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HIGH-RESOLUTION SEISMIC VELOCITY AND ATTENUATION MODELS OF THE CAUCASUS-CASPIAN REGION

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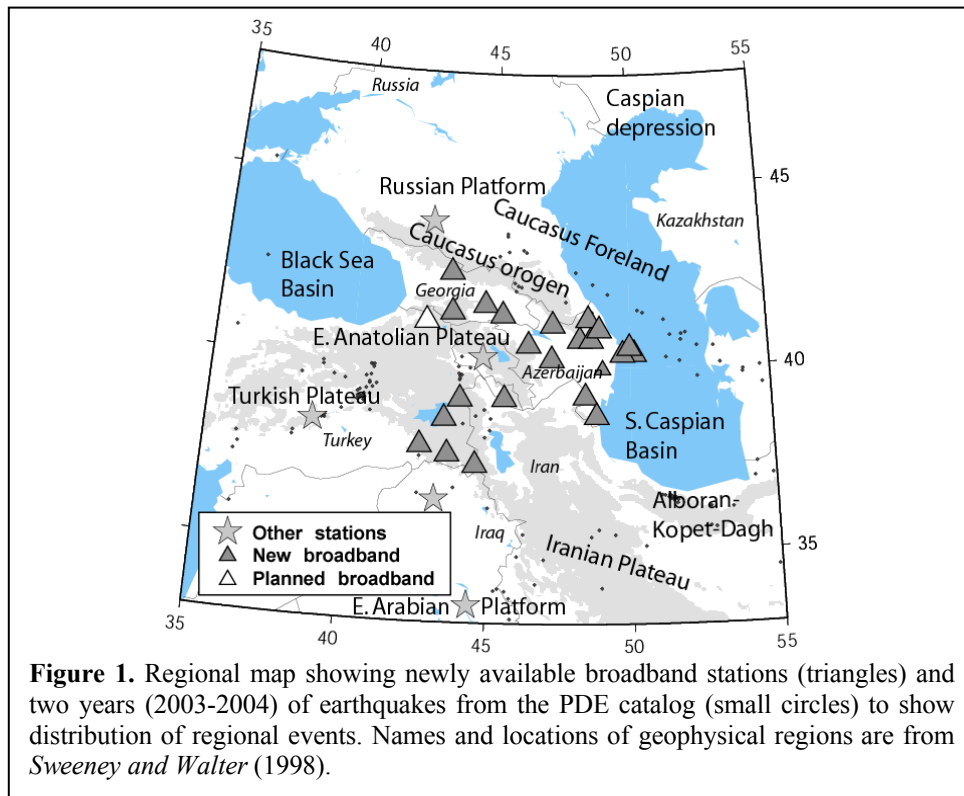
ABSTRACT

The southwest edge of Eurasia is a tectonically and structurally complex region that includes the Caspian and Black Sea basins, the Caucasus Mountains, and the high plateaus south of the Caucasus. Using data from 25 broadband stations located in the region, new estimates of crustal and upper mantle thickness, velocity structure, and attenuation are being developed. Receiver functions have been determined for all stations. Depth to Moho is estimated using slant stacking of the receiver functions, forward modeling, and inversion. Moho depths along the Caspian and in the Kura Depression are in general poorly constrained using only receiver functions due to thick sedimentary basin sediments. The best fitting models suggest a low velocity upper crust with Moho depths ranging from 30 to 40 km. Crustal thicknesses increase in the Greater Caucasus with Moho depths of 40 to 50 km. Pronounced variations with azimuth of source are observed indicating 3D structural complexity and upper crustal velocities are higher than in the Kura Depression to the south. In the Lesser Caucasus, south and west of the Kura Depression, the crust is thicker (40 to 50 km) and upper crustal velocities are higher. Work is underway to refine these models with the event based surface wave dispersion and ambient noise correlation measurements from continuous data. Regional phase (*Lg* and *Pg*) attenuation models as well as blockage maps for *Pn* and *Sn* are being developed. Two methods are used to estimate Q: the two-station method to estimate inter-station Q and the reversed, two-station, two event method. The results are then inverted to create *Lg* and *Pg* Q maps. Initial results suggest substantial variations in both *Pg* and *Lg* Q in the region. A zone of higher Pg Q extends west from the Caspian between the Lesser and Greater Caucasus and a narrow area of higher *Lg* Q is observed.

OBJECTIVES

The Caucasus-Caspian region is an area of complex structure accompanied by large variations in seismic wave velocities and attenuation (e.g. Ritzwoller and Levshin, 1998; Murphy et al., 2005; Mitchell et al. 1997). In such areas, accurate geophysical models are fundamentally important to nuclear monitoring. In particular, the great thickness and irregular geometry of the low velocity and low density sediments in the Caspian and Black Sea basins (e.g. Laske and Masters, 1997) creates profound effects on seismic waveforms, especially on surface waves and regional phases. These effects are compounded by variations in crustal structure in the Caucasus and by high attenuation under the East Anatolian plateau (Al-Lazki et al., 2003; Sandvol et al., 2001). Because regional models based on widely spaced stations may suffer from insufficient spatial sampling, we are developing comprehensive velocity and attenuation models using new broadband data that have become available in this area.

The primary focus is the Caucasus-Caspian region, which is roughly defined as lying between 40 and 55 E longitude and between 37 and 44 N latitude (Figure 1). A unified upper mantle/crustal velocity model will be developed using multiple techniques. In addition, the same data will be used to construct detailed maps of regional phase attenuation (Lg, Pg, Pn, and Sn). Finally, the results will be compared and validated using the various algorithms as well as independent datasets (local and regional events and active source studies).

Figure 1. Regional map showing newly available broadband stations (triangles) and two years (2003-2004) of earthquakes from the PDE catalog (small circles) to show distribution of regional events. Names and locations of geophysical regions are from *Sweeney and Walter* (1998).

Previous work.

The region shows considerable spatial variability in travel times and phase propagation throughout the area (Table 1). Myers and Schultz (2000) noted errors of 42 km when locating events in the Caucasus Mountains with sparse regional stations and a standard model (prior to application of an empirical correction). They also noted that arrivals at regional distances are "strongly affected by upper-mantle-discontinuities". Regional phase variations have been documented on a regional basis by a number of studies but reliable direct phase Q measurements are still lacking, mainly because of sparse station coverage and irregular distribution of earthquakes (e.g. Kadinsky-Cade et al., 1981; Rodgers et al., 1997a; Mitchell, 1997; Cong and Mitchell, 1998; Sarker and Abers, 1998; Baumgardt, 2001; Sandvol et al., 2001; McNamara and Walter, 2001; Gök et al., 2000; Gök et al, 2003). Here we summarize the regions and relevant seismic characteristics, where known.

The South Caspian and the Black Sea basins are thought to be underlain by oceanic crust, although it is possible that the South Caspian may simply be thinned continental crust overlain by thick sediments (Mangino and Priestly, 1998; Baumgardt, 2001). The great thickness (up to 20 km) of sediments in the South Caspian strongly affects surface waves as well, but efforts to resolve the situation by modeling higher frequency surface waves were inconclusive due to possible 3D effects (Priestley et al., 2001). Improved coverage and the use of ambient noise tomography should be useful in resolving this question. *Lg,* which is critical for discrimination purposes, is blocked by both the Black Sea and South Caspian basins. *Sn* does propagate through the South Caspian (Rodgers et al., 1997b; Sandvol et al., 2001). A large amount of active source data have been collected, which is useful for constraining the shallow velocity structure and depth of the sedimentary cover (Neprochnov et al., 1970; Belousov et al., 1992, Davies and Stewart, 2005; Knapp et al, 2004).

West of the Caspian in the Caucasus orogenic belt and foreland, events (Myers and Schultz, 2000) are subject to substantial travel-time anomalies at regional distances. It is unclear whether the *Lg* blockage observed in the South Caspian extends into the Greater Caucasus, as the available studies disagree. Rodgers et al. (1997b) and McNamara and Walter (2001) infer partial blockage of *Lg* in a belt extending from the Black Sea to the South Caspian. Alternatively, Sandvol et al. (2001) observe relatively efficient *Lg* propagation in the Caucasus and Central Caspian and attribute most of the attenuation to raypaths that cross the Anatolian plateau. Baumgardt (2001) reports unblocked *Lg* from Caucasus events to stations in Iran but blockage in the Caspian depression. The discrepancies among studies may reflect the poor station coverage with resulting poor resolution of ray paths. The crustal structure of this region still remains unclear given the lack of the data in the region. The boundary between the South Caspian and the Central Caspian is called the Absheron-Balkhan sill, an area of high seismicity and possibly of incipient subduction (Jackson et al., 2002; Brunet et al., 2003).

The South Caspian blends into the southern Caucasus in the Kura depression, a sedimentary basin with uncertain structure (i.e. is it an onshore extension of the South Caspian or is it underlain by continental crust?). Poor *Sn* propagation is evident throughout the Anatolian Plateau. The southern Caucasus (or Lesser Caucasus) differs from the Greater Caucasus to the north due to extensive Quaternary volcanism. Near the South Caspian, the southern Caucasus merges into the Alborz Mountain belt, an area of clear *Lg* propagation as well as *Pg* and *Pn*.

Until now, little broadband data has been available for the region. Relevant global stations exist in the S. Caucasus (GNI), Eurasian platform (KIV), east of the Caspian (ABKT) and to the south (MSL and BHD). A broadband array was temporarily installed in 1992 at ABKT and a broadband network was installed in the Caucasus from 1991 to 1994. A limited amount of broadband data was collected from a temporary deployment of broadband stations at three sites (LNK, BAK, and SHE) occupied during the two year Caspian Seismic Deployment. However, data return from these sites was limited and Mangino and Priestley (1998) presented receiver functions only from one station (LNK). Recently, permanent broadband stations have been deployed across the region as part of various national networks. Much of this data remains under the control of various institutes and we are working with these institutes to analyze the data.
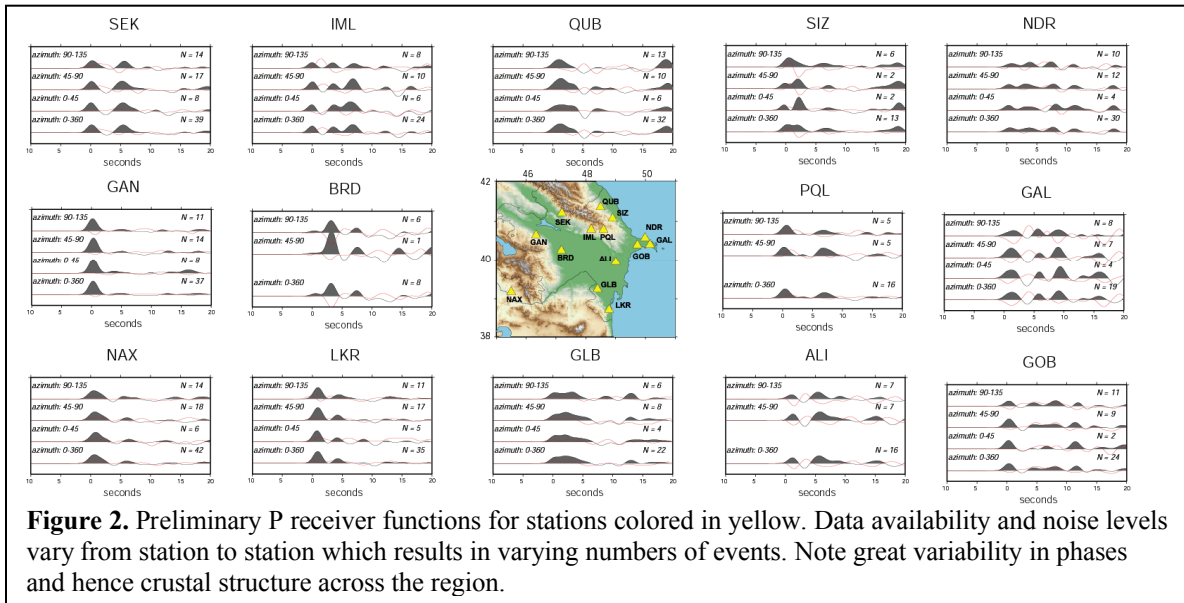
Methods and data

The work consists of four basic tasks: data collection, regional phase analysis, velocity model development, and model validation.

Regional phase analysis will define crustal and upper mantle propagation and attenuation within the region. By using the relatively dense coverage of broadband stations we intend to construct a detailed map of regional phase propagation in and around the region (*Pg*, *Pn*, *Lg*, and *Sn*). The primary questions are: What is the lateral extent of *Lg* blockage in the South Caspian and Black Sea? How far and to what degree does it extend into the Caucasus? What are the boundaries of *Sn* propagation? Do we see effects due to the Central, North, and Pre-Caspian basins on *Lg*? Two methods will be used to isolate the regional wave path: the two-station method for measuring inter-station Q and the reversed two-station, two-event spectral ratio method (Chun et al., 1987; Zor et al., 2007). This method has the advantage that we should be able to isolate the relative station response without having to assume that our response information is reliable. Once *Lg* Q has been measured, the results will be inverted to create *Lg* Q tomography maps, as is required for a regional phase Q model. The rapid changes in *Lg* in the region require dense station spacing. The two-station methods will also be used to measure *Pg*, *Pn*, and *Sn* Q. Laterally varying *Pn* Q models are more difficult to develop than *Lg* or *Pg* Q models because *Pn* is observed only in a limited distance range (between ~2-14°), thus reducing the number of Pn paths available and making inversion difficult. However, it is

expected that the resulting blockage maps will be superior to existing maps. We will further refine our existing blockage maps for *Sn* (e.g. Sandvol et al., 2001) and then use to these to estimate a maximum allowable Q for those regions with *Sn* blockage.

In parallel with the attenuation work, crustal and upper mantle velocity structure will be determined using surface wave and receiver functions modeling. Results from the surface wave work and receiver functions will be jointly inverted for a unified model (Gök et al., 2006). Both phase and group velocities will be measured. The phase velocities will be event based (Forsyth et al., 1998). The ambient noise correlation will be measured using continuous data (Shapiro and Campillo, 2004). Pasyanos and Walter (2002) performed a study of surface wave group velocity dispersion across Western Eurasia and North Africa and a larger-scale across Eurasia, North Africa and the surrounding regions (Pasyanos, 2005) using 30,000 Rayleigh and 20,000 Love wave paths. We will be adding group velocity measurements to existing Rayleigh and Love measurements. Receiver functions are a well-established technique (e.g. Langston, 1979; Ammon et al, 1990; Zhu and Kanamori, 2000) that use teleseismic P(or S) phases to estimate crustal and upper mantle velocity structure in the vicinity of the seismometer. Mangino and Priestley (1998) applied receiver function analysis to the Caspian Seismic Experiment station LNK (near the current broadband station LKR) and found "considerable variation over fairly short horizontal distances". Their results under LNK showed a thinner crust and approximately 13 km of sediment over a high velocity mid to lower crust. As receiver functions are effective at identifying discontinuities, combining receiver function analysis with surface wave data is a powerful technique. The joint inversion method of Julia et al. (2000) will be used.

Figure 2. Preliminary P receiver functions for stations colored in yellow. Data availability and noise levels vary from station to station which results in varying numbers of events. Note great variability in phases and hence crustal structure across the region.

RESEARCH ACCOMPLISHED
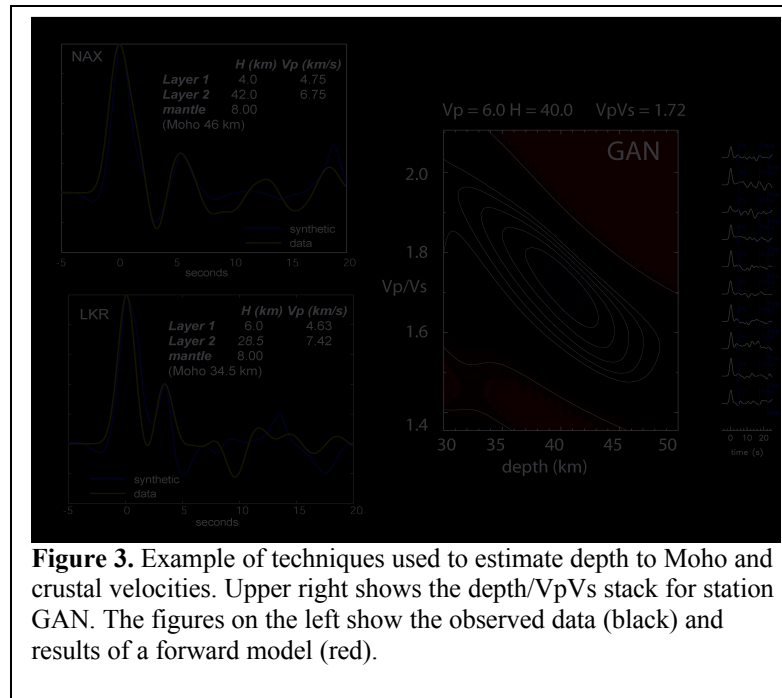
Data collection

Figure 3. Example of techniques used to estimate depth to Moho and crustal velocities. Upper right shows the depth/VpVs stack for station GAN. The figures on the left show the observed data (black) and results of a forward model (red).

Both event (triggered and windowed) data and event data has been collected for the years 2006 and 2007 for stations in all three networks. The data have a number of different sample rates and seismometer types. We have been working to reliably remove the instrument response for all stations in the KOERI, Azeri and Georgian networks. The event data are used for receiver functions and surface wave analysis. The continuous data are collected for ambient noise tomography.

Receiver functions

Receiver functions have been calculated for all stations (Figures 2 and 3). Teleseismic events with magnitude greater than 5.2 and at distance between 30 and 90 degrees were selected. Iterative deconvolution and a variety of filter windows were applied. Slant stacking (e.g. Zhu and Kanamori, 2000) was applied to all data to provide an estimate of the depth to Moho and VpVs ratio. In general, stations in areas with thick sediments and high noise levels (such as those near the Caspian) the PS converted phase at the Moho is not as clear and our slant stacking process is not as well resolved. This is most likely due to the interference of multiples phases with the sedimentary basin.

Figure 4. shows the results of our slant stacking analysis. We plan to reduce the uncertainties and improve the reliability of the slant stacking with additional data from 2008 as well as adding results from the eastern portion of the Kandilli (KOERI) seismic network in eastern Turkey. We will also be adding new results from several of the broadband stations in Georgia. Overall our results seem to suggest that there is only a modest root beneath the Lesser Caucasus, similar to that observed in eastern Turkey (e.g. Zor et al., 2003). Our results also suggest that there may be a significant root beneath the Greater Caucasus, however we only have a few stations on the southern edge of this mountain range.
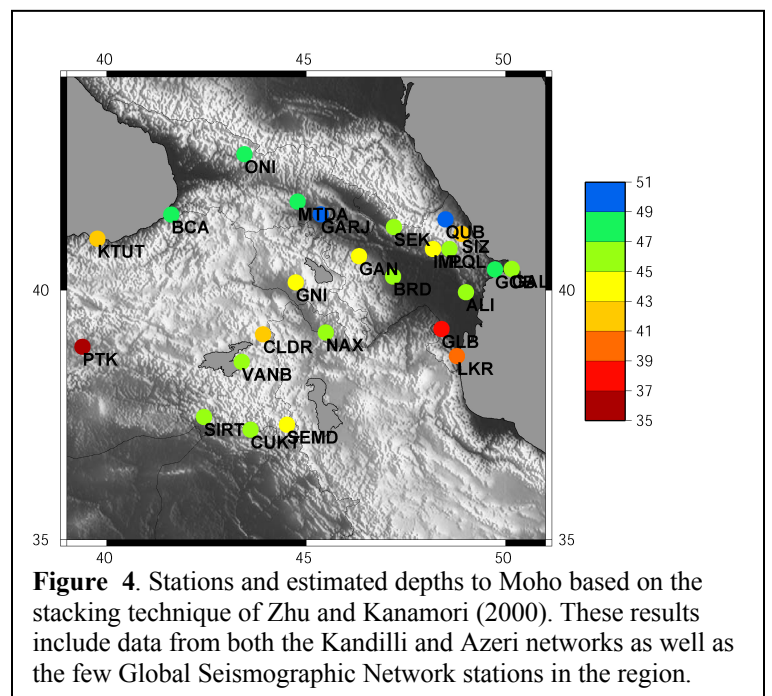

Figure 4. Stations and estimated depths to Moho based on the stacking technique of Zhu and Kanamori (2000). These results include data from both the Kandilli and Azeri networks as well as the few Global Seismographic Network stations in the region.

Surface Wave Analysis

In addition to the receiver function analysis we are analyzing surface waves in order to create a three dimensional region velocity model for this region. We have measured phase velocities of Rayleigh waves in the period band 30-150 s using the two plane wave approach of *Forsyth et al.* (1998) and *Yang and Forsyth* (2004). Our initial data inversions for Rayleigh wave phase velocity used a grid with roughly 50 km spacing. This very preliminary model
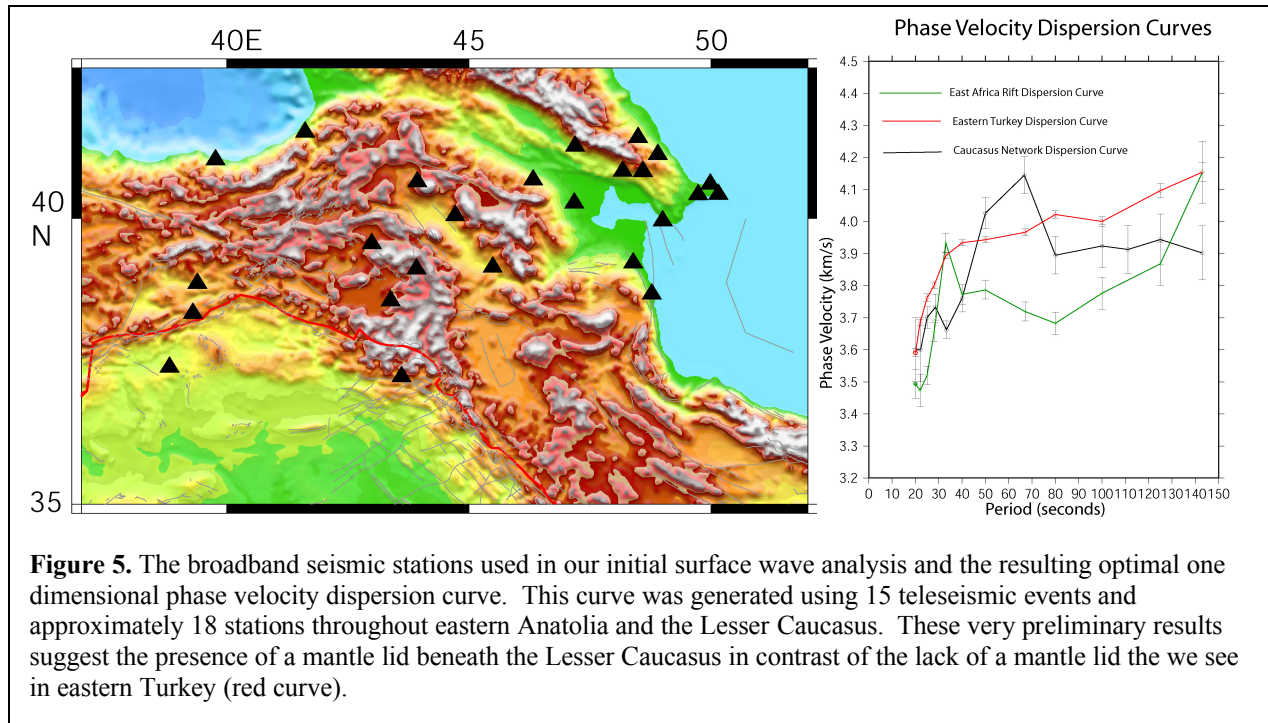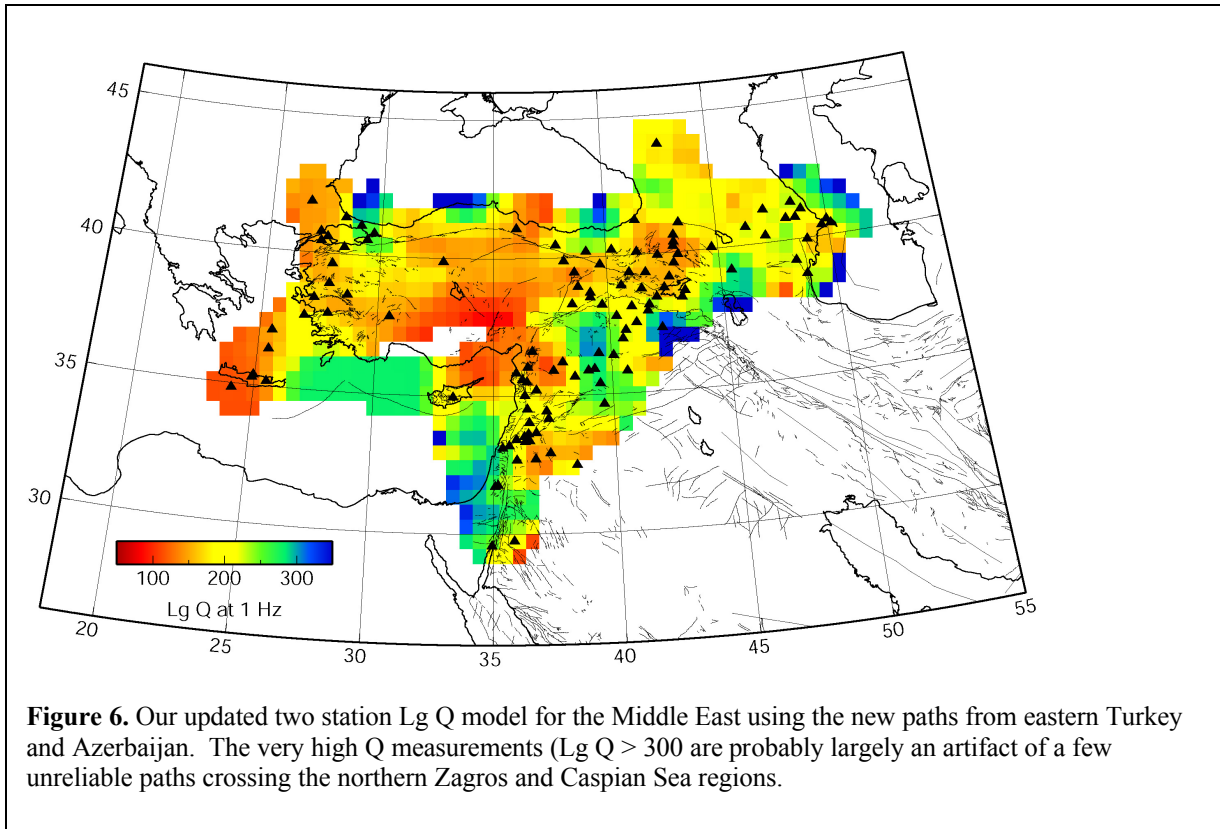

Figure 5. The broadband seismic stations used in our initial surface wave analysis and the resulting optimal one dimensional phase velocity dispersion curve. This curve was generated using 15 teleseismic events and approximately 18 stations throughout eastern Anatolia and the Lesser Caucasus. These very preliminary results suggest the presence of a mantle lid beneath the Lesser Caucasus in contrast of the lack of a mantle lid the we see in eastern Turkey (red curve).

has a relatively high error because we have only analyzed approximately 6 months of data (15 events) recorded by both the Azeri and Kandilli networks. Despite the higher errors and the relatively few events analyzed we have found preliminary evidence for an uppermost mantle lower velocity zone at about 75 seconds period. This is in strong contrast with our phase velocity measurements in eastern Turkey which do not show any evidence of a lithosphere-asthenosphere boundary.

Regional Wave Attenuation

We have continued to update our Lg Q model using new two station paths from new stations in Azerbaijan and eastern Turkey and imposing a much more restrictive maximum and minimum distance requirement. Our updated frequency dependent Q models for both Lg and Pg have included approximately 4000 waveforms from approximately 200 events recorded by 10 permanent and temporary networks throughout the Middle East.

We have found, similar to the previous models, efficient Lg propagation throughout much of the Arabian plate. We continue to find the lowest Qo values in the East Anatolian plateau (~70 to 100) and East Anatolian Fault Zone (~80 to 120). The frequency dependent exponent for Lg is less than that of Pg in the Middle East. Resolution tests for Q tomography in our work indicate that we have very good resolution throughout much of the Anatolian Plateau. We also continue to observed evidence of modest to low Q throughout most of the lesser Caucasus. Our preliminary model is limited due to the elimination of events that cross the south Caspian Sea basin, thus blocking Lg. We do however observe some inefficient Lg paths that we are able to use to estimate Lg Q's in the Lesser Caucasus mountains. Additional paths are needed, however, as our model is still relatively unstable in northwestern Iran and the Caspian Sea. This can be seen by the relatively high Lg Q values that we are currently obtaining.

Figure 6. Our updated two station Lg Q model for the Middle East using the new paths from eastern Turkey and Azerbaijan. The very high Q measurements (Lg Q > 300 are probably largely an artifact of a few unreliable paths crossing the northern Zagros and Caspian Sea regions.

We have also made progress on estimating reliable Lg and Pg geometrical spreading terms by calculating high frequency synthetic seismograms in a 1D velocity structure using the finite difference and reflectivity methods. We used the synthetics to compute the geometrical spreading terms for a uniform Q crust.

CONCLUSIONS AND RECOMMENDATIONS

Preliminary analysis of receiver functions shows clear consistency between events and the outlook is promising for this technique despite the complex structure and basin sediments. Results for station LKR are similar to those from the Mangino and Priestley (1998) study, which was situated near the same site. The uppermost mantle structure looks similarly very complex. The very different looking surface wave phase velocities that have been seen in eastern Turkey (Sandvol et al., 2004) compared with our initial results suggest that there is a change in lithospheric thickness from easternmost Anatolia to the Lesser Caucasus. The Lg attenuation also suggests a strong lateral variation in crustal attenuation from eastern Anatolia to the Lesser Caucasus. Our measurements suggest that the highest attenuation ($Q_{Lg} < 100$) is restricted to easternmost Anatolia.

ACKNOWLEDGEMENTS

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