CRUSTAL STRUCTURE OF THE IRAN REGION FROM IN-COUNTRY AND GROUND TRUTH DATA

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Sponsored by Air Force Research Laboratory[1] and National Nuclear Security Administration[2]

Contract No. FA8718-08-C-0020[1] and DE-AC52-07NA27344[2]
Proposal No. BAA08-69

ABSTRACT

We are investigating the crustal and upper mantle structure of the Iran region using in-country data sets of seismic phase arrival times, supplemented by ground-truth data sets developed from our previous research efforts. Other data sets from global, regional, and national bulletins in the region are being integrated as well. The in-country data sets, covering approximately the last 10 years of seismicity in the region, are being carefully reviewed for quality control, selectively re-picked, and combined with ground truth and other data sets for careful relocation of all seismic sources with magnitudes of approximately 2.5 and larger. Using these relocated sources with well-characterized uncertainties and the associated phase readings for crustal and regional phases, we perform forward modeling and tomographic inversion, under the assumption of isotropic velocities, to study the velocity structure and variability of the crust and upper mantle in this region. The resulting models and datasets will provide a well-characterized baseline for more detailed studies in the future. We are continuing efforts to discover and develop new ground truth data sets in this region.

We present some of the currently available data sets for this effort, along with preliminary tomographic inversion results based on them. We present a strategy for tomography based on ray-tracing in a region for which substantial variations in crustal thickness are expected, and using datasets that have different characteristics than those normally employed for this type of study. Through relative event relocation, clusters of events have very strong constraints on relative location, depth, and origin time. For each cluster, then, there will be only a single set of free parameters addressing uncertainty in location, depth, and origin time of the cluster's hypocentroid, rather than independent parameters for each event in the cluster. This dramatically reduces the number of free parameters in an inversion. Furthermore, we have a large dataset (~500) of events in calibrated clusters that qualify as GT5 or better. Arrival-time data from subsets of these events can be set aside for use in validation of models derived from tomography.

OBJECTIVES

This research has the goal of developing in-country data sets that can be used to improve ground-based monitoring capabilities in the Iran region, by providing information needed to develop and test more accurate travel time models for seismic phases that propagate in the crust and upper mantle. The main data set to be produced is a bulletin of earthquakes in the region at magnitudes of 2.5 and higher, associated with readings from seismograph stations operating in-country for the period 1995–2005. These events and readings will be integrated with the best available catalog of regional seismicity for that period that includes associated regional and teleseismic phase-arrival times. All events will be relocated, carefully reviewed, and calibrated, where possible, with ground-truth data. We will conduct preliminary modeling experiments with these data, using Pn/Sn tomography to image broad-scale features of the crust and upper mantle in the region. The resulting data sets and model results will provide a solid foundation for further research.

RESEARCH ACCOMPLISHED

We have only recently begun work on this project, but we have made progress in several areas related to data acquisition and using tomographic studies as a quality control method.

ISC Data

We have begun integrating the latest International Seismological Centre (ISC) data release, from early 2004 through early 2006, with our existing catalog (Engdahl et al., 2008) of earthquakes in the study region. The ISC data add a large amount of data at far regional and teleseismic distances for events for which we previously held mainly in-country data. The expanded data set (Figure 1) will make it feasible to form new clusters of earthquakes for analysis with a multiple event relocation method that has been specialized for location calibration work. It also adds many Pn raypaths for events and/or station that are at the margins of our study area, which nevertheless add important coverage of the study area.

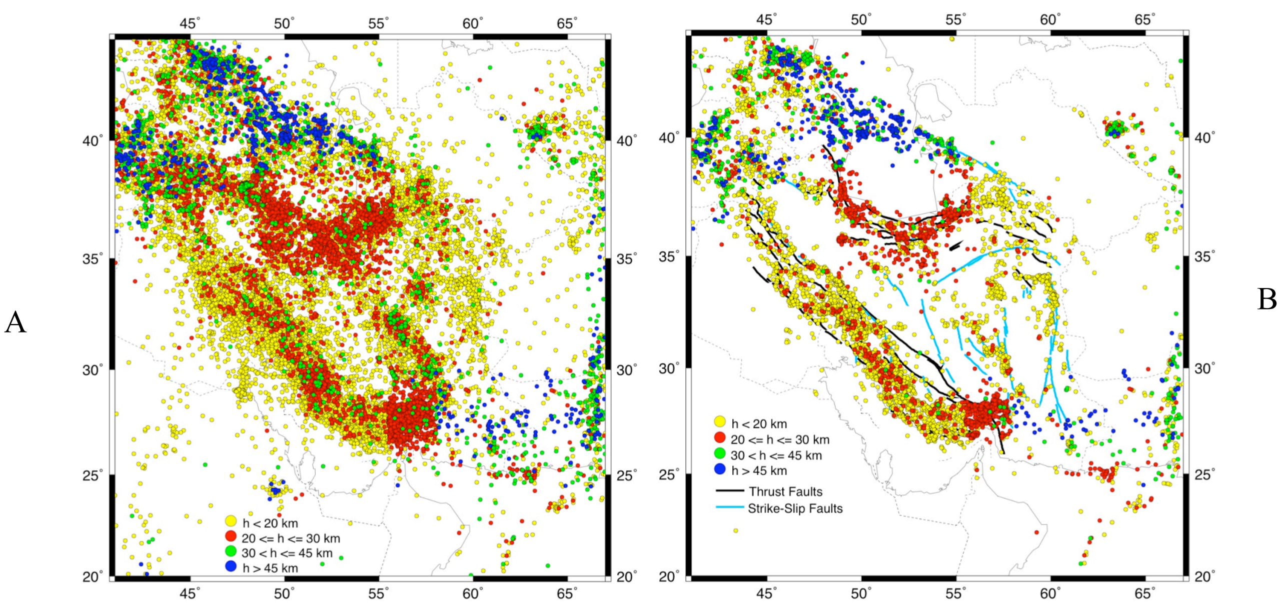

Figure 1. A) Seismicity map (25,661 events from 1923-2008, M ≥ 2.5) of the study region color coded by depth, based on the new catalog of Engdahl et al. (2008). B) 7,592 events meeting a constraint on secondary azimuth gap (<180°, applied to stations at all distances), which greatly reduces location bias.

For location calibration and tomographic research, we concentrate on events with better azimuthal coverage. In the study region, 7,592 events meet a criterion of having a secondary azimuth gap of less than 180° (stations at all distances), and these will be of the greatest use in our project (Figure 1B). The distribution of seismic stations is also of great importance to provide good azimuthal coverage for tomography (Figure 2). Station coverage in the eastern (especially southeastern) part of the study region is still problematic, but new stations have been installed recently (or are planned) that should improve the coverage somewhat through the course of this project.

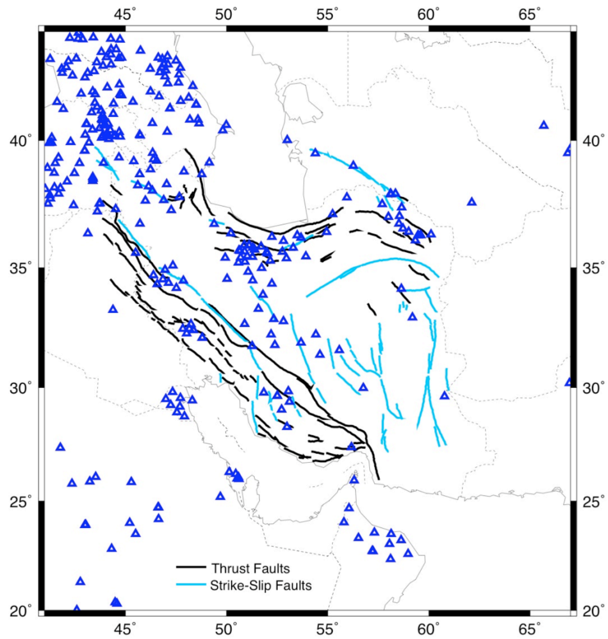

Figure 2. Seismic stations for which we have phase readings in the study area.

In-Country Data

One of us (Bergman) traveled to the study region in June 2008 and acquired several data sets of relevance to this project. These include the full set of phase picks made for earthquakes in 2006, 2007, and early 2008 by in-country analysis for all events with a magnitude of 3.5 and larger, 809 events in all. We also acquired a data set of phase readings for earthquakes in the study area that were made at stations of the Oman seismograph network for 2004–2007. These data will provide very strong improvements in azimuthal coverage for seismic events in the southern portion of the study area.

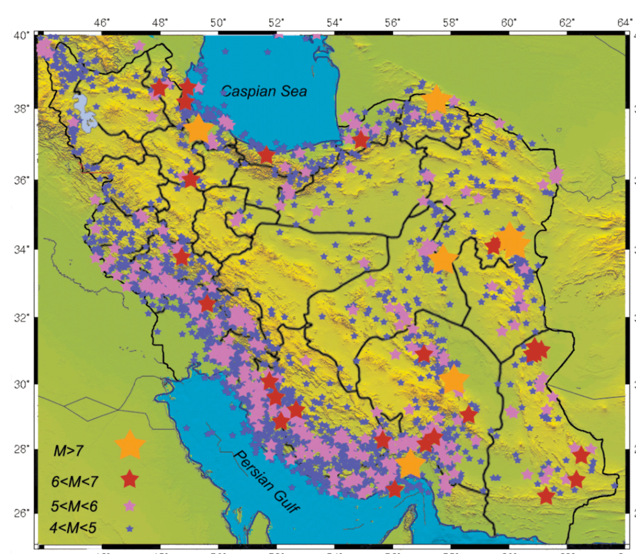

Figure 3. Data from 2,760 events are available from a network of accelerometers. In almost all cases (except the largest events), the presence of data implies that an accelerometer station was within a few tens of kilometers of the event.

We have also gained access to data from a network of ~1,000 accelerometers covering much of the study region, going back several decades (Figure 3). Because it is common for these stations to be found close to earthquakes of interest, these data provide exceptional depth resolution, and we expect this new data set to help greatly with our location calibration studies. Most of the accelerometer data has been recorded with uncalibrated timing systems, but we have successfully used S-P times to constrain the distance of events from the station. Since the stations are typically within a few tens of kilometers of recorded events, they provide a strong constraint on depth.

<u>Pn Tomography</u>

We have begun developing our existing code for Pn tomography (Barmin et al., 2001) to meet the needs of the current project. As part of this process, we have conducted a preliminary inversion of our data set of Pn readings, which has been augmented by the recently-added ISC data for the period 2004–2006. We restrict the data set to raypaths between 2° and 9° to avoid complications with diving rays at greater epicentral distances. The distribution of stations and events used for this exercise is shown in Figure 4. The raypaths and raypath density distribution are shown in Figure 5. The central part of the study region is very well covered. Because of the scarcity of stations, the southeastern part of the study region is the least sampled.

A

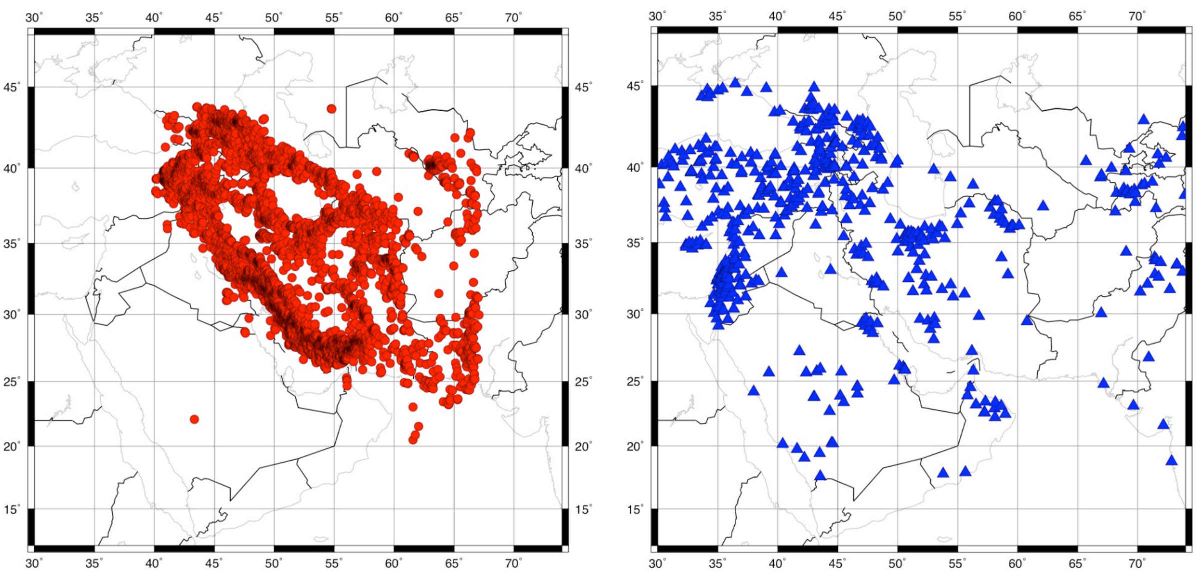

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Figure 4. 6,037 events (A) and 603 stations (B) used in a preliminary tomographic inversion using Pn phase readings with path lengths between 2° and 9°.

The starting model for Pn tomography was CRUST5.1 (Mooney et al., 1998). Using a grid size of 0.5°, we solved for the best-fitting Pn velocity, holding crustal thickness fixed. The results are shown in Figure 6, compared to the results of Pn tomography for the same region by Ritzwoller et al. (2002), extracted from a larger-scale study that covered most of Eurasia. The latest tomographic study (Figure 6A) benefits from far more data from in-country stations than was available for the earlier study, and it is not surprising to see velocity variations at much shorter wavelengths in the new study. The velocity anomolies seen in the 2002 study are also seen in the recent study, but with higher resolution, and additional anomalies are revealed. It is likely, however, that much of the signal in Figure 6A is due to unmodelled variations in crustal thickness. This will be a central focus of our research.

A

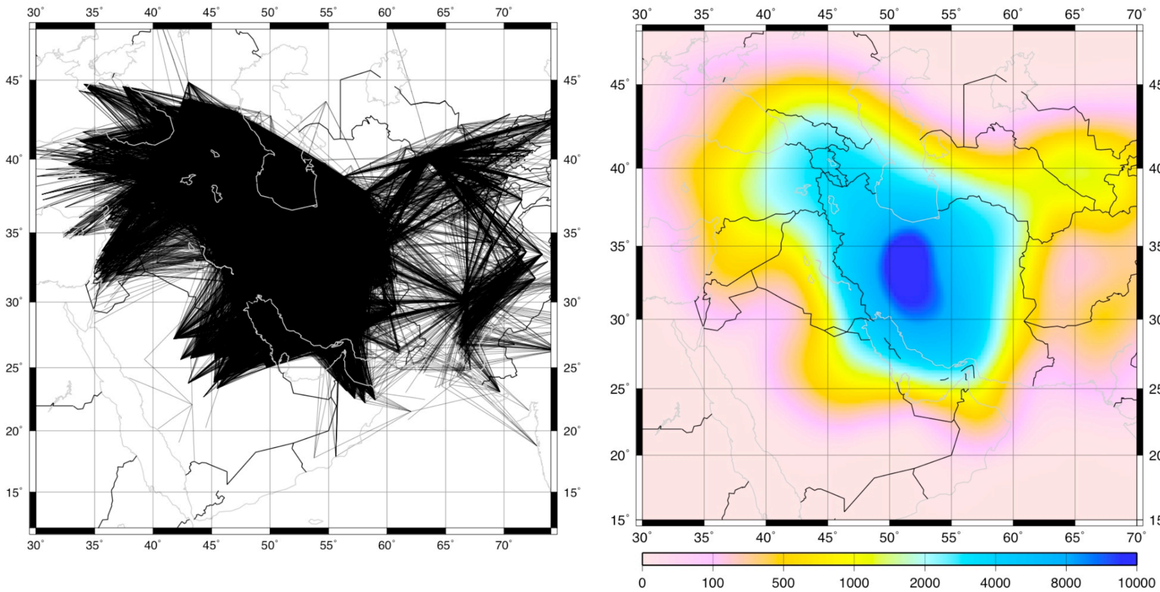

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Figure 5. A) 59,213 raypaths used in the preliminary Pn tomographic study. B) Ray path density.

Independent Constraints on Crustal Thickness

For our Pn tomography it will be very useful to have independent information on crustal thickness in the study region. It is known that crustal thickness varies substantially across the region, and these variations are a major cause of variations in the travel times of seismic phases.

The effects of the continental collision between the Arabian Peninsula and Asia are evident in the heterogeneity of crustal structure in and around the study region. Recent studies report crustal thickness in the Arabian shield ranging from 32–37 km, thickening to 43–45 km in the foredeep basin of the Zagros Mountains (Gok et al., 2008). The increase in crustal thickness is attributed to the sediment load and downward flexure of the crust. To the northwest of the foredeep, folding and faulting in the Zagros Mountains is exposed at the surface and surface elevation steadily increases. However, crustal thickness remains relatively constant from the foredeep to the main Zagros thrust fault (Paul et al., 2006). From the main Zagros thrust to ~50-90 km northwest of the main Zagros thrust, the crust abruptly thickens to approximately 70 km, before returning to a thickness of ~42 km further to the northwest (Paul et al., 2006). Jackson et al. (2002) report even more dramatic variations in crustal thickness in the vicinity of the south Caspian basin. The crust in the south Caspian Basin proper is relatively thin (~30 km), but to the west and east the crust thickens dramatically to 60 km and 45+ km, respectively.

In our recent trip to the study region we consulted researchers who have assembled substantial data sets related to estimates of crustal thickness in the region (e.g., Mokhtari et al., 2004), and these data will be utilized in our Pn tomography both as constraints and for validation of tomographic results.

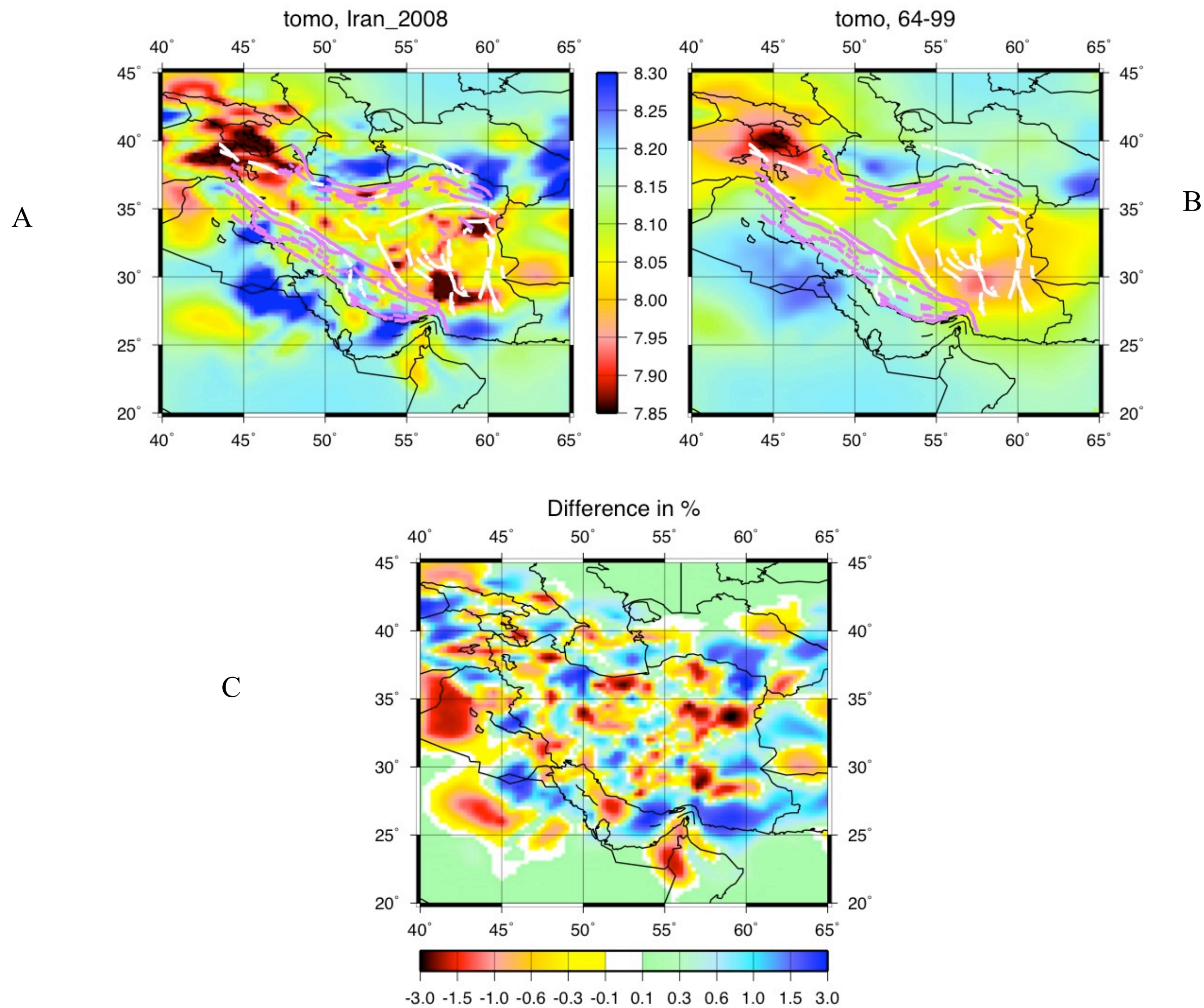

Figure 6. A) Results of preliminary Pn tomography using our most recent data set, with crustal thickness fixed according to the CRUST5.1 model (Mooney et al., 1998). B) Result of Pn tomography by Ritzwoller et al. (2002), using a data set taken from the EHB catalog for the years 1964–1999, containing few in-country data. C) Difference (in percent) between the tomographic results shown in A and B.

Our tomographic studies under this project will be most focussed on their use as a means of grooming the data set of earthquake locations and phase readings, for application to a variety of research strategies. However we also hope to make progress towards a better understanding of the variations of crustal thickness and velocities in the crust and upper mantle.

Ground Truth Studies

We have recently completed a comprehensive study of ground-truth locations for earthquakes in the study area (Engdahl et al., 2008). The data set of more than 500 earthquakes with calibrated (at GT5 or better) locations and origin times will be of great value in the current study for validating our tomographic results. During the course of this project, we will continue to expand the ground truth database as the opportunity occurs, with special emphasis placed on acquiring ground truth in regions which are as yet poorly sampled. Access to new sets of in-country data, as discussed above, and the ongoing occurrence of seismic activity in an increasingly more-densely instrumented region will ensure that such opportunities exist.

CONCLUSIONS AND RECOMMENDATIONS

We have already had significant success in acquiring the in-country data on which this project is most dependent. In fact we have already acquired data with which we would be able to satisfy the technical requirements of this project. Nevertheless, with the continued development of working relationships with in-country seismologists and institutions we are optimistic of further progress and expect to continue acquiring important new data sets and auxilliary data that will further improve the data set available for studying the crustal and upper mantle structure of this complext region. We are planning a return trip to the study region in the fall of 2008 for this purpose.

REFERENCES

Barmin, M. P., M. H. Ritzwoller, and A. L. Levshin (2001). A fast and reliable method for surface wave tomography, *Pure Appl. Geophys.* 158: 1351–1375.

Engdahl, E. R., E. A. Bergman, S. C. Meyers, and F. Ryall (2008). Improved ground truth in southern Asia using in-country data, analyst waveform review, and advanced algorithms, these Proceedings.

Jackson. J., K. Priestley, M. Allen, and M. Berberian (2002). Active tectonics of the South Caspian Basin, *Geophys. J. Int*. 148: 214–245.

Paul, A., A. Kaviani, D. Hatzfeld, J. Vergne, and M. Mokhtari (2006). Seismological evidence for crustal-scale thrusting in the Zagros mountain belt (Iran), *Geophys. J. Int.* 166**:** 227–237

Gok, R., H. Mahdi, H. Al-Shukri, and A. Rodgers (2008). Crustal structure of Iraq from receiver functions and surface wave dispersion: implications for understanding the deformation history of the Arabian-Eurasian collision**.** *Geophys. J. Int.* 172: 1179–1187.

Mokhtari, M., A. M. Farahbod, C. Lindholm, M. Alahyarkhani, and H. Bungum (2004). An approach to a comprehensive Moho depth map and crust and upper mantle velocity model for Iran, *Iranian Int. J. Sci.* 5: 2, 223–244.

Mooney, W.D., G. Laske, and T.G. Masters (1998). CRUST 5.1: A global crustal model at 5° × 5°, *J. Geophys. Res.* 103: 727–747.

Ritzwoller, M. H., M. P. Barmin, A. Villaseñor, A. L. Levshin, and E. R. Engdahl. (2002). Pn and Sn tomography across Eurasia to improve regional seismic event locations, *Tectonophysics* 358: 39–55.