SEISMIC TOMOGRAPHY OF THE ARABIAN-EURASIAN COLLISION ZONE AND SURROUNDING AREAS

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ABSTRACT

The objectives of this study are to determine *P*- and *S*-wave velocity structures in the crust and upper mantle, and to characterize seismic wave propagation in the Arabian-Eurasian collision zone and surrounding areas, including Iran, Arabia, Eastern Turkey, and the Caucasus. The Arabian-Eurasian plate boundary is a complex tectonic zone shaped by continent-continent collision processes. In recent years the number of seismic stations has increased greatly in the region because of expanded seismic networks in Azerbaijan, Turkey, Iran and the Gulf countries. We have been collecting the data through cooperation with individual network operators and the countries. Considerable effort has been directed to collecting *P* and S seismic arrival time data recorded by the new networks in Iran. Using arrival time data we obtained *Pn* and *Sn* images of the uppermost mantle beneath Arabian-Eurasian Collision Zone including Iran, the Caucasus, and the Arabian Peninsula by tomographic inversion. With the newly obtained data from Central Asia incorporated into our database, we improved the ray coverage in our study region.

Our current plan is to utilize the new data from Iran to improve the velocity models. This effort will include tomographic inversions for velocity structure in the crust and upper mantle, relocation of all events, and the validation of models using synthetic seismograms to fit available broad-band waveforms.

OBJECTIVES

The objectives of this study are to determine *P*- and *S*-wave velocity structures in the crust and upper mantle, and to characterize seismic wave propagation in the Arabian-Eurasian collision zone and surrounding areas, including Iran, Arabia, Eastern Turkey, and the Caucasus. The area of the study, shown in Figure 1, extends east-west from the Mediterranean to Central Asia, and north-south from the Caspian to the Gulf of Aden and the Arabian Sea. The area covers all of the Arabian plate, the collision zone, and the areas in the Eurasian plate whose structure and tectonics are affected by the collision. The project will include data from countries whose seismic networks have expanded significantly in recent years, such as Turkey, Azerbaijan, Iran, Kuwait, United Arab Emirates (UAE), Oman, and Saudi Arabia. These locations provide data for high-resolution P and S wave travel-time tomography. Recent observations show that wave propagation and attenuation vary significantly even with small changes across the suture zone, indicating rapid spatial changes in the crust and mantle properties.

A number of unanswered questions remain about the structure and processes in the upper mantle beneath the collision zone. The fate of the Neotethys plate subducted prior to the continental collision remains largely unknown. There are no intermediate and deep earthquakes under the Zagros-Bitlis suture zone, yet the subduction is too recent for the slab to reach thermal equilibrium and be assimilated. Some studies have suggested that the slab has recently broken off beneath the suture zone (Bird, 1978; Molinaro et al., 2005). In the Makran subduction zone in the south, seismicity and structure have been studied with the deployment of dense seismic networks (Yamini-Fard and Hatzfeld, 2006), confirming the Makran subduction, yet the nature of the transition from the subduction zone to the Zagros suture zone has not been fully resolved. High-resolution travel-time tomography would be a major step towards defining the present-day crustal and mantle structure of the Middle East region.

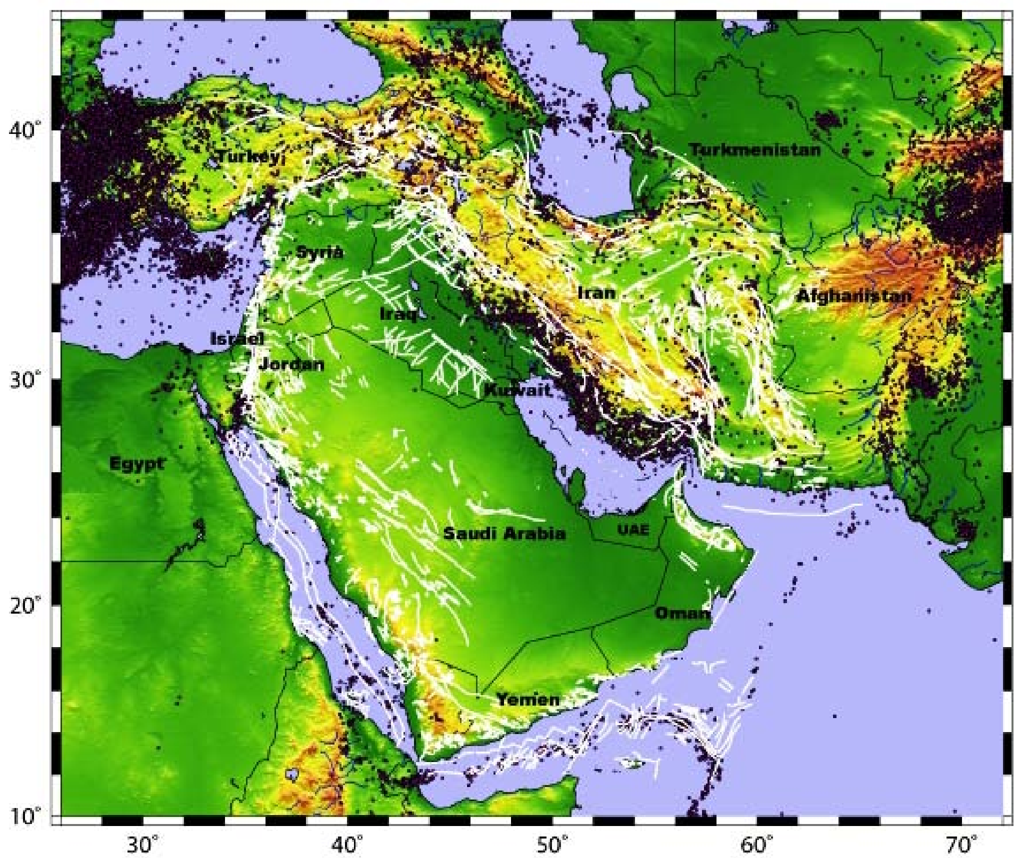

Figure 1. Topographic map of the Middle East and surrounding regions. White lines denote the location of known faults, while the black dots represent the epicenter locations of earthquakes in the region.

RESEARCH ACCOMPLISHED

Tectonic Setting

The Arabian-Eurasian plate boundary is extremely complex, and it is an ideal region to study a young (geologically) continent-continent collision belt. The current tectonics of the region are controlled by the collision and continuing convergence of the Arabian and Eurasian plates. The Arabian and Eurasian plates collided in the early Miocene, after the Neotethys Sea was subducted beneath Eurasia (Bird, 1978; Şengör and Yılmaz, 1981; Jackson and McKenzie, 1984; Dewey et al., 1986). Pre-, syn-, and post-collision tectonics produced very complex structures in the region. Over the last decade, a number of seismic studies have examined the crust and upper mantle structure beneath the Middle East to constrain the nature of the Arabian-Eurasian collision zone. Large-scale surface-wave tomography studies have shown variable crustal thickness and upper mantle velocities (Ritzwoller and Levshin, 1998; Pasyanos et al., 2001; Villasenor et al., 2001; Pasyanos and Walter, 2002; Shapiro and Ritzwoller, 2002; Alinaghi et al., 2007; Reiter and Rodi, 2006). Regional-scale surface wave tomographic studies further highlight the complexity of the collision zone (Mindevalli and Mitchell, 1989; Rodgers et al., 1999; Mokhtar et al., 2001; Maggi and Priestley, 2005) showing a thickened crust under the Caucasus and Zagros, and low shear velocity beneath the Turkish and Iranian plateaus.

Hearn and Ni (1994), Ritzwoller et al. (1998), Al-Lazki et al. (2003; 2004), and Phillips et al. (2007) found slow *Pn* velocities (≤ 8 km/s) beneath the Anatolian plateau, northwestern Iran, the Greater Caucasus, and southwestern Arabia. The Pn velocities beneath northern Arabia and the Caspian region are faster than average (Al Lazki et al., 2004; Ritzwoller et al., 2002). This high degree of variability suggests that the Earth structure may be extremely complicated in the region.

Studies of the propagation and attenuation characteristics of regional waves (e.g., Pn, Sn, and Lg) provide additional evidence for strong heterogeneities. Surface wave studies show high shear wave attenuation beneath Iran, Anatolia and the western part of the Arabian plate, and relatively low attenuation in central and eastern Arabia (Seber and Mitchell, 1992; Sandvol et al., 2001; Jamberie and Mitchell, 2004; Molinaro et al., 2005; Bergman et al., 2008; Priestley et al., 2008; Pasyanos et al., 2009). Sn and Lg waves are attenuated through much of the collision zone between the Arabian and Eurasian plates (Kadinsky-Cade et al., 1981; Rodgers et al., 1987; Mitchell et al., 1997; Cong and Mitchell, 1998; Gök et al., 2000; Sandvol et al., 2001; Al-Damegh et al., 2004; Zor et al., 2007). An Lg blockage exists across the Bitlis suture zone and across the Zagros fold and thrust belt. The studies mentioned above present consistent results for the crust and uppermost mantle seismic properties on a regional scale. Significant variation in waveforms, observed particularly in short-period seismograms, over propagation paths that are close to each other, suggests structural variations over short distances at regional boundaries. Delineating these features requires seismic data from dense local and regional seismic networks. During this year we were able to increase the phase (arrival time) data significantly by adding readings from Iran and other regional networks.

Travel-Time Data and *Pn* and *Sn* Tomography

An important task under this project is to collect arrival time data from seismic stations situated in more than 20 countries in the region. A significant number of these stations are in networks that are relatively new and whose data are not available from global data centers such as IRIS or ISC. Figure 2 shows seismic stations in the region from which data may be obtained either through data centers or by bilateral arrangements. In the past year, Iran started to make available phase data from its networks. In Iran there are seven regional networks, deployed around major cities, with a total of 73 stations. Recently, Tehran University was designated as the central location that would collect and integrate data from the regional networks into a central database. The use of data from stations in Iran required deciphering of nomenclature and resolution of some apparent discrepancies between data from individual networks and the central database. We were able to obtain 100,000 *P* and 70,000 *S* arrival time recordings from local earthquakes in the time period between January 2006 and March 2008. Our database for the *Pn* tomography in the whole study region includes 160,000 arrival times from 850 stations and 18,000 earthquakes. The source-station ray paths are shown in Figure 3A. For *Sn*, the data are fewer, with 75,000 total phase reading. The ray paths are shown in Figure 3B.

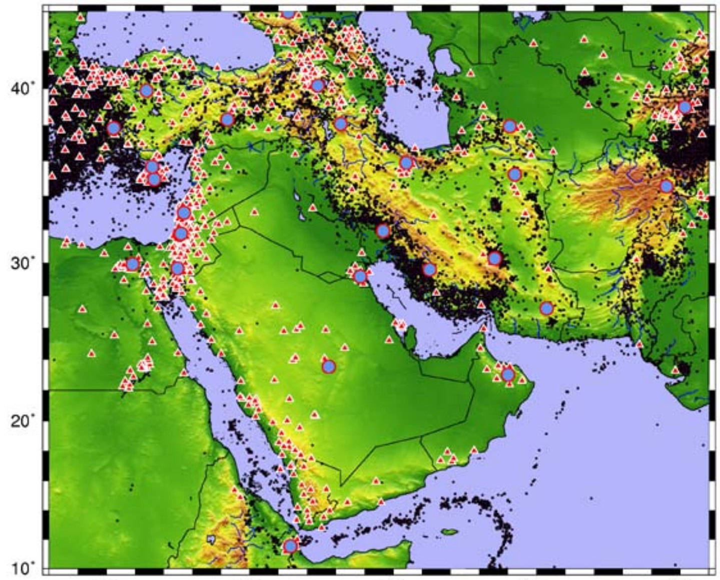

Figure 2. Seismic stations (triangles) and events (black dots) in the region. Circles show broadband stations.

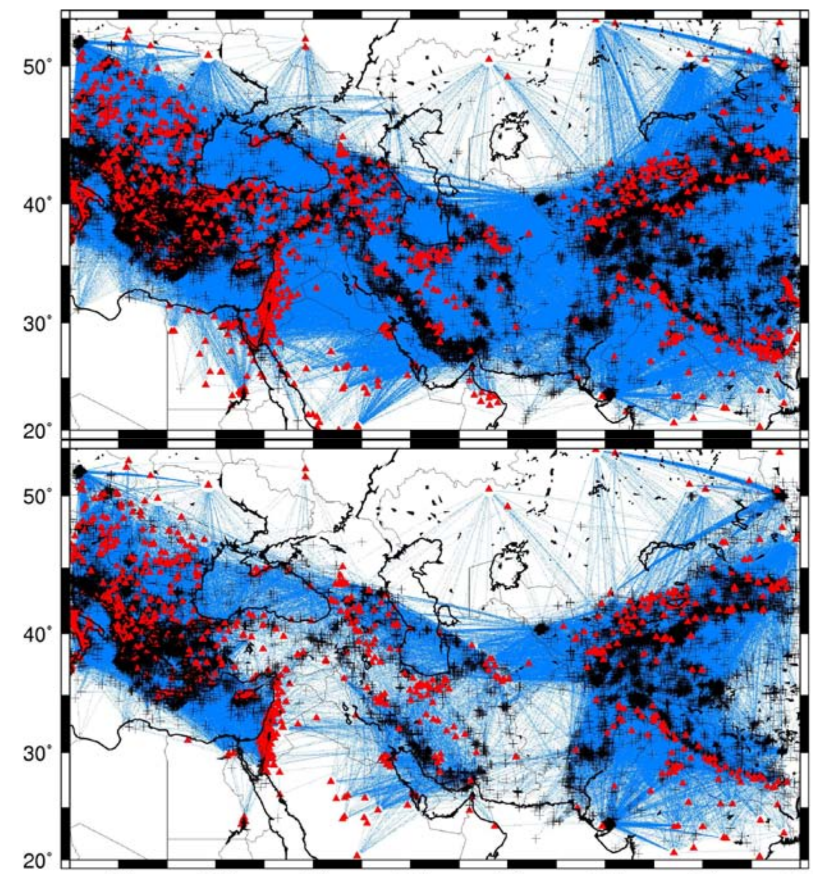

Figure 3. (A) Top: Ray paths for Pn travel times. From 18,000 events recorded by 850 stations (red triangles), 160,000 Pn rays were obtained (black crosses). (B) Bottom: Ray paths for 75,000 Sn travel times.

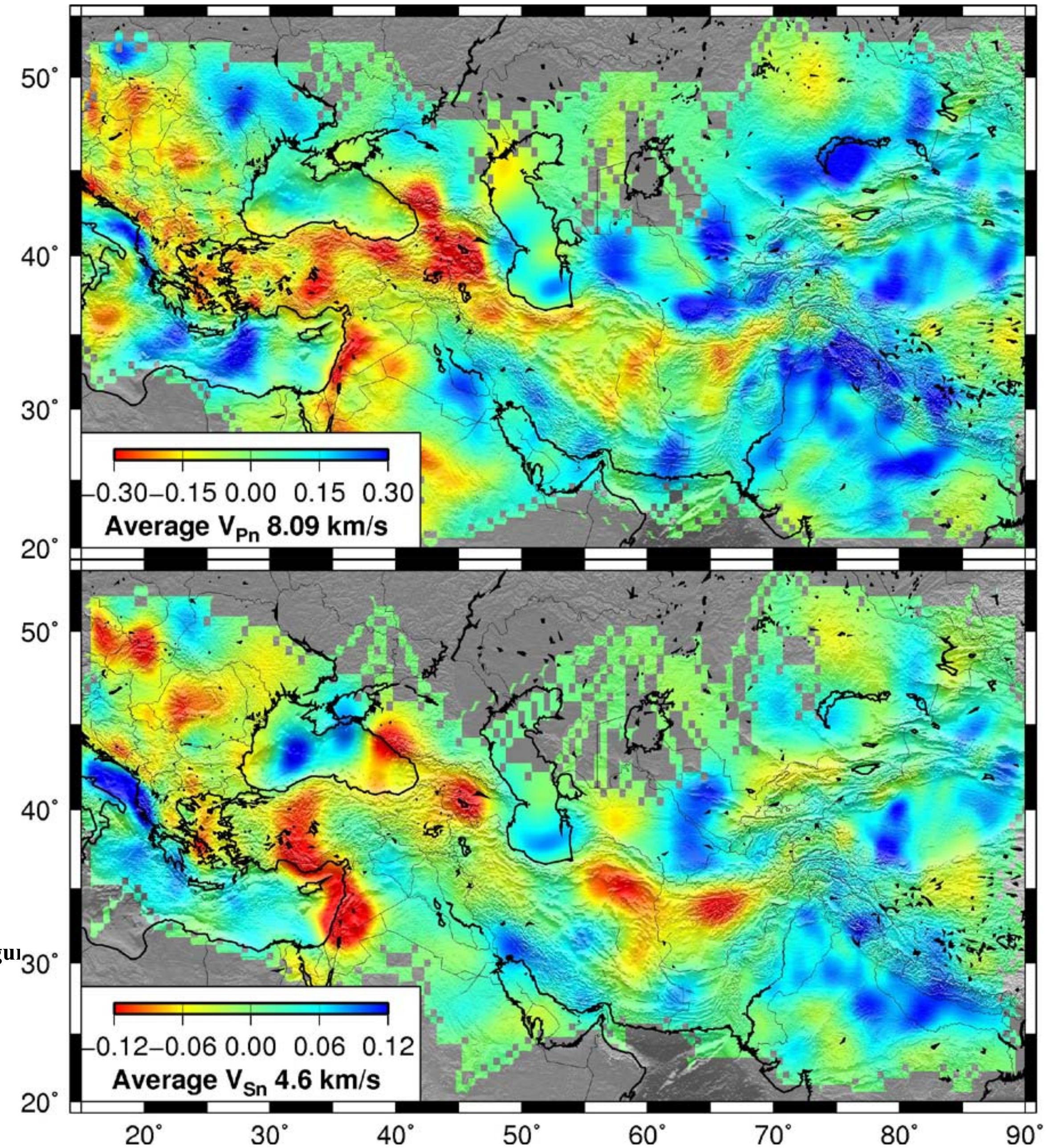

Figure 4. (A) Top: Pn velocity lateral variations. Average Pn velocity is 8.09 km/s. (B) Bottom: Sn velocity lateral variations. Average Sn velocity is 4.6 km/s.

The *Pn* and *Sn* travel times (residuals) are inverted for lateral velocity variations using Hearn's approach (Hearn, 1996; Hearn et al., 2004), modified by Pei et al. (2007). Figures 4A and 4B show *Pn* and *Sn* velocities, respectively. The general features of *Pn* velocities are similar to those of Philips et al. (2007) except that Figure 4A has finer spatial resolution. *Pn* velocities are low under eastern Anatolia, NW Iran, and the Southern Caucasus. Isolated low-velocity anomalies exist along the Levant Fracture (Dead Sea Fault) Zone. A prominent low-velocity feature is observed just to the south of the Caspian Sea. The Iranian plateau is characterized by lower than average *Pn* velocity. *Pn* velocities are high under the Arabian platform, the Persian Gulf, and under the Zagros fold belt. Most likely these are the velocities associated with the top of the Neotethys lithosphere. In the north, the higher velocities are under the Black Sea, the Rioni and Kara Basins between the Greater and Lesser Caucasus, under the southern

Caspian, and the Kyzyl and Kara Kum Basins of Turkmenistan. These are most likely the remnants of the Paleotethys (Gülen, 1989). *Sn* velocities shown in Figure 4B are similar to *Pn*. In general, the regional features correlate quite well. Some isolated anomalies (e.g., the Levant Fracture Zone) are very similar between the *Pn* and *Sn*.

Data from Iran

Most important new data for this study come from two seismic networks in Iran: Iranian Seismic Telemetry Network (ISTN) and Iran National Seismic Network (INSN) (Figure 5). The ISTN was founded in 1995. In total 73 stations are grouped into ten sub-networks distributed in most parts of Iran. There are 67 three-component short period stations and six analogue stations. The International Institute of Earthquake Engineering and Seismology operates the other nation wide seismic network: INSN. All 30 INSN stations use broadband seismographs. Figure 5 shows the station distributions in both networks.

The Institute of Geophysics at Tehran University serves as the central processing facility for ISTN. Under their management, the data quality has improved significantly in the past few years. They make available through their website travel time, amplitude, and, for selected events, waveform data. Figure 6 shows examples of travel time data from both ISTN and INSN networks. We collected phase arrivals and maximum amplitudes reported by both networks from July, 2004 to May, 2009. This dataset provides abundant local and regional phase arrivals, which are useful in extracting crustal seismic structure. The ISTN catalogue includes 25,471 earthquakes between Feb, 2006 and Apr, 2009. More than 240,000 arrivals were reported. There are about 160,000 *P* arrivals and 80,000 *S* arrivals. The INSN reported 3,342 events before 2008 and used 15,112 *P*-wave arrivals, 4,927 *S*-wave arrivals to locate events.

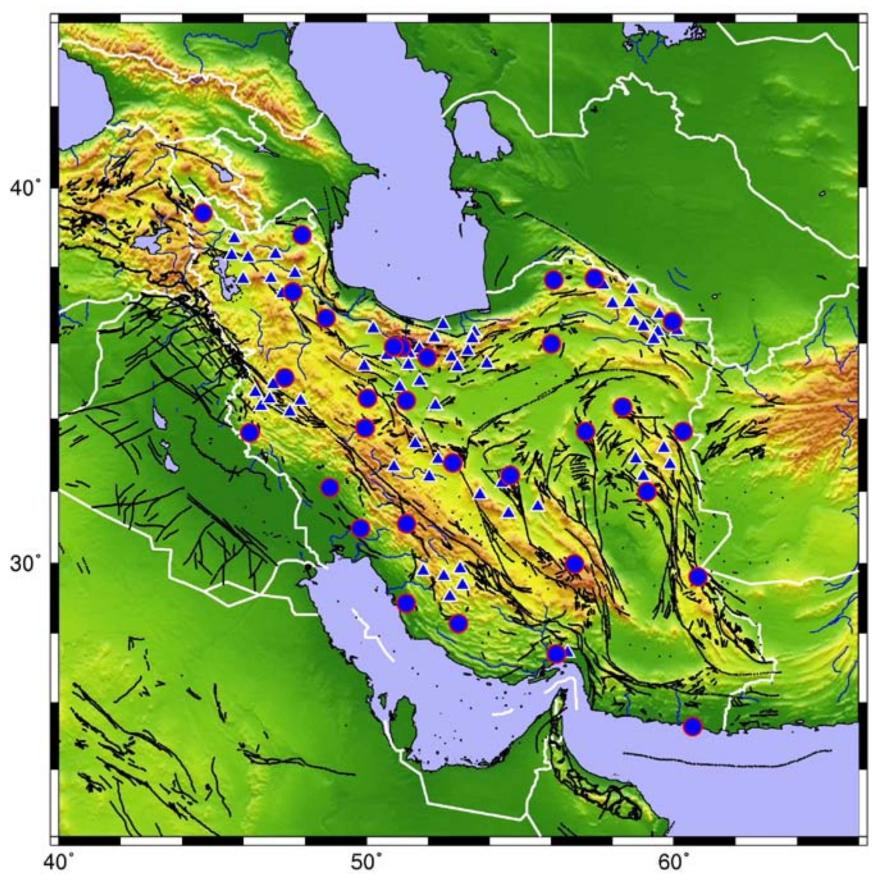

Figure 5. Seismic stations in Iran. INSN stations are in circles and ISTN stations are in triangles.

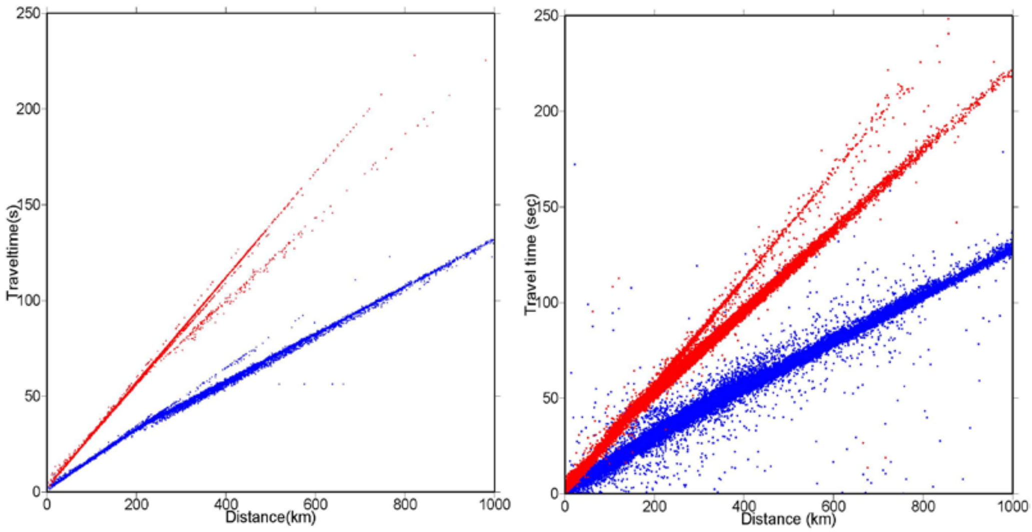

Figure 6. Available *P* and *S* travel times from INSN (left) and ISTN (right) networks.

Relocation of Earthquakes in Iran

The local and regional networks (shown in Figure 5) provide good data coverage (Figure 6) to relocate earthquakes using high-quality *P*- and *S*-wave travel-times. We apply an adaptive-mesh, double-difference tomography method to the Iranian data set to improve event locations and to obtain preliminary velocity models (Zhang and Thurber, 2003; 2005). Figure 7 shows the comparison of travel-time residuals using 1-D and 3-D models for event relocation. The 1-D *P* and *S* models used for relocation were adopted from Crust 2.0 and the 3-D models were obtained while simultaneously locating events. The overall residuals are reduced from 1.2 s to 0.9 s. Figure 8 shows the relocation of a group of events in the year of 2006 and an example of event relocation using 1-D and 3-D models. The average difference between the original locations and the 3-D relocations is 10 km.

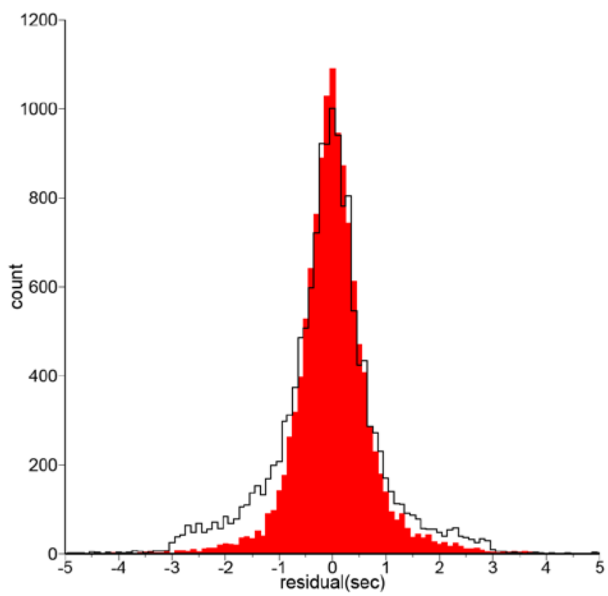

Figure 7. Comparison of residuals using 1-D model (solid line) and 3-D model (red).

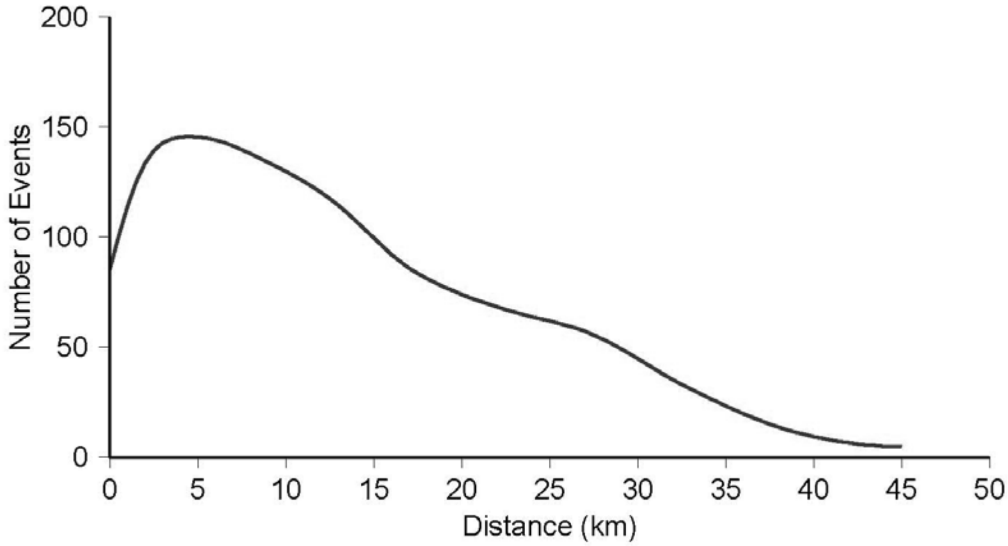

Figure 8. Epicentral differences between the relocations and original locations of earthquakes in Iran.

CONCLUSIONS AND RECOMMENDATIONS

Primary activities were dedicated to collecting P and S wave local/regional arrival time data from more than 750 stations in the study area. For the first time we were able to obtain arrival-time data from 103 stations in Iran. Altogether 200,000 *P* arrivals and 100,000 *S* arrivals from Iran were added to the database to do a seamless tomography of the crust and upper mantle. The tomographic results reveal a significant low velocity zone to the south of the Caspian Sea. Along the Zagros belt, a large low-velocity zone is clearly observed. Other prominent low *Pn* and *Sn* anomalies are visible in the Northwestern Iran, the Caucasus Anatolian Plateau and the Easternmost Mediterranean. We are in the process of testing these models using well-located ground-truth events and synthetic seismograms to fit available broad-band waveforms.

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