We have begun work on estimating the Pg geometrical spreading term and have preliminary results suggesting that it does not vary a great deal across the Middle East.

The Lg and Pg Q models are fairly consistent with regional variations in amplitude ratios for the region. The low Pg Q along the Dead Sea Fault helps to explain the relatively large Lg/Pg amplitude ratios that we have observed there (Sandvol et al., 2001).

Not surprisingly, we found that the Pg-Q does not vary quite 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  $\eta$  value, however, is higher ( $\sim 0.4$ ) for Pg than for Lg (Figure 5). 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 5** Frequency dependence for Pg. The average  $\eta$  value for the Middle East is 0.25. We have found relatively constant frequency dependence. The only significant variation occurs in regions where we have relatively low resolution (see Figure 4b.).

## CONCLUSION(S) AND RECOMMENDATIONS

In this study, we processed a large set of new broadband waveform data to obtain an Lg Q model for much of the Middle East. The resulting tomographic model in Figure 2a 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  $Q_0$  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). We also observe substantial variation in Lg  $Q_0$  values within the Arabian Plate itself; we observe higher values beneath the Arabian Shield than beneath the Arabian and northern Arabian Platforms. These higher values could be due, in part, to systematic errors, given the lack of crossing paths in this portion of our model. Similarly, the Turkish Plateau also shows some significant variation in crustal attenuation, with normal Lg  $Q_0$  values observed beneath the central Taurus Mountains and very low Lg  $Q_0$  values beneath the eastern Anatolian Plateau and western Turkey around the Menderes Massif. Of course some sub-regions are not sampled by the two-station paths because of the lack of stations in central Anatolia from south to north.

High Pg and Lg attenuation values within the Anatolian Plateau ( $Q_0 \sim 100$  to 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 wide spread crustal melting. However, the low  $Q_0$  values in the eastern Anatolian Plateau ( $\sim 70$  to 100) and portions of western Turkey ( $\sim 60$  to 150) 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 heavily attenuate Pg. Similarly, the receiver function waveform inversion in eastern Turkey has suggested that there is no rapid change in the crustal thickness across the Bitlis Suture and East Anatolian Fault Zone. They also observed localized mid-

## 28th Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies

crustal seismic low-velocity zones scattered throughout the eastern Anatolian Plateau. These low-velocity zones might be an indication of partial melt within the eastern Turkey crust (Zor et al., 2003). This inference is also supported by the widespread young (less than 6 Ma) volcanism in the region (e.g., Keskin, 2003) and low Pn velocities (Hearn and Ni, 1994; Al-Lazki et al., 2004) coupled with high Sn attenuation (Gok et al., 2003; Al-Damegh et al., 2004) as an indication of anomalously hot lithosphere.

Beneath the western Taurus Mountains in southern Anatolia, relatively normal Pg and Lg  $Q_0$  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. It is important to note that our paths are all parallel to the strike of the mountain front. Gok (2000) suggests that paths that are perpendicular to the Taurides tend to be inefficient or blocked. We were unable to test this because of the lack of perpendicular two-station paths in this region. For northeastern Turkey, the Caucasus, and Azerbaijan, we also found some low-to-normal Lg  $Q_0$  values (~170-180), as well as some blocked two-station paths.

We found large variations in Pg and Lg  $Q_0$  for paths crossing the Arabian Peninsula (~300-800). Our Lg  $Q_0$  values are roughly consistent with the observations from Lg coda-Q (350-500) by Mitchell et al. (1997) and Cong and Mitchell (1998). However, they did not observe Lg  $Q_0$  values as high as ours (~800) in the Arabian Plate. This slight inconsistency may be caused by the difference in sampling area between direct Lg and Lg coda. However, it is important to note that we still have relatively few paths crossing the Arabian Shield; therefore, systematic errors caused by the effect of lateral changes in the crustal structure may have a large effect on our measurements. The northern Arabian Platform crust has low-to-normal Lg  $Q_0$  values (~300-350). In addition, we observe high  $Q_0$  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 for the western Arabian Plate. Additionally, we have found a dramatic decrease in Lg  $Q_0$  across the Arabian-Eurasian plate boundary. This is 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  $Q_0$  values of ~350-550, but the paths crossing the Bitlis Suture have an Lg  $Q_0$  of ~200. This decrease may be related to the higher intrinsic attenuation from 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.

We have found that in order to achieve sufficiently dense two-station paths to cover the Middle East, it is necessary to integrate data from a variety of temporary and permanent, short-period and broadband seismic stations. Using these large data sets, it is possible to construct a reliable model for Lg Q throughout the northern portions of the Middle East and DSFS. We are currently in the process of calculating Q models for Pn, Pg, and Lg.

Clearly, one of the most challenging aspects of calculating Lg in the Middle East is the large number of blocked paths. Therefore, it is critical to accumulate a large number of waveforms at local and near-regional distances in order to better constrain the Q in the very high attenuation zones such as the eastern Anatolian Plateau. Prior work has established the blockage zones, and these blocked paths will also be used to help create a robust attenuation model for the majority of the Middle East. It is therefore essential that more data be collected for these regions of exceptionally low Lg Q, such as the lesser and possibly greater Caucasus and western Turkey.

After we finalize our Lg Q model, we expect to include more than 1,400 two-station paths using Newton-like nonlinear method for inversion with multiple colocated events. Pg and Lg  $Q_0$  and  $\eta$  values measured using these methods are of very high quality because they are not subject to the trade-off between source and path parameters. Therefore in the tomographic inversion of laterally varying  $Q_0$  and  $\eta$  values, the input  $Q_0$  and  $\eta$  values along approximately 900 paths will be used to derive a more long-wavelength Q map for those regions of the Middle East with good two-station path coverage.

It is also important that the two-station Q measurements and coda-based methods are reconciled, especially the systematic variations in the frequency dependence of coda-Q and the direct-phase Q. We plan to apply available methods for Lg Q determination in order to better quantify the potential differences in the techniques. This should help build a more-robust model for high-frequency wave attenuation in the Middle East. Furthermore, our model

## 28th Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies

needs to be further validated using calibration events with well-known source spectra.

### ACKNOWLEDGEMENTS

We would like to thank Randa Mohamad and Dr. Niyazi Turkelli for providing data from the SNSN and the KOERI network, respectively, and for assisting in the analysis of portions of the data. We would also like to thank Dr. Rob Mellors for providing data from the Azerbaijan Seismic Network and Dr. Arthur Rodgers for providing data from two Lawrence Livermore National Laboratory broadband stations in Jordan.

### REFERENCES

- Al-Damegh, K., E. Sandvol, A. Al-Lazki, and M. Barazangi (2004). Regional seismic wave propagation (Lg and Sn) and Pn attenuation in the Arabian Plate and surrounding regions, *Geophys. J. Int.* 157: 775-795.
- Al-Lazki, A., E. Sandvol, D. Seber, M. Barazangi, N. Turkelli, and R. Mohamad (2004). Pn tomographic imaging of mantle lid velocity and anisotropy at the junction of the Arabian, Eurasian and African Plates, *Geophys. J. Int.* 158: 1024-1040.
- Cong, L. and B. Mitchell (1998). Lg coda Q and its relation to the geology and tectonics of the Middle East, *Pure appl. geophys.* 153: 563-585.
- Der, Z., M. E. Marshal, A. O'Donnell, and T. W. McElfresh (1984). Spatial coherence structure attenuation the Lg phase, site effects, and interpretation of the Lg coda, *Bull. Seismol. Soc. Am.* 74: 1125-1148.
- Gok, R. (2000). Regional wave propagation in Turkey and surrounding regions, *Geophys. Res. Lett.* 27: 429-432.
- Gok, R., E. Sandvol, N. Turkelli, D. Seber, and M. Barazangi (2003). Sn attenuation in the Anatolian and Iranian Plateaus and surrounding regions, *Geophys. Res. Lett.* 30: 8042, doi:10.1029/2003GL018020.
- Göktürkler, G., Salk, M., and Sari, C. (2003). The numerical modelling of the conductive heat flow in western Anatolia, *The Journal of the Balkan Geophysical Society* 6: 1-15.
- Hearn, T., and J. Ni (1994). Pn velocities beneath continental collision zones: the Turkish-Iranian Plateau, *Geophys. J. Int.* 117: 273-283.
- İlkişik, O.M., (1995). Regional heat flow in western Anatolia using silica temperature estimates from thermal springs, *Tectonophy.* 244: 1-3, 175-184.
- Keskin, M. (2003). Magma generation by slab steepening and breakoff beneath a subduction-accretion complex: An alternative model for collision-related volcanism in Eastern Anatolia, Turkey, *Geophys. Res. Lett.* 30: 8046, doi: 10.1029/2003GL018019.
- Mitchell, B. J., Y. Pan, J. Xie, and L. Cong (1997). Lg coda Q variation across Eurasia and its relation to crustal evolution, *J. Geophys. Res.* 102: 22767-22779.
- Nuttli, O.W. (1973). Seismic wave attenuation and magnitude relations for eastern North America, *J. Geophys. Res.* 78: 5212-5218.
- Sandvol, E., K. Al-Damegh, A. Calvert, D. Seber, M. Barazangi, R. Mohamad, R. Gok, N. Turkelli, and C. Gurbuz (2001). Tomographic imaging of observed regional wave propagation in the Middle East, *Pure Appl. Geophys.* 158: 1121-1163.

## 28th Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies

Xie, J., R. Gok, J. Ni, and Y. Aoki (2004). Lateral variations of crustal seismic attenuation along the INDEPTH profiles in Tibet from Lg Q inversion, *J. Geophys. Res.* 109: B10308, doi:10.1029/2004JB002988.

Zhu, L., B. Mitchell, N. Akyol, I. Çemen, and K. Kekovalı (2006). Crustal thickness variation in the Aegean region and its implications for the extension of continental crust, *J. Geophys. Res.* 111: doi:10.1029/2005JB003770.

Zor, E., E. Sandvol, C. Gurbuz, N. Turkelli, D. Seber, and M. Barazangi (2003). The crustal structure of the east Anatolian Plateau from receiver functions, *Geophys. Res. Lett.* 30: 8044, doi:10.1029/2003GL018192.