

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

### 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. We have collected waveform data from a wide variety of sources in the Middle East. A large number of digital seismograms (approximately 8,000) yield dense path coverage for all four regional seismic phases throughout most of the northern portion of the Arabian plate as well as the Anatolian and Iranian plateau regions. These waveform data are collected from PASSCAL experiments in Turkey, Saudi Arabia, and the Caspian Sea region and from national networks, ground station network (GSN) stations, and various other permanent and temporary sites. This dense coverage should dramatically improve the resolution of the Q tomography. Moreover, it allows the bias in Q measurements to be minimized by using methods that are more reliable, but require restrictive path geometries. The tomography will yield high-resolution maps of laterally varying Lg  $Q_0$  and h (Lg Q at 1 Hz and its power-law frequency dependence, respectively) as well as  $Q_{Pg}$  in the Middle East. This study will also yield regionalized Q models for Pn and Sn.

Our strategy is to begin in regions where we have very dense two station ray paths; therefore, we have chosen to begin our focus on the eastern Anatolian plateau and northern Arabian plate where we have data from the Kandilli Observatory and Earthquake Research Institute (KOERI), Jordanian Seismic Observatory, and from the temporary PASSCAL network in eastern Turkey (ETSE). This region has been shown to be a region of anomalously high Lg and Sn attenuation and blockage. Our Q-models will be used to quantify the level of attenuation within the Anatolian plateau.

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### OBJECTIVE

The objective of this study is to obtain laterally varying Q models for multiple regional waves, including Lg, Pg, Pn and Sn, 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 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.

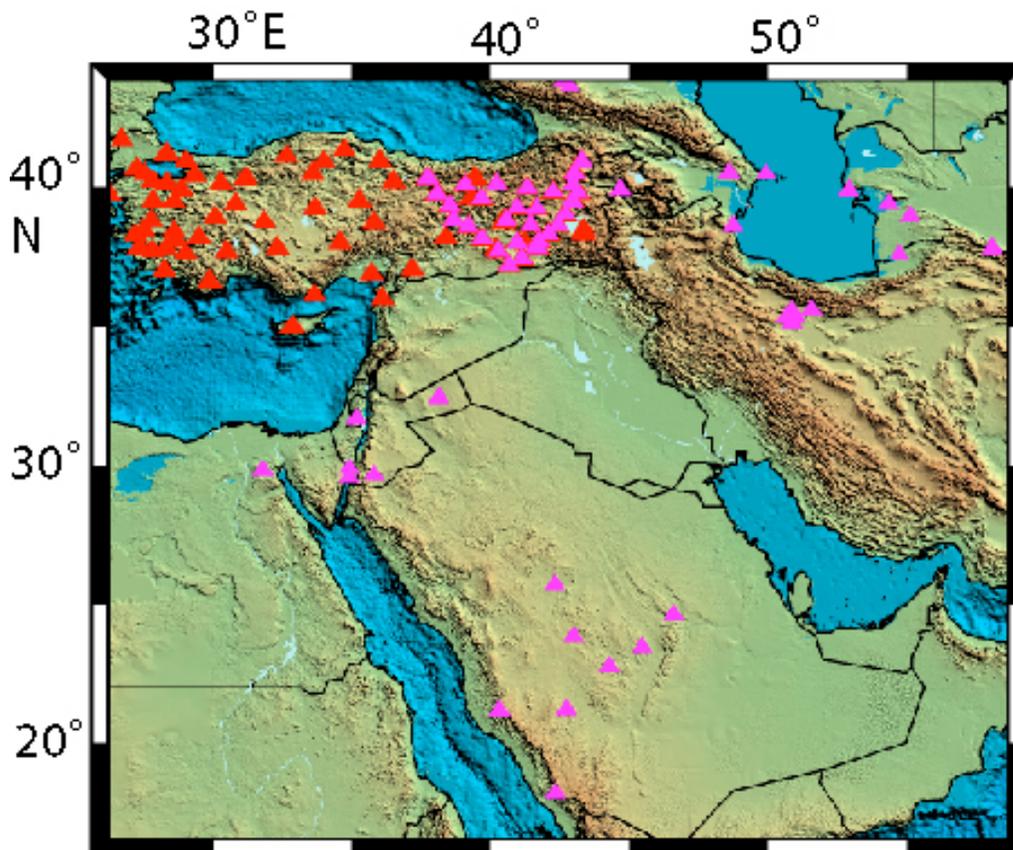
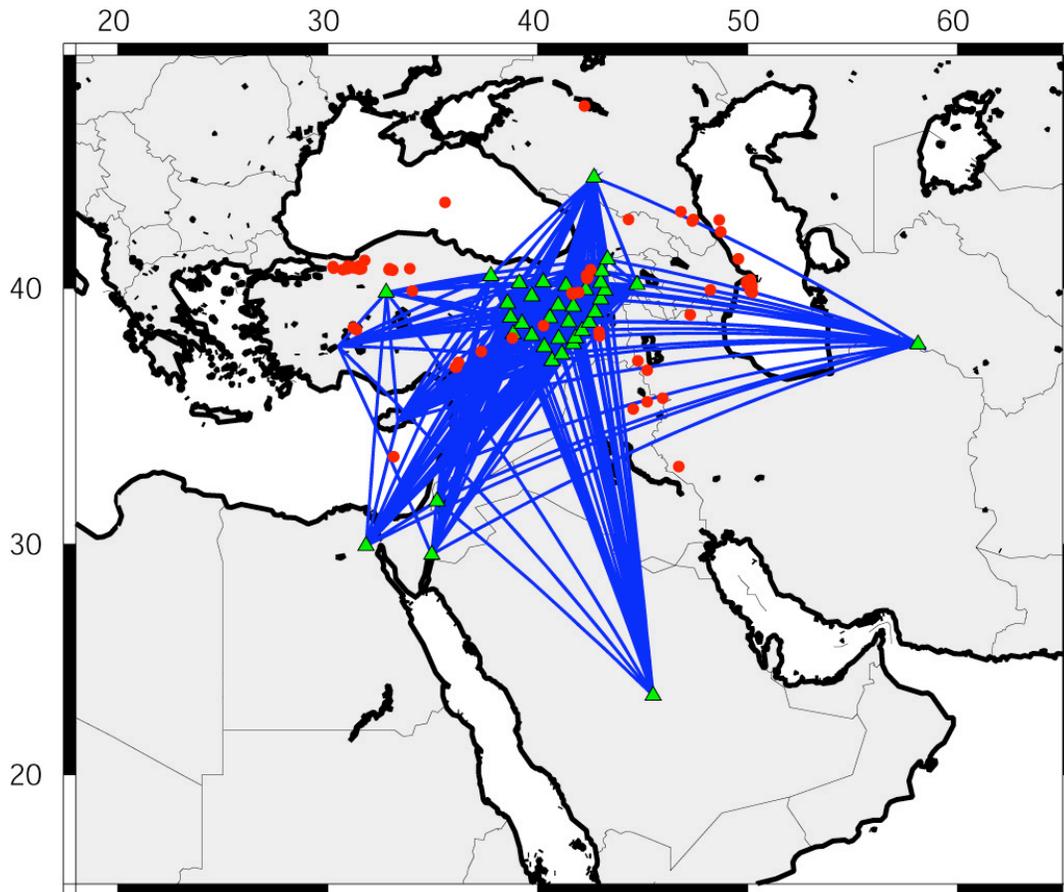


Figure 1. Stations for which we will have waveform data in the Middle East. Red triangles are stations for which we plan to acquire data; magenta triangles are those for which we already have waveform data.

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The difficulty of precise Q measurement is clearly demonstrated by two examples involving the Lg phase. This first is given by Xie and Mitchell (1990), who lists eight published Lg Q models for the Basin and 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. Despite the difficulties, the problem of measuring Q using regional waves has been a rapidly evolving research topic. Recently, progress has been made on mapping laterally varying regional wave Q structure, particularly through Q tomography. There are two reasons for this progress: first, there is high demand from the scientific and nuclear monitoring community to acquire realistic Q models. Second, 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-principal investigator's, on regional wave Q tomography.



**Figure 2.** All existing two station paths for in the Middle East between 1999 and 2001. Given the excellent coverage in eastern Turkey we are beginning to calculate inter-station Q values for all of these paths except for those events with blocked Lg.

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### 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. The KOERI national network combined with the temporary PASSCAL networks give us dense and rather uniform data coverage for all of Anatolia and many of the surrounding regions (see Figure 1). This network is composed of 16 broadband stations and another 32 short period stations. These data will be combined to give excellent ray path coverage for the all of the Anatolian plateau and a large portion of the Eastern Mediterranean and northern Arabian plate. The data have all been digitized by either 16 or 24 bit digitizers and a substantial portion of the data has been visually inspected to confirm the existence or absence of the primary regional phases as a part of the Ph.D. thesis work of Rengin Gok.

Furthermore, we have made an agreement with Prof. Eid Tarazi to collaborate on analyzing waveform data from the Jordanian Seismological Observatory (JSO). The JSO consists entirely of short period single component instruments that are distributed throughout Jordan. We have begun to select waveforms for key events and analyze them during Professor Tarazi's visit to the University of Missouri. We are also continuing to work to establish a collaborative agreement with Syrian National Seismic Network (SNSN).

We are also 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.

#### Methodology

We are using a number of methodologies to isolate the regional wave path attenuation ( $Q_0$  and  $\eta$ ) 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 was recorded during the operation of the ETSE array.

##### *Methods of inversion for path-variable regional wave $Q$*

Over the years the P.I.'s have developed and/or implemented several methods for measuring regional wave  $Q$ . These methods are briefly described in the following sections.

- (1) *The standard two-station method for measuring inter-station  $Q$ .* 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  $L_g Q$ , and presented rigorous error analyses.
- (2) *The reversed two-station, two-event spectral ratio method.* This method was developed by Chun et al. (1987) and requires that regional waves (e.g.,  $L_g$ ) 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 (factor (4) in §1.1).
- (3) *The event-based, Bayesian method that simultaneously determines source  $M_0$  and  $f_c$  and path-variable  $Q_0$  and  $h$  by Xie (1993, 1998).* This method is based on Tarantola's Bayesian inverse scheme (Tarantola, 1987). With a priori information on path obtained using methods (1) and (2), and on source obtained using method (5) below, this method is robust and capable of reducing or eliminating the trade-off between source and path parameters.

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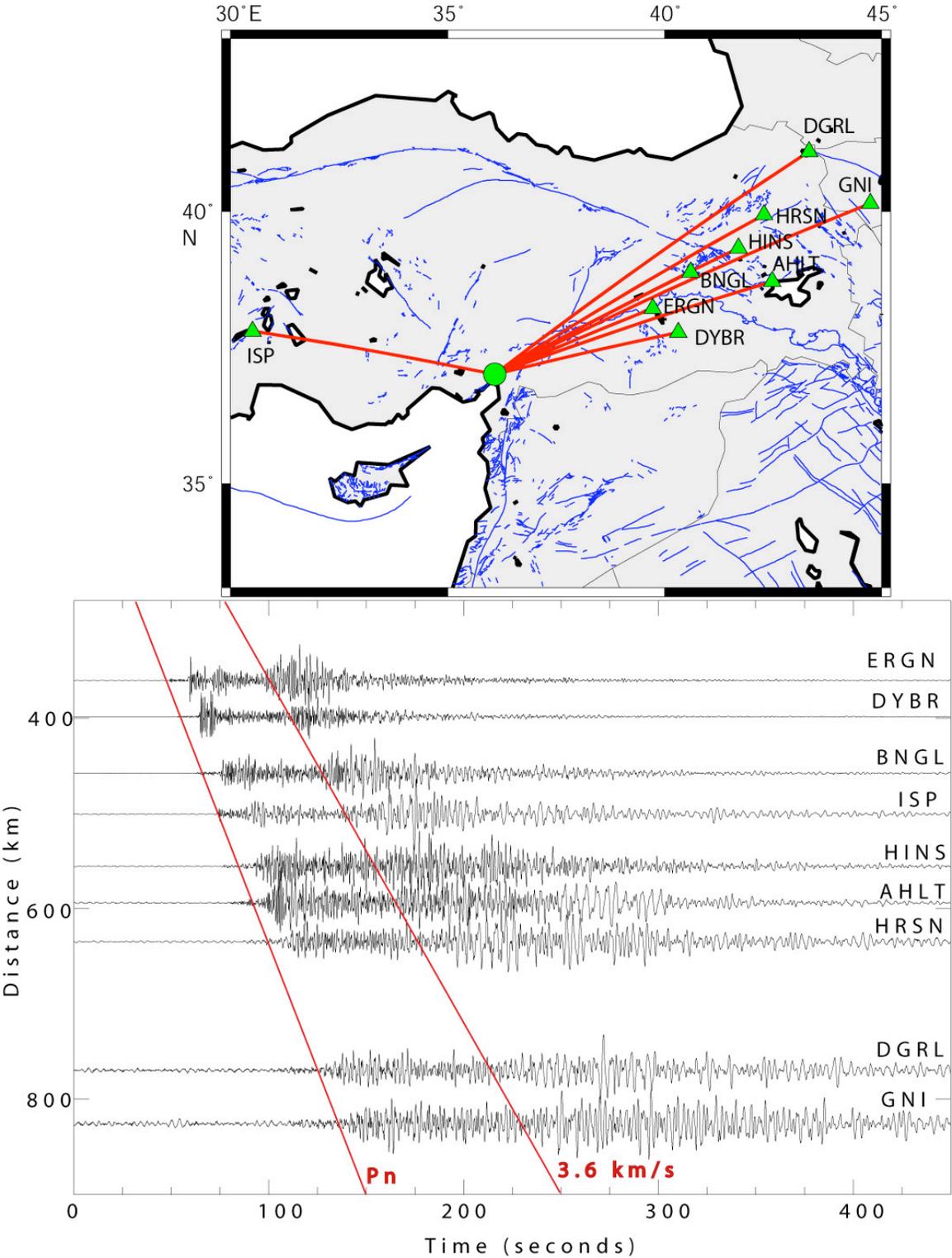
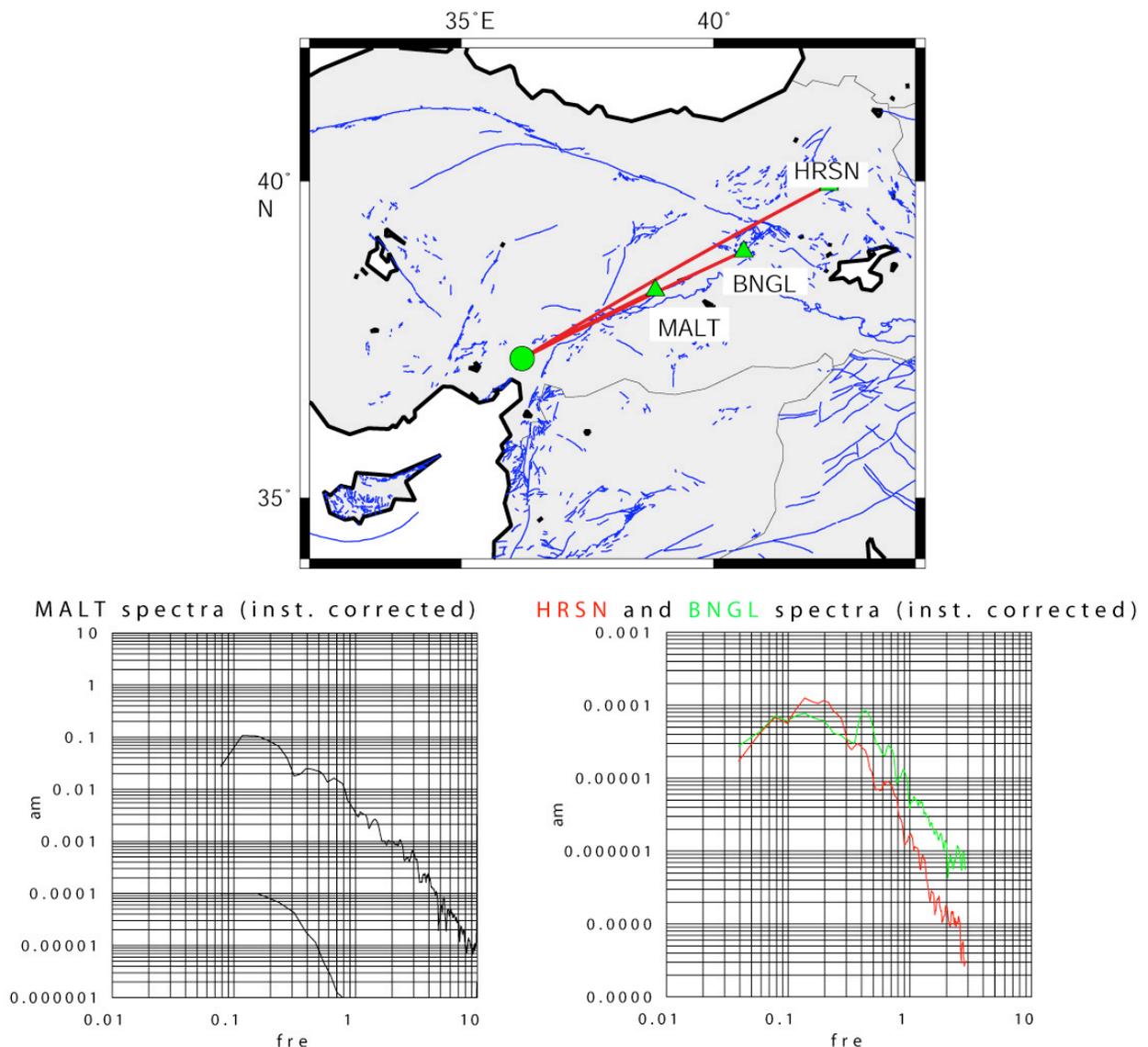


Figure 3. Record section from an earthquake along the east Anatolian Fault Zone (06/25/2001;  $M_b = 5.0$ ; located at  $40.693^\circ\text{N}$ ,  $32.993^\circ\text{E}$ ). The seismograms are collected from ETSE temporary array and GSN stations in the region. Station code is shown to the right of each trace.



**Figure 4. Instrument corrected Lg spectra for an earthquake along the East Anatolian Fault Zone (06/25/2001;  $M_b = 5.0$ ; located at  $40.693^\circ\text{N}$ ,  $32.993^\circ\text{E}$ ). The seismograms are collected from ETSE temporary array and GSN stations in the region. Note the change in the spectral character with increasing distance across the east Anatolian plateau. In general, Lg is eliminated past 500 km within the plateau.**

**Method for establishing the geometrical spreading terms**

Of the various regional waves, long-period surface waves and high-frequency Lg have well known geometrical spreading terms (G.S.T.). For other high-frequency regional waves, the G.S.T. can be established using synthetic seismograms in one dimensional structures that are developed for the geographic region of interest. Sometimes the G.S.T. are also directly fit simultaneously with Q models (Zhu et al., 1991; Taylor et al., 2000, Walter and Taylor, 2002). We will also need to determine the G.S.T. for Pn phases in the Middle East given that little work has been done there. For Pg, Xie (2002b) fit synthetic seismograms (Saikia, 1994) in three 1D models for central Asia and obtained G.S.T. that are generally similar to that of Pn. The G.S.T. of Sn is probably the most difficult to estimate precisely because the upper mantle in sub-regions of the Middle East probably has abnormal Poisson ratios and  $V_p/V_s$  ratios (McNamara et al., 1995; Owens and Zandt, 1997; Rapine et al., 1997; Rodgers and Schwartz, 1998).

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The estimated G.S.T. for Sn using synthetic seismograms will thus be less reliable. If the G.S.T. is biased, the estimated Q will not faithfully reflect the true Q of the crust or upper mantle. However, for the users of our research products, errors in the G.S.T. will have virtually no effect on event detection and identification because the Q models, when used in conjunction with the specified G.S.T., will adequately predict the frequency-dependent amplitude decay of various regional waves.

### Lg Q tomography for the Middle East

We anticipate that Lg Q over about 900 paths can be measured with the two-station methods (methods 1 and 2 in the last section) or the Newton-like non-linear method for inversion with multiple co-located events (method 4). We may also use the Bayesian method (method 3) or the EGF method (method 5) which both take advantage of our extensive regional ray path coverage for regions where we do not have good 2 station coverage. Lg  $Q_0$  and  $\eta$  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  $\eta$  values, the input  $Q_0$  and  $\eta$  values along approximately 900 paths will be used to derive a long-wavelength Q map for those regions of the Middle East with good 2 station path coverage. This model will be subsequently used as *a priori* knowledge when Q over the rest of 8,000+ paths is inverted for (for the detailed methodology to achieve this, see Appendix A). Figure 4 shows a subset (about 900) of the 1,500 anticipated paths over which  $Q_0$  and  $\eta$  values can be measured with methods (1), (2), (3 with (5)), and (4). We anticipate that the initial  $Q_0$  and  $\eta$  maps will be available near the end of September, 2004.

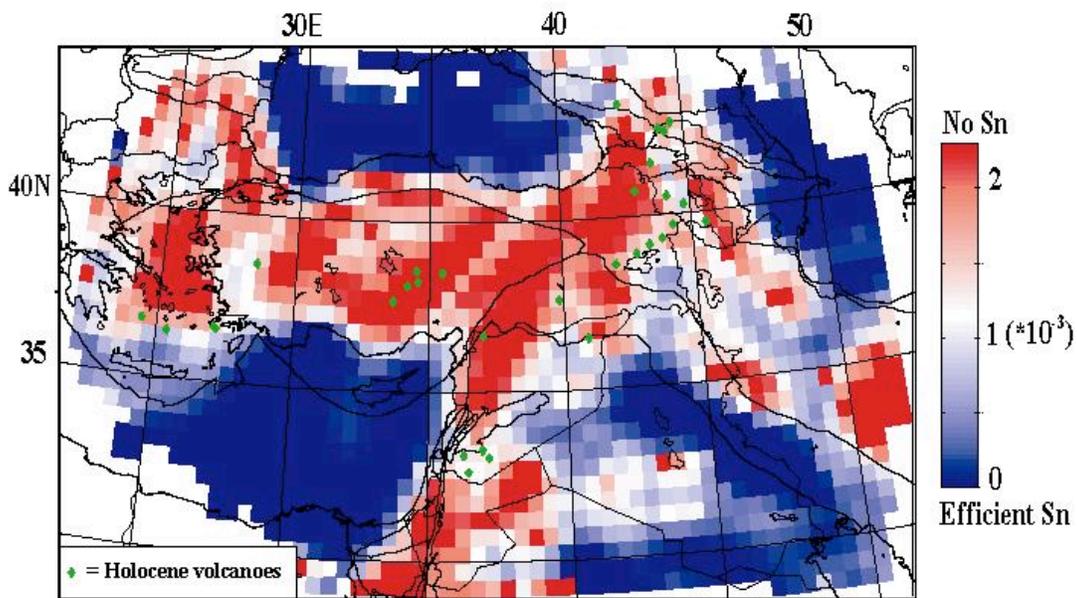


Figure 5. Our most recent Sn efficiency map for the Middle East and surrounding regions (Gok et al., 2003). Red areas denote regions of Sn blockage.

### Upper Mantle Attenuation

Laterally varying Pn Q models are more difficult to develop than Lg Q models because Pn is observed only in a limited distance range (between 2°-14°), thus reducing the number of Pn paths available. We are not certain that high resolution tomographic mapping is viable for Pn  $Q_0$  and  $\eta$ . However, at the very minimum we can develop representative Pn  $Q_0$  and models for sub-regions of Anatolia and for portions of the Arabian plate. Sn Q determination will be the most difficult due to the large amount of blockage that occurs for Sn paths in the Middle East. We will create blockage maps for Sn (e.g. Sandvol et al., 2001) and then use these to estimate a maximum allowable Q for those regions with Sn blockage.

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### CONCLUSIONS AND RECOMMENDATIONS

We have found that in order to achieve sufficiently dense two station paths to cover the majority of the middle east, it is necessary to integrate data from a variety of temporary and permanent, short period and broadband seismic stations within the Middle East. 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 and especially Sn Q 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.

### ACKNOWLEDGMENTS

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