LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-CONF-232663

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

Robert Mellors, Rengin Gok, Eric Sandvol

July 11, 2007

Monitoring Research Review
Denver, CO, United States
September 25, 2007 through September 27, 2007

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


Robert Mellors[1], Rengin Gök[2], and Eric Sandvol[3]

San Diego State University[1], Lawrence Livermore National Laboratory[2]
and University of Missouri-Columbia[3]



Sponsored by Air Force Research Laboratory

Contract No. FA8718-07-C-0007
and
Contract No. W-7405-ENG-48


## 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. Crustal and upper mantle velocities show great heterogeneity in this region and regional phases display variations in both amplitudes and travel time. Furthermore, due to a lack of quality data, the region has largely been unexplored in terms of the detailed lithospheric seismic structure. A unified high-resolution 3D velocity and attenuation model of the crust and upper mantle will be developed and calibrated. This model will use new data from 23 new broadband stations in the region analyzed with a comprehensive set of techniques. Velocity models of the crust and upper mantle will be developed using a joint inversion of receiver functions and surface waves. The surface wave modeling will use both event-based methods and ambient noise tomography. Regional phase (*Pg*, *Pn*, *Sn*, and *Lg*) Q model(s) will be constructed using the new data in combination with existing data sets. The results of the analysis (both attenuation and velocity modeling) will be validated using modeling of regional phases, calibration with selected events, and comparison with previous work. Preliminary analyses of receiver functions show considerable variability across the region. All results will be integrated into the KnowledgeBase.

## 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). As regional models based on widely spaced stations they may suffer from insufficient spatial sampling, a comprehensive velocity and attenuation model is being developed using new broadband data that has 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).

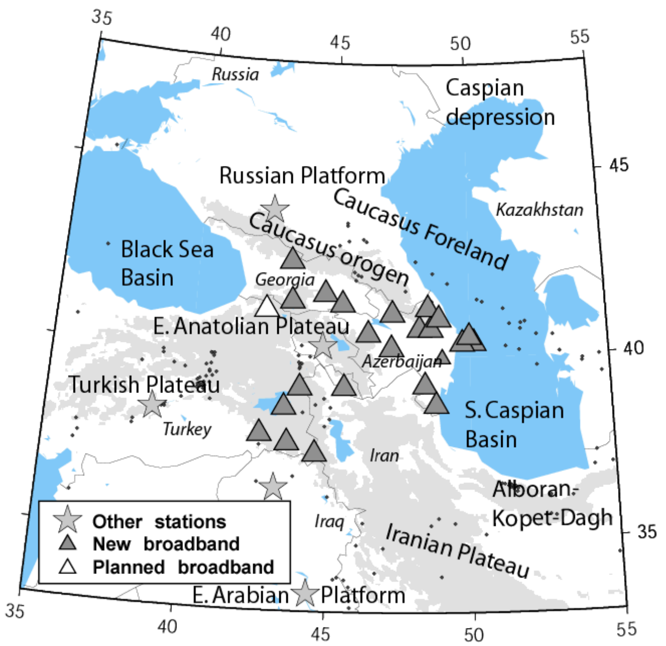


**Figure 1.** Regional map showing newly available broadband stations (triangles) and two years (2003-2004) of earthquakes from the PDE catalog (small circles) to show distribution of regional events. Names and locations of geophysical regions from *Sweeney and Walter* (1998).

## 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 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 may be an area of incipient subduction (Jackson et al., 2002; Brunet et al., 2003).

The South Caspian blends into the southern Caucaus 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*.

**Table 1. Phase propagation in the Caucasus.**

| Area | Regional phases | Seismicity | Other |
|---|---|---|---|
| Caucasus orogen | *Pn, Sn?* | High | |
| Caucasus foreland | *Pn,Pg,Lg?* | Mod deep? | Sediments<br>Subduction? |
| Black Sea | *Pn,Sn* | Low | Sediments/ oceanic crust |
| S. Caspian | *Pn,Sn* | Low | Thick sediments; oceanic crust? |
| E. Anatolian | *Pn* | High | Volcanic |
| Iranian Plateau | *Pn,Pg,Lg* | Mod. | |

**Table 1.** Summary of regional phase propagation among regions addressed in this proposal. Note great variation across short distances. Adapted from *Sweeney and Walters* (1998).

Little broadband data has been previously 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. Data collection is ongoing and will include data from at least 23 new broadband stations in the region from several different adjoining countries and operated by different institutions. These stations will allow us to extend many of the high resolution models created in eastern Turkey into the Caucasus.

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 this will make 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 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.

Finally, the velocity and attenuation models will be validated using alternate data sources (such as reflection data), modeling, and ground truth data. The velocity model will be calibrated in two ways: by calculating source locations and mechanisms using our velocity models and with comparison with previous (especially seismic refraction and reflection) datasets.

## RESEARCH ACCOMPLISHED

### Data collection

Station data availability from all stations in the region is being compiled for continuous data to achieve maximum coverage for ambient noise tomography and data from all stations will be collected over the next few weeks. Some event data has been collected (Figure 2). Initial analysis of teleseismic data from the region has begun using receiver functions (Figure 3).

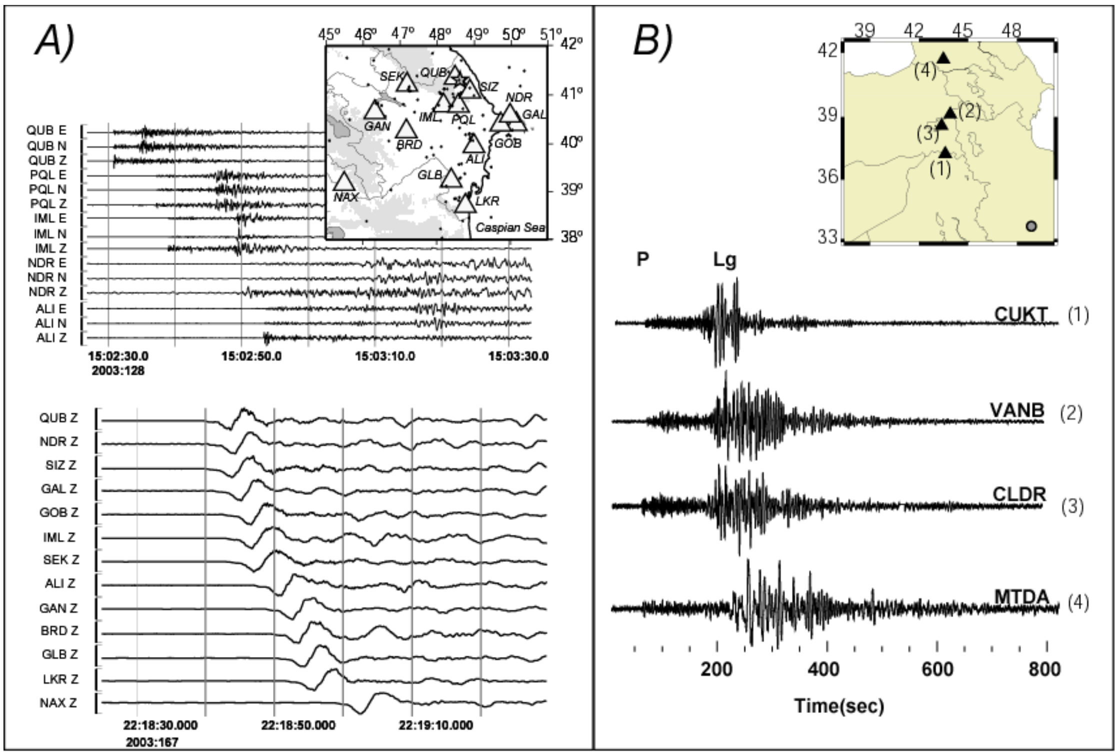


**Figure 2. A)** (*top*) Example of a local event recorded by the Azerbaijan network located near station QUB (no filter). Dots are local events recorded by network in three months.(*Bottom*) Example of 16 June 2003 teleseism approximately 67 degrees away recorded by the Azerbaijan network. Lowpass filtered at 1 s. Traces are normalized. **B)** Example of regional event (small circle) recorded by stations in Eastern Turkey and Georgia.

### Receiver functions

A preliminary set of events for receiver functions have been calculated for some of the stations using the data in hand (Figure 3). Both spectral division and time domain iterative deconvolution are being applied to telesismic events within 30-90º. Receiver functions in Figure 3 were determined using deconvolution by spectral division with a waterlevel of 0.01 and a Gaussian filter of 1.5. Noise levels vary greatly from station to station, which leads to differing number of events possessing high signal to noise at each station. In general, noise levels (likely due to water waves in Caspian) were highest near the coast. Coastal stations also lie on sedimentary bedrock and some of the variability is probably due to multiples and possibly structure within the crust. Modeling is ongoing to match the receiver functions.

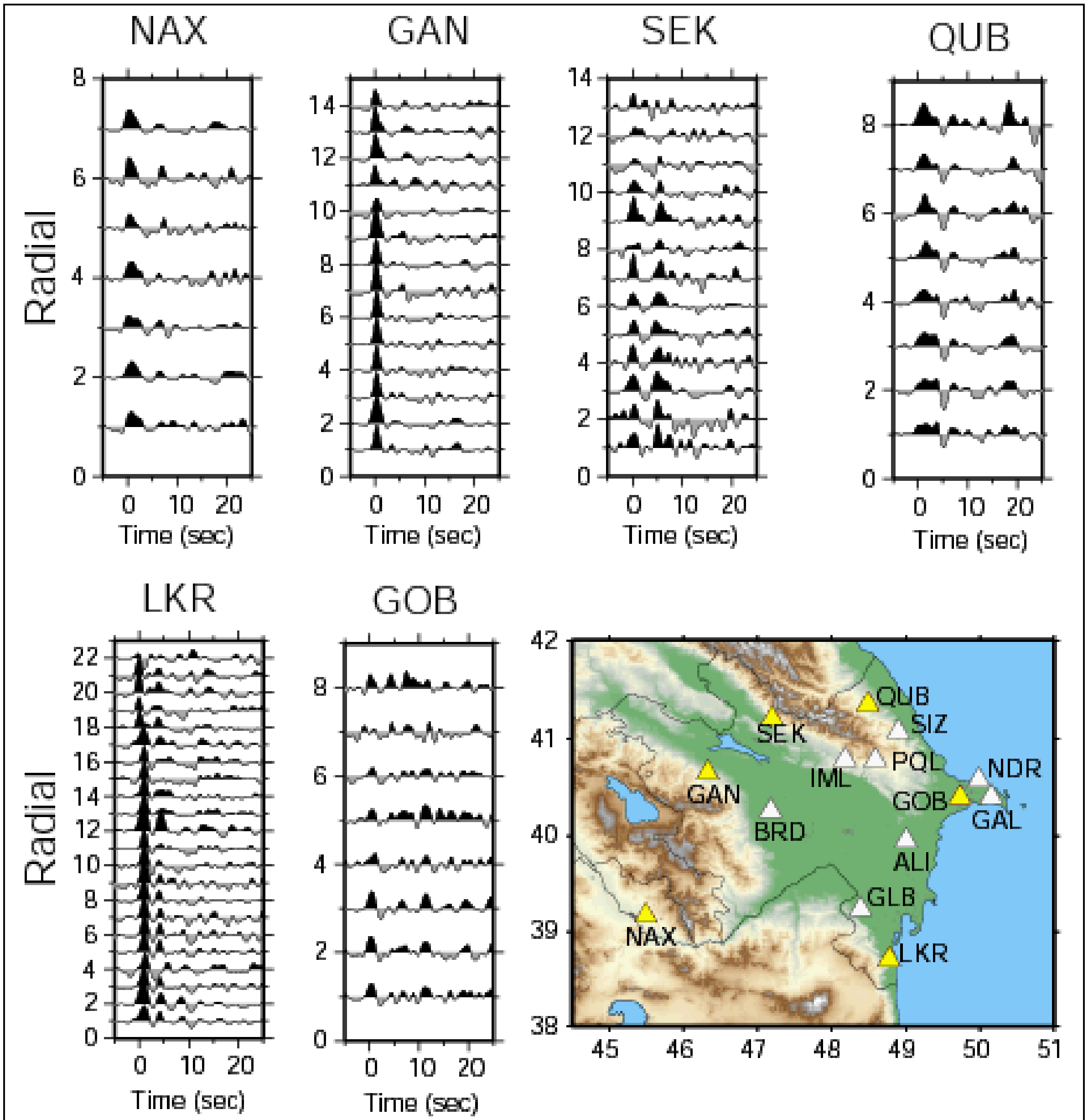


**Figure 3.** Preliminary P receiver functions for stations colored in yellow. Data availability and noise levels vary from station to station which results in varying numbers of events. Note great variability in phases and hence crustal structure across the region.

## 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. Alternate methods of deconvolution will be tested to improve the results and the examples shown so far represent a fraction of the available data. We will be using higher Gaussian filter widths to be able to resolve the smaller scale variation within the crust. We will be calculating the S-receiver functions to be able to calculate the depth of the Lithospheric Asthenospheric Boundary (LAB). The Moho conversion can be seen on S-receiver functions where we will be using our P-receiver functions to fix the Moho depth. Once sufficient data has been collected, event based and noise correlated surface wave analysis will begin. Similarly, the event data is being collected for regional phase attenuation maps.


## ACKNOWLEDGEMENTS

Thanks to A. Gasanov and G. Yetirmishli for providing this initial set of data from the Azerbaijan network. C. Ammon and J. Julia provided software used in the analysis of this data.


## REFERENCES


Al-Lazki, A.I.,D. Seber, E. Sandvol, E.,N. Turkelli, R. Mohamad, and M. Barazangi (2003), Tomographic Pn velocity and anisotropy structure beneath the Anatolian plateau (eastern Turkey) and the surrounding regions, Geophys. Res. Let. 30, (24).

Ammon, C., J., G. E. Randall, and G. Zandt, (1990). On the nonuniqueness of receiver function inversions, Jour. Geophys. Res., 95, (10), 15,303-15,318, 1990.

Baumgardt, D. R. (2001). Sedimentary basins and the blockage of Lg wave propagation in the continents, Pure and Appl. Geoph., 158, 1207-1250.

Belousov, V. V., N. I. Pavlenkova, and G. N. Kvyatkovskaya (1992). Structure of the crust and upper mantle of the [Former] USSR, International Geology Review, 34, (3), 213-338.

Brunet, M.F., M. V. Korotaev, A. V. Ershov, and A. M. Nikishin (2003). The South Caspian Basin; a review of its evolution from subsidence modeling, Sedimentary Geology, 156, 1-4, 119-148.

Chun, K.-Y., G. F. West, R. J. Kokoski, and C. Samson (1987). A novel technique for measuring Lg attenuation; results from Eastern Canada between 1 to 10 Hz, Bull. Seismo. Soc. Amer., 77, (2), 398-419.

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, 2-4, 563-585.

Davies, R. J. and S. A. Stewart (2005). Emplacement of giant mud volcanoes in the South Caspian Basin: 3D seismic reflection imaging of their root zones, Jour. of the Geo. Soc., 162, no. 1, pp. 1-4(4).

Forsyth, D.W., Webb, S.C., Dorman, L.M., Shen, Y. (1998). Phase velocities of Rayleigh waves in the MELT experiment on the East Pacific Rise. Science, 280, 1235-1238.

Gök, R., N. Turkelli, E. Sandvol, D. Seber and M. Barazangi, (2000). Regional wave propagation in Turkey and surrounding regions, Geophys. Res. Let., 27, 3, 429-432.

Gök R.,E. Sandvol,N. Türkelli, D. Seber and M. Barazangi,(2003), Sn attenuation in the Anatolian and Iranian plateau and surrounding regions, Geophys. Res. Lett., 30, 24, 8042

Gök, R., M.E. Pasyanos and E. Zor (2006), Lithospheric Structure of the Continent-Continent Collision Zone: Eastern Turkey, submitted to J. Geophys. Res.

Jackson, J., Priestley, K., M. Allen, and M. Berberian (2002). Active tectonics of the South Caspian Basin, Geophys. Jour. Inter.,148, (2), 214-245.

Julia, J., C. Ammon, R. Herrman, and A. Correig, (2000). Joint inversion of receiver function and surface wave dispersion observations, Geophys. Jour. Int., 143,1, 99-112.

Kadinsky-Cade, K., Barazangi, M., Oliver, J. and Isacks, B.(1981). Lateral variations of high-frequency seismic wave propagations at regional distances across the Turkish and Iranian plateaus, J. Geophys. Res., 86, 9377–9396.

Knapp, C., J. Knapp, and J. A. Connor (2004) Crust-scale structure of the South Caspian Basin revealed by deep seismic reflection profiling, Marine and Petro. Geology, 21, 1073-1081.

Langston, C. A., (1979), Structure under Mount Rainier, Washington, inferred from teleseismic body waves. Jour. Geophys. Res., 84, 4749-4762.

Laske, G. and G. Masters, (1997). A Global Digital Map of Sediment Thickness, EOS Trans. AGU, 78, F483.

Mangino, S and K. Priestley, (1998). The crustal structure of the southern Caspian region, Geophys. Jour. Inter., 133,(3),630-648.

McNamara, D. and W. Walter, (2001), Mapping crustal heterogeneity using Lg propagation efficiency throughout the Middle east, Southern Europe, and Northern Africa. Pure and appl. geophys., 158, 1165-1188.

Mitchell, B., Lg coda variation across Eurasia and its relation to crustal evolution, (1997). J. Geophys. Res 102, (10), 22,767-22,779.

Murphy, J. R., W. Rodi, M. Johnson, D. Sultanov, T. Bennett, M. Toksoz, V. Ovtchinnikov, B. Barker, D. Reiter, A. Rosca, and Y. Shchukin, (2005), Calibration of International Monitoring System (IMS) Stations in Central and Eastern Asia for Improved Seismic Event Location. Bull. Seismo. Soc. of Amer., 95(4): 1535 – 1560.

Myers, S. C., and C. A. Schultz, (2000), Improving sparse network seismic location with Bayesian kriging and teleseismically constrained calibration events, Bull. Seismo. Soc. Of Amer., 90, (1), 199-211.

Neprochnov, Y. P., Kosminskaya, I. P., and Malovitsky, Y. P., (1970). Structure of the crust and upper mantle of the Black and Caspian seas, Tectonophysics, 10, (5-6),517-538.

Pasyanos, M.E., and W.R. Walter, (2002), Crust and upper mantle Structure of North Africa, Europe, and the Middle East from inversion of surface waves, Geophys. J. Int., 149, 462-480.

Pasyanos M.E., (2005), A variable resolution surface wave dispersion study of Eurasia, North Africa, and surrounding regions, . J. Geophys. Res., 110, B12301, doi: 10.1029/2005JB003749.

Priestley, K., H. Patton, and C. Schultz (2001), Modeling anomalous surface-wave propagation across the southern Caspian Basin, Bull. Seismo. Soc. Amer., 91, (6), 1924-1929.

Ritzwoller, M.H. and A.L. Levshin (1998). Eurasian surface wave tomography: Group velocities, J. Geophys. Res. 103, 4839-4878.

Rodgers, A. J., T. Lay, W. Walter, K. M. Mayeda, (1997a). A comparison of regional-phase amplitude ratio measurement techniques, Bull. Seismo. Soc. Amer., 87, (6), 613-1621.

Rodgers, A. J., J. F. Ni, T. M. Hearn, (1997b). Propagation characteristics of short-period Sn and Lg in the Middle East, Bull. Seismo. Soc. Amer., 87, (2), 396-413.

Sandvol E., Seber, Barazangi, M., Vernon, F., Mellors, R., and Al-Amir, A.,(1998). Lithospheric velocity discontinuities beneath the Arabian Shield, Geophys. Res. Lett., 25, 2873-2876.

Sandvol, E., K. Al-Damegh, A. Calvert, D. Seber, M. Barazangi, Mohamad, R, R. Gök, N. Turkelli, and C. Gurbuz, (2001). Tomographic imaging of Lg and Sn propagation in the Middle East, Pure and Applied Geophysics, 158, 1121-1163.

Sarker, G. and G. A. Abers, (1998). Deep structures along the boundary of a collisional belt: attenuation tomography of P and S waves in the Greater Caucasus. Geophysical Journal International 133 (2), 326-340. doi: 10.1046 j.1365-246X.1998.00506.x,.

Shapiro, N.M. M. Campillo, L. Stehly, and M.H. Ritzwoller (2005). High resolution surface wave tomography from ambient seismic noise, Science, 307(5715), 1615-1618.Sweeney, J., and W. R. Walter, 1998, Preliminary definition of geophysical regions for the Middle East and North Africa, UCRL-ID-132899 Lawrence Livermore National Laboratory Report, 38 pp.

Sweeney, J. and W. R. Walter (1998), Preliminary definition of geophysical regions for the Middle East and North Africa, UCRL-ID-132899, LLNL (http://www.llnl.gov/tid/lof/documents/pdf/235042.pdf).

Zhu, L., and H. Kanamori, (2000). Moho depth variation in Southern California from teleseismic receiver functions, J. Geophys. Res., 105 (2), 2969-2980.

Zor, E., E. Sandvol, J. Xie, N. Türkelli, B. Mitchell, A. Gasanov, and G. Yetirmishli.,(2007). Crustal Attenuation within the Turkish Plateau and Surrounding Regions, Bull. Seism. Soc. of Amer, 97, 151-161.

This work was performed under the auspices of the U. S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.