HIGH-RESOLUTION TOMOGRAPHIC MAPPING OF REGIONAL PHASE Q IN THE MIDDLE EAST

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ABSTRACT

To develop reliable discriminants for a given region, it is essential that source, station, and path effects be isolated. This is even more critical for paths through a region such as the Middle East, where both crustal and uppermost mantle attenuation are very high.

The most efficient method for developing path corrections for potential discriminants is to construct a frequency dependent Q model for the corresponding regional seismic phases Pn, Pg, Sn, and Lg. In Turkey and the surrounding regions, we have finished the collection and distillation of total regional waveforms of 55 stations from the Eastern Turkey Seismic Experiment (ETSE), the Western Turkey Regional Network (WTRN), the Midsea array of ETHZ, GEOFON, MEDNET, and GSN, using the IRIS data management center request tools. We have also used all available waveform data from the broadband stations of the KOERI network that have reliable instrument response information. We calculated 1760 Lg spectra from ~150 events. We obtained Lg Q values from 1151 two-station paths; we only used paths with interstation distances between 150 and 2000 km. Waveforms with complete Lg blockage and unstable values with standard deviations higher than 50% of the estimated Lg Q were excluded from the final data file for tomography. After this data reduction, we had a total of 715 two-station paths with good quality Lg Q and 209 two-station paths with Lg blockage. We expect to improve our tomographic image using the short period stations with this method.

We have found exceptionally low Q_0 values within both the eastern Anatolian plateau (~ 80 to 100) and the western Anatolian active extensional zone, especially the Menderes massif (~80 to 150). We also found low to normal Lg Q_0 values for the northern Arabian plate (~200 to 300) and part of the Taurus Mountains in western Anatolia. Resolution tests of 2ºx2º cell size for our Lg-Q tomography indicate that we have very good resolution throughout much of the Anatolian plateau. We expect to improve on our existing coverage by including waveform data from the JSO (Jordanian Seismological Observatory) and the SNSN (Syrian National Seismic Network).

OBJECTIVE(S)

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.

The difficulty associated with 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.

The difficulty of precise Q measurement is clearly demonstrated by two examples involving the Lg phase. This first is given by Xie & Mitchell (1990), who list eight published Lg Q models for the Basin & Range Province. The 1 Hz Lg Q (Q_0) values in these models vary between 139 and 774, despite the area's being one of the best studied. The second is given by Fan and Lay (2003b), who list a number of previously and recently published models in Tibet. In these models, the Q_0 for the same sub-region (i.e., southern or eastern Tibet) ranges between 60 and 400. Because of these difficulties, the problem of measuring Q using regional waves has been a rapidly evolving research topic. Recently, progress has been made in mapping laterally varying regional wave Q structure, particularly through Q tomography. The primary reason for this progress is that the digital seismic database has grown rapidly, permitting the use of methods for measuring Q that are more precise but require abundant data and/or a specific pattern of path geometries. In the following sections, we will briefly summarize the work of various researchers, including both the Co-P.I.'s, on regional wave Q tomography.

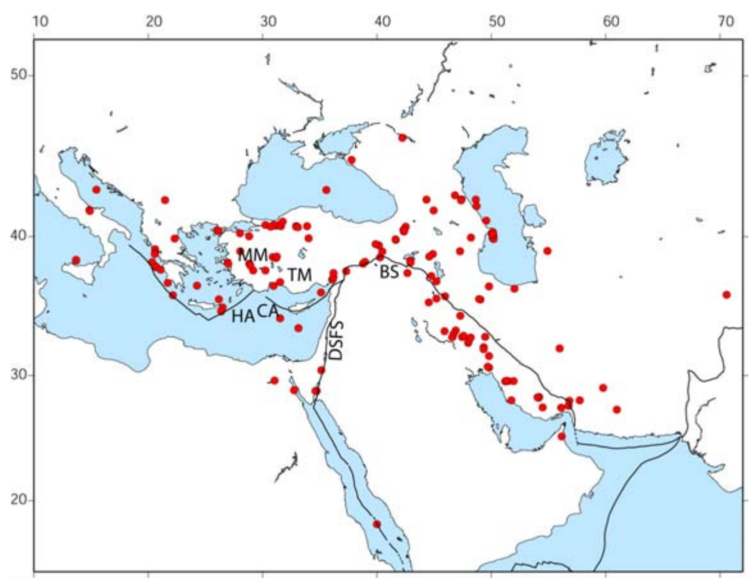

Figure 1. Seismic events used in our study of Lg Q and η. BS- Bitlis Suture; TM- Tauride Mountains; MM-Menderes Masif; DSFS-Dead Sea Fault System; CA-Cyprean Arc; HA-Hellenic Arc.

RESEARCH ACCOMPLISHED

Data Collection

A major component of this proposal is the acquisition and processing of new waveform data in the region. In order to successfully formulate a robust Q model for the four fundamental regional phases, we need to collect and construct a large waveform database for the Middle East. Given the large regions within the Middle East that are not accessible for a variety of reasons, this will continue to be an ongoing problem that we will address.

We have made agreements with scientists in several countries for them to share data for the Middle East. These new databases will greatly improve the existing ray coverage, especially the two station path coverage. Most significantly, we have reached a collaborative agreement with Kandilli Observatory and Earthquake Research Institute (KOERI) to exchange software and waveform data for Turkey. In Turkey and the surrounding regions, we have finished the collection and distillation of total regional waveforms of 55 stations from the Eastern Turkey Seismic Experiment (ETSE), the Western Turkey Regional Network (WTRN), the Midsea array of ETHZ, GEOFON, MEDNET, and GSN, using the IRIS data management center request tools. We have also used all available waveform data from the broadband stations of the KOERI network that have reliable instrument response information. We calculated 1760 Lg spectra from ~150 events. We obtained Lg Q values from 1151 two station paths; we only used paths with apertures greater than 150 km and less than 2000 km. Waveforms with a blocked Lg and unstable values with standard deviations higher than 50% from linear regression were excluded from the final data file for tomography. After this data reduction, we had total 715 two-station paths with good quality Lg Q and 209 two-station paths with zero Lg efficiency. We are still working on developing a method for the short period stations that do not have reliable instrument response. In order to accomplish this task, Dr. Eric Sandvol visited Dr. Jiakang Xie from Lamont Doherty National Laboratory and worked on the test data. We expect to improve our tomographic image using the short period stations with this method. We are still trying to obtain reliable instrument responses for the short period stations in our current database. We are also continuing to work on finalizing the JSO data.

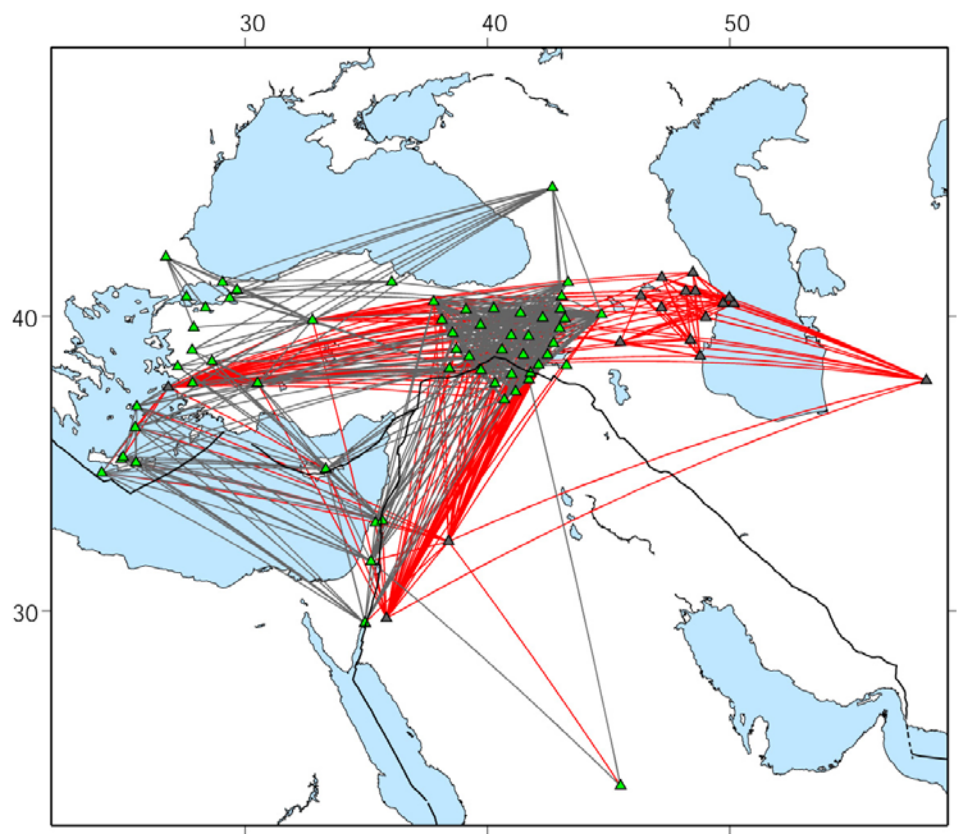

Figure 2. Existing (grey) and potential (red) two station paths for the Turkey and surrounding regions. We have determined reliable Q measurements for all existing paths.

Furthermore, we have begun to process data from the Azerbiajan Seismic Network (ASN). The ASN is composed of 10 broadband stations deployed throughout the Lesser Caucasus. We have begun to select waveforms for key events and analyze them. We have found that a large number of the seismic records that we have examined have little or no Lg energy.

We have also finished collecting waveform data from a number of temporary seismic networks in the Middle East, including the St. Louis University western Turkey Array. This array consisted of 4 broadband and 4 short period instruments running continuously for about a year starting in the fall of 2002. We are also utilizing the large waveform database from the 29-station ETSE broadband seismic network that ran from late 1999 to August 2001 and spanned much of Eastern Anatolia. ETSE in particular has provided us with excellent coverage throughout the eastern Anatolian plateau

Methodology

We are using or planning on using a number of methodologies to isolate the regional wave path attenuation (Q_0 and η) in the Middle East. In the following sections we outline each of the planned methods. Due to the rather non-uniform ray path coverage, we will need to apply different techniques depending upon the regional data availability. Figure 2 shows the two station paths that we have analyzed or plan to analyze in the near future. These paths were selected from data that were recorded during the operation of the ETSE array.

We have employed a two-station method for measuring Lg Q. This method cancels the source effect in Q measurement by using station pairs aligned with the source. Xie and Mitchell (1990) and Xie (2002a) used this method for measuring Lg Q, and presented rigorous error analyses. We have used event-station pairs that are aligned with 15 degrees of being on the same great circle path.

We have begun to collect data in order to examine regional waveform data using the event-pair spectral ratio method. This method was developed by Chun et al. (1987) to measure Pn Q and requires that regional waves (e.g., Lg) be recorded at two stations from two events; all must be located approximately on the same great circle. If this very restrictive recording condition can be met, then the method can simultaneously determine inter-station Q and the station site response**.** This method will then will allow us to incorporate data for which we cannot necessarily trust the instrument response information. For example, although we have instrument response information for many of the short period stations in the northern Middle East, the gain factors can be many orders of magnitude. The reverse two-station method will allow us to remove those stations that do not have reliable instrument parameters. The short period stations in the Middle East do not have reliable response data although our collaborators have provided us detailed gain values and instrument types**.** We are working to eliminate those waveforms with unreliable instrument response information by comparing a number of relative instrument response data.

Qualtiy Control

We have found that it is essential to carefully review our two-station Q measurements in order to ensure that the measurements are reliable. We have manually determined the appropriate frequency range used in the linear regression analysis used to estimate Q_0 and η. We also manually eliminated those two station spectral ratios that had: (1) large estimated uncertainties (larger than 50% errors), (2) large amounts of scatter in the spectral ratio, (3) a clearly nonlinear relationship between amplitude and frequency, or (4) a narrow frequency range (>0.5 Hz) over which the linear regression is determined. These quality control procedures help eliminate a substantial amount of scatter in our Q_0 and η determinations. The majority of our two station Q measurements are repeatable within the estimated errors.

We also chose to include those Q measurements with negative η values. We have found that even for negative values of η, the spectral ratios are very well behaved (i.e. decreasing linearly with decreasing frequency). We are currently working on developing a model of spatial variations in η across the northern Middle East in order to test whether there is any spatially coherent variation in η that would correlate with a tectonic or geologic boundaries such as the Arabian-Eurasian plate boundary.

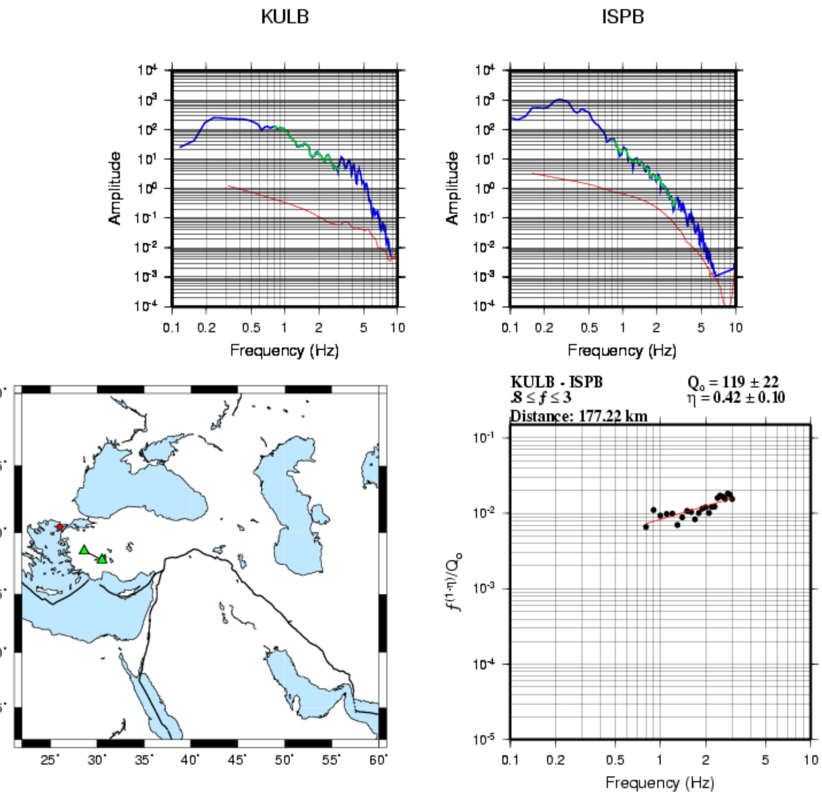

Figure 3. An example of a single Q measurement for a two-station path crossing the Menderes Massif in western Turkey. We have found low Lg Q values throughout most of the regions that are undergoing large amounts of crustal extension.

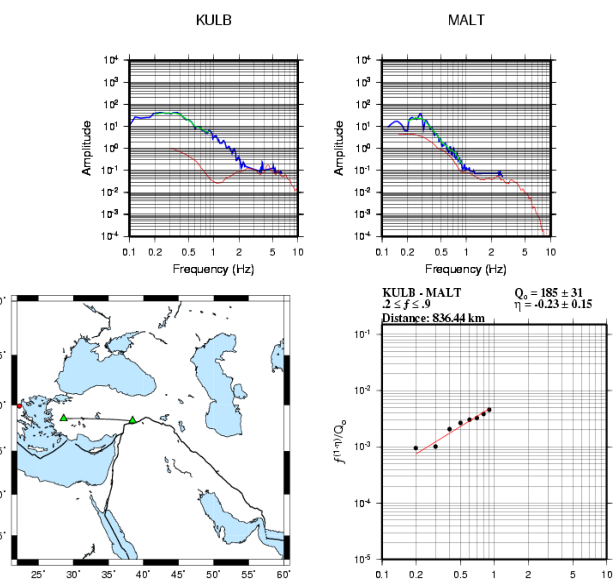

Figure 4. An example of a single Q measurement for a two-station path crossing the eastern Anatolian plateau.

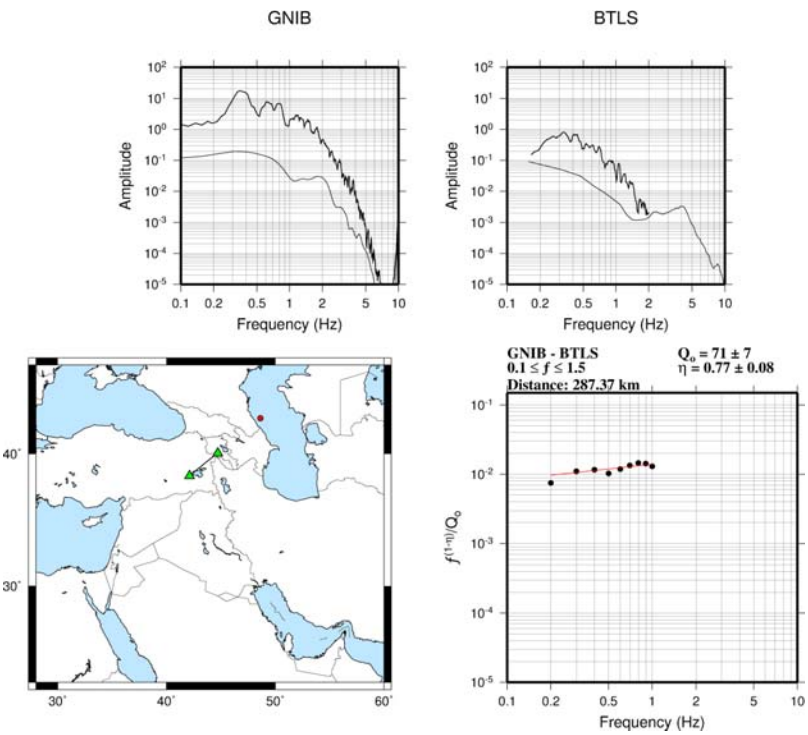

Figure 5. An example of a single Q measurement for a two-station path crossing the eastern Anatolian plateau. We have found exceptionally low Lg Q values throughout most of the Anatolian plateau.

Lg Q tomography for the Middle East

Figures 3, 4, and 5 illustrate some of the example measurements throughout the northern Middle East. We have finished developing a fully automated process of calculating spectra to apply a two-station method for measuring inter-station Q_0. We have taken these two station Q_0-values and developed a tomographic Q_0 model for Turkey and the surrounding region. We have tested several different tomographic algrorithms and found small variations between the different models (Figure 6).

We have found exceptionally low Q_0 values within both the eastern Anatolian plateau (~ 80 to 100) and in western including the Menderes Massif that is consistent with crustal melting. This is to some degree consistent with the Quaternary volcanism that is widespread throughout the Anatolian plateau. In fact, we observe relatively good correlation between very low Q values (less than 100) and the location of Holocene volcanism in the region. We also observe very low Q values in the western Anatolian active extensional zone, especially the Menderes massif (~80 to 150). We also found fairly normal Lg Q_0 values for the northern Arabian plate (~200 to 300), beneath Uludag and part of the Taurus Mountains in western Anatolia. It is important to note that all of the paths traversing the Taurides are east-west paths, so our results may be biased (Gok et al., 2000 observed Lg blockage for ray paths that are perpendicular to the strike of the Taurides).

We found low to normal Lg Q_0 values for the northern Arabian plate (~200 to 300). Variations in crustal structure across the Dead Sea Fault System and across the Palmyride fold and thrust belt do not appear to effect Lg propagation. Within the northernmost Arabian plate, near the Bitlis suture, we find low Q values that once again correspond well with the location of Holocene Volcanism. We observe very little attenuation for paths traversing western Arabian plate (Lg Q = 800) where there are few or no sediments. In eastern Arabia, Lg Q is substantially lower (~450). We also observe inefficient Lg propagation for the paths crossing the southeastern part of Aegean Sea (Figure 5).

In summary, we have found that our initial Lg Q tomography agrees to first order with our Lg/Pg ratio tomography in the region. We observe a good correlation between the high Q in the Arabian plate and the low Q in the Eurasian and Anatolian Plates. We also observe very high Lg Q values along the western Arabian plate and lower Q values within the eastern Arabian plate (Arabian platform).

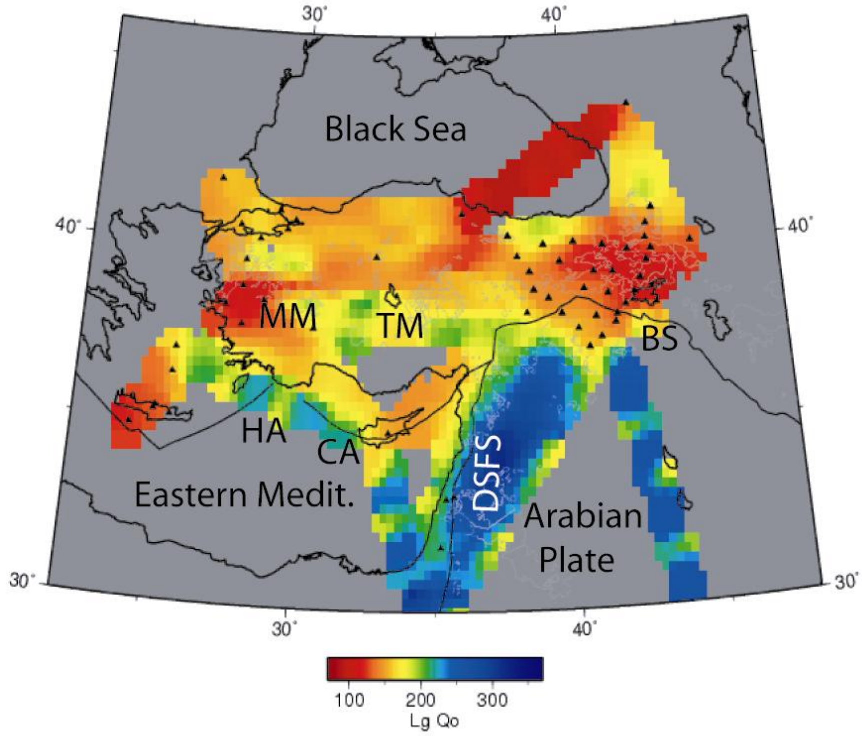

Figure 6. Preliminary Lg Q-tomography for Turkey and surrounding regions. BS- Bitlis Suture; TM-Tauride Mountains; MM- Menderes Masif; DSFS-Dead Sea Fault System; CA-Cyprean Arc; HA-Hellenic Arc.

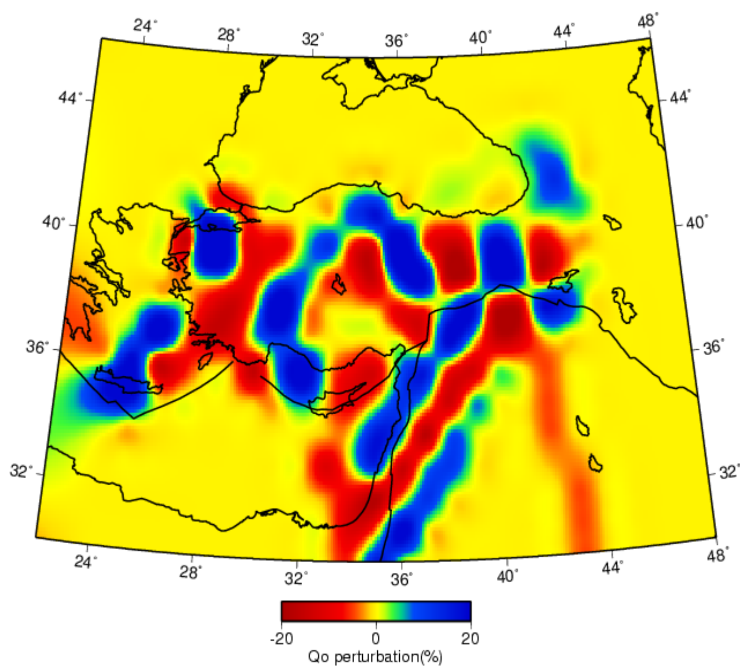

Figure 5. Checkerboard resolution of 2x2 cell for the preliminary Lg Q-tomography for eastern Turkey and the surrounding regions.

Resolution tests of 2x2 cell size for our Lg-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. We expect to improve on our existing coverage by including waveform data from the JSO (Jordanian Seismological Observatory) and the SNSN (Syrian National Seismic Network).

CONCLUSION(S) AND RECOMMENDATION(S)

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 Dead Sea Fault System. 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 over 1200 two station paths using methods 1 and 2 in the last section or the Newton-like non-linear method for inversion with multiple co-located events. Lg Q_0 and η values measured using these methods are of very high quality since they are not subject to the trade-off between source and path parameters. Therefore in the tomographic inversion of laterally varying Q_0 and η values, the input Q_0 and η 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.

We believe that it is essential to reconcile our two station Q measurements with those using alternative methods and coda based methods. We plan to apply available methods for Lg Q determination in order to better quantify the potential differences among the techniques. This should help build a more robust model for high frequency wave attenuation in the Middle East.

ACKNOWLEDGMENTS

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