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M. Nafi Toksöz¹, Robert D. Van der Hilst¹, Youshun Sun¹, Levent Gülen¹, Dogan Kalafat², Huseyin S. Kuleli¹, Chang Li¹, and Haijiang Zhang¹

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14. 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. Unfortunately, the phase readings and waveform data cannot be obtained from a single data center. We are collecting the data through cooperation with individual network operators and the countries.

The travel-time tomography is carried out in three steps. First, obtain Pn and Sn velocities using local and regional arrival time data. Second, obtain the 3-D crustal P and S velocity models. Third, extend the model into the upper mantle and transition zone by combining local, regional, and teleseismic data and crust model constraints. We obtained the regional Pn velocity tomograms using 160,000 arrival times (including data from Iran) from 850 stations and 18,000 earthquakes. For Sn tomography, 75,000 phase readings were used. The Pn and Sn velocity variations agree quite well with some local differences. Pn velocities are very low under eastern Anatolia, northwest Iran, and the Lesser Caucasus. There are localized low-velocity anomalies. Velocities are low under the Iranian plateau. Pn velocities are high under the Arabian Platform, the Gulf, and the Zagros. In the north, high Pn velocities extend from the Black Sea to the Caspian and east to the Kara Kum Basin.

The upper mantle tomograms show the images of the subducted Neotethys slab. The slab geometry is quite complex, reflecting the history of the changes in plate motions and collision processes.

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

M. Nafi Toksöz¹, Robert D. Van der Hilst¹, Youshun Sun¹, Levent Gülen¹,
Dogan Kalafat², Huseyin S. Kuleli¹, Chang Li¹, and Haijiang Zhang¹

Massachusetts Institute of Technology¹ and Kandilli Observatory and Earthquake Research Institute,
Bogaziçi University²

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The travel-time tomography is carried out in three steps. First, obtain Pn and Sn velocities using local and regional arrival time data. Second, obtain the 3-D crustal P and S velocity models. Third, extend the model into the upper mantle and transition zone by combining local, regional, and teleseismic data and crust model constraints. We obtained the regional Pn velocity tomograms using 160,000 arrival times (including data from Iran) from 850 stations and 18,000 earthquakes. For Sn tomography, 75,000 phase readings were used. The Pn and Sn velocity variations agree quite well with some local differences. Pn velocities are very low under eastern Anatolia, northwest Iran, and the Lesser Caucasus. There are localized low-velocity anomalies. Velocities are low under the Iranian plateau. Pn velocities are high under the Arabian Platform, the Gulf, and the Zagros. In the north, high Pn velocities extend from the Black Sea to the Caspian and east to the Kara Kum Basin.

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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 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.

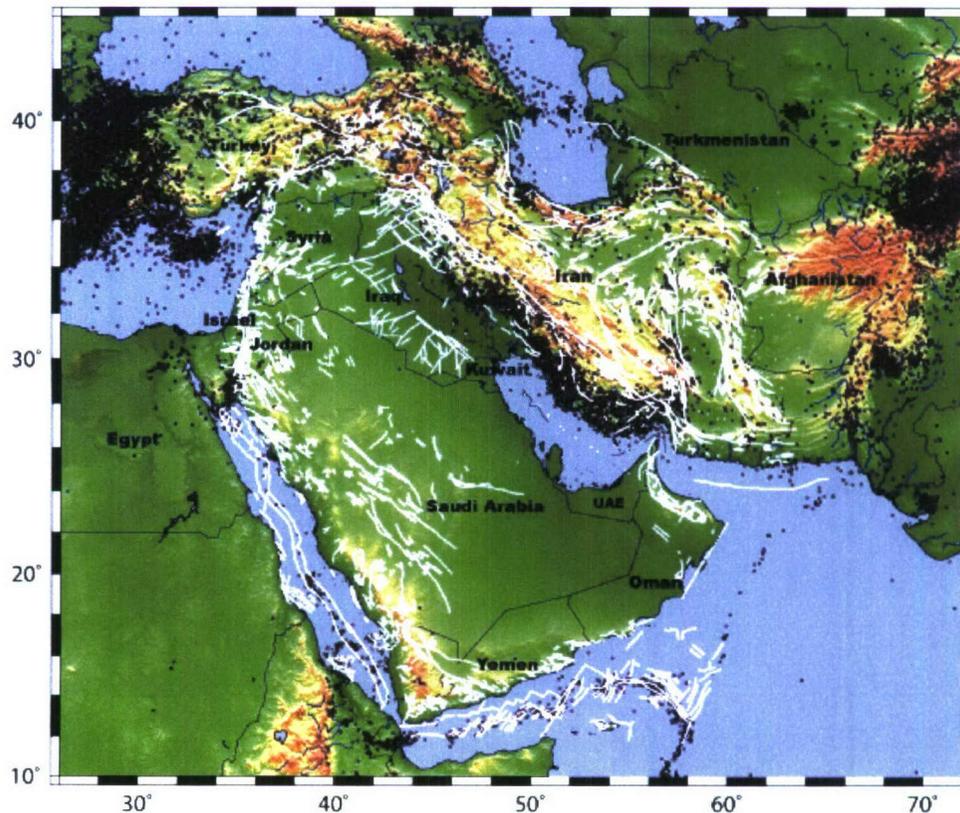


Figure 1. Topographic map of the Middle East and surrounding regions. White lines denote the location of known faults, while the black dots represent the epicenter locations of earthquakes in the region.

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; Mohkhtar 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; Cong and Mitchell, 1998; Jamberie and Mitchell, 2004). 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). 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 the Incorporated Research Institutions for Seismology (IRIS) or the International Seismological Centre (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 50 stations (Figure 3). Recently, Tehran University was designated as the central location that would collect and integrate data from the regional networks into a central database. Use of data from stations in Iran required the deciphering of nomenclature and the 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 for 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 4A. For Sn, the data are fewer, with 75,000 total phase readings. The ray paths are shown in Figure 4B.

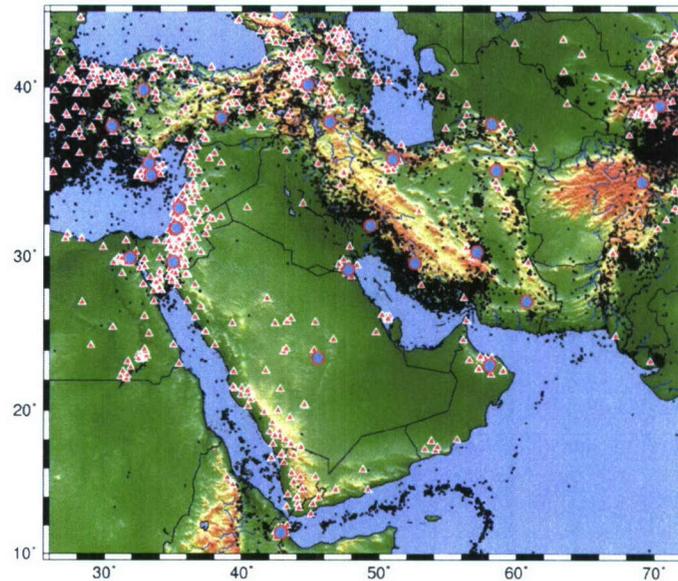


Figure 2. Seismic stations (triangles) and events (black dots) in the region. Circles show broadband stations.

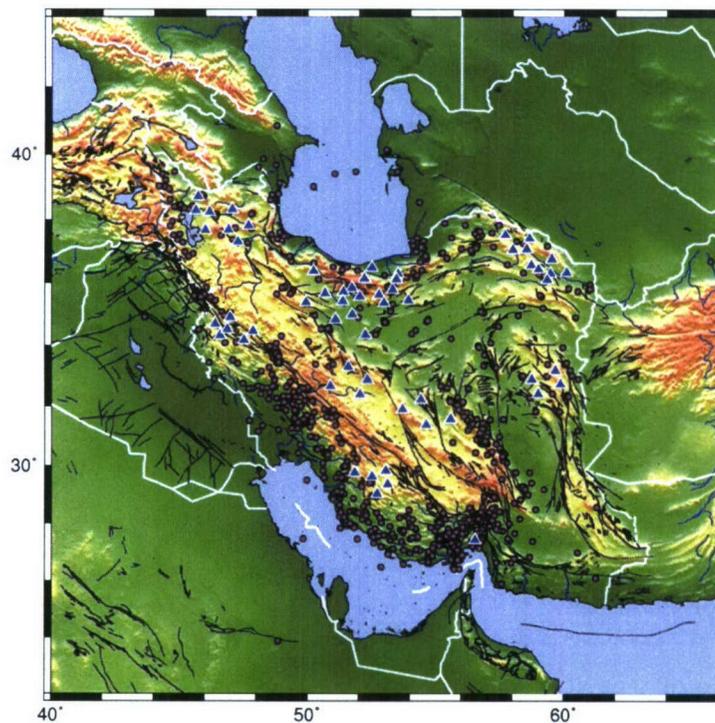


Figure 3. Seismic stations (triangles) and events (dots) in Iran from January 2006 to March 2008.

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). Figure 5 shows the travel-time residuals before and after the Pn and Sn tomographic inversions. Figures 6A and 6B show Pn and Sn velocities, respectively. The general features of Pn velocities are similar to those of Philips et al. (2007), except that Figure 6A has finer spatial resolution. Pn

velocities are low under eastern Anatolia, northwest 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, 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 6B are similar to Pn. In general, the regional features correlate quite well. Some isolated anomalies (e.g., Levant Fracture Zone) are very similar between the Pn and Sn.

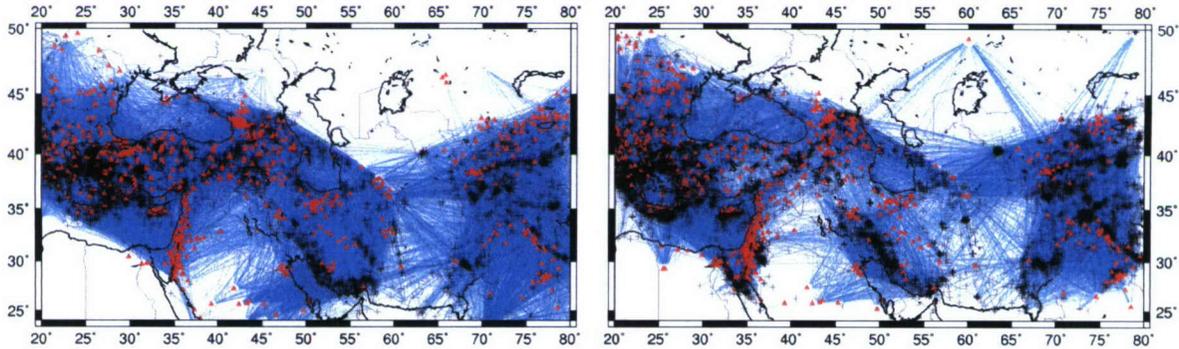


Figure 4. (A) Left: Ray paths for Pn travel times. From 18,000 events recorded by 850 stations (red triangles), 160,000 Pn rays were obtained (black crosses). (B) Right: Ray paths for 75,000 Sn travel times.

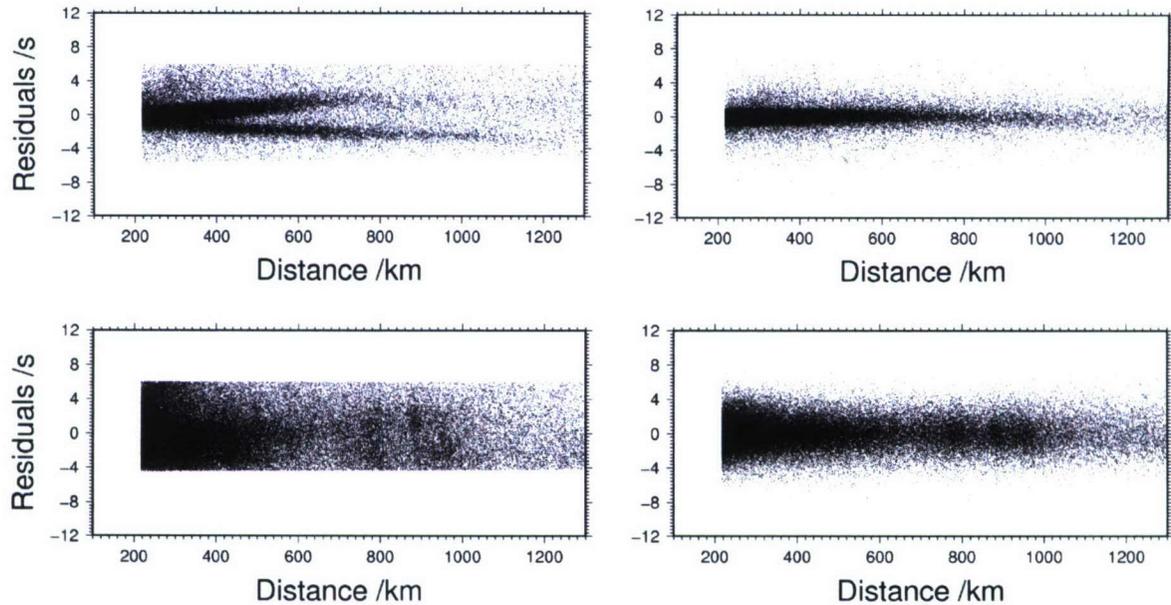


Figure 5. (A) Top: Pn travel-time residuals before inversion (left) and after inversion (right). The standard deviation of travel-time residuals decreased to 1.26 s from 1.73 s. Bottom: Sn travel-time residuals before inversion (left) and after inversion (right). The standard deviation of travel-time residuals decreased to 1.89 s from 2.54 s.

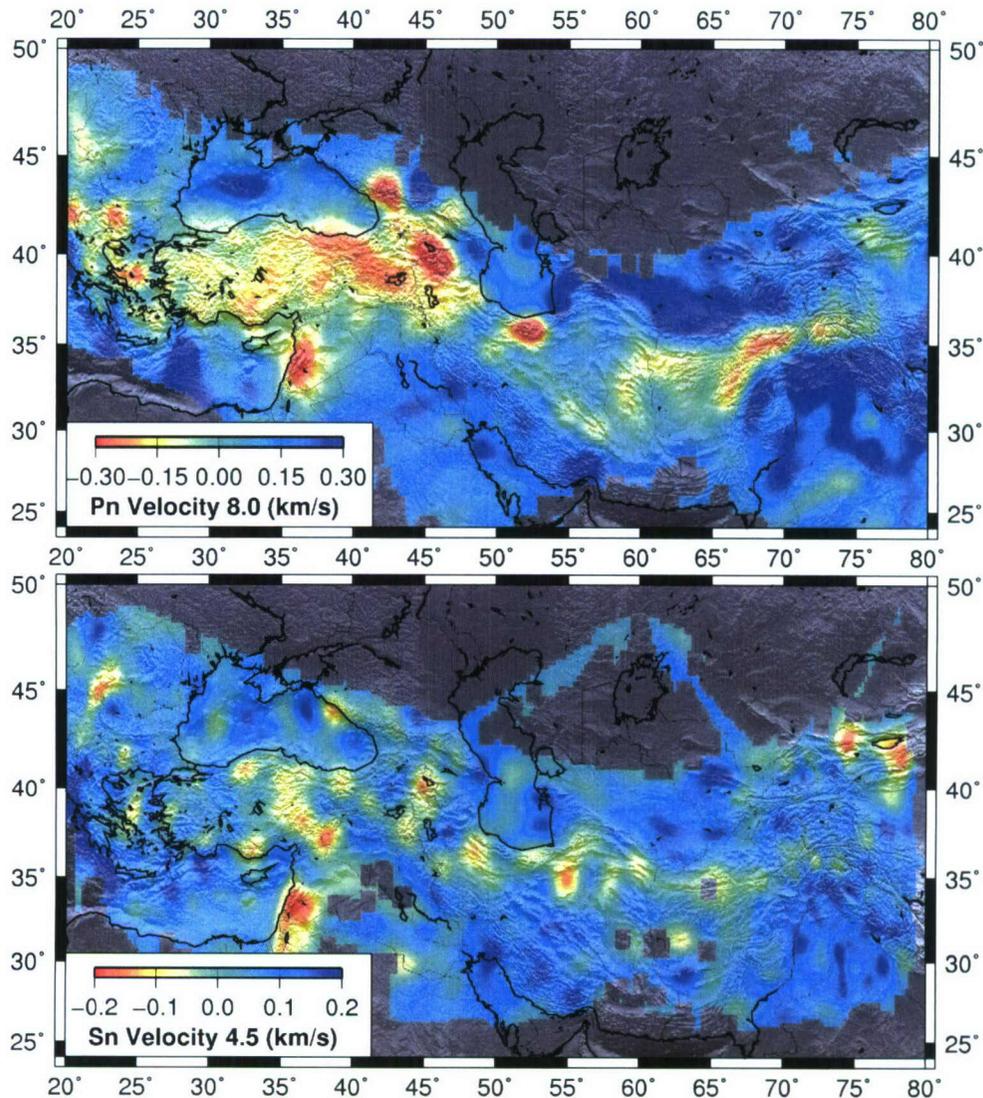


Figure 6. (A) Top: Pn velocity lateral variations. Average Pn velocity is 8.0 km/s. (B) Bottom: Sn velocity lateral variations. Average Sn velocity is 4.5 km/s.

Upper Mantle Structure Beneath the Middle East

We used teleseismic and local data for determining the velocity structure. The data used come from three sources: (1) the EHB (Engdahl, van der Hilst, and Buland, 1998) datasets, reprocessed from the ISC between 1964 and 2007; (2) picked arrival times from regional (temporary) seismic stations and arrays, including stations in Saudi Arabia and Ethiopia; and (3) the global PP-P differential travel-time dataset.

Travel-time residuals are then computed by subtracting travel times calculated based on the *ak135* reference model (Kennett et al., 1995). Although inversion is done for the whole mantle, a substantial number of stations of the EHB catalog are located within the Middle East region, and they provide key constraints on the subduction along the Zagros-Bitlis suture zone. In Figure 7, we show P-wave velocity variations beneath the Middle East in map view at four different depths. The coastlines and plate boundaries are shown for reference.

The model reveals the low-velocity anomaly beneath Ethiopia from 100 km down to 500 km depth. Another low-velocity anomaly is located beneath the northwestern part of the Arabian plate from 100 km to 300 km depth (Figure 7). These low-velocity anomalies extend to the transition zone and at the lower mantle, suggesting that they may be associated with deep mantle upwelling (Benoit et al., 2006).

The high-velocity anomalies associated with the Neotethys subducted lithosphere is clearly evident at velocity images at depths of 300, 500, and 700 km.

Cross sections across the collision zone (Figures 8A and 8B) provide other views of the convergence zone. The subducting slab is clearly visible under Makran and extends down to a 660-km discontinuity. Under the Persian Gulf and Zagros (Figure 8B), the slab geometry is more complete. This may be associated with changing velocities of the Arabian plate since the initial collision about 28 million years ago.

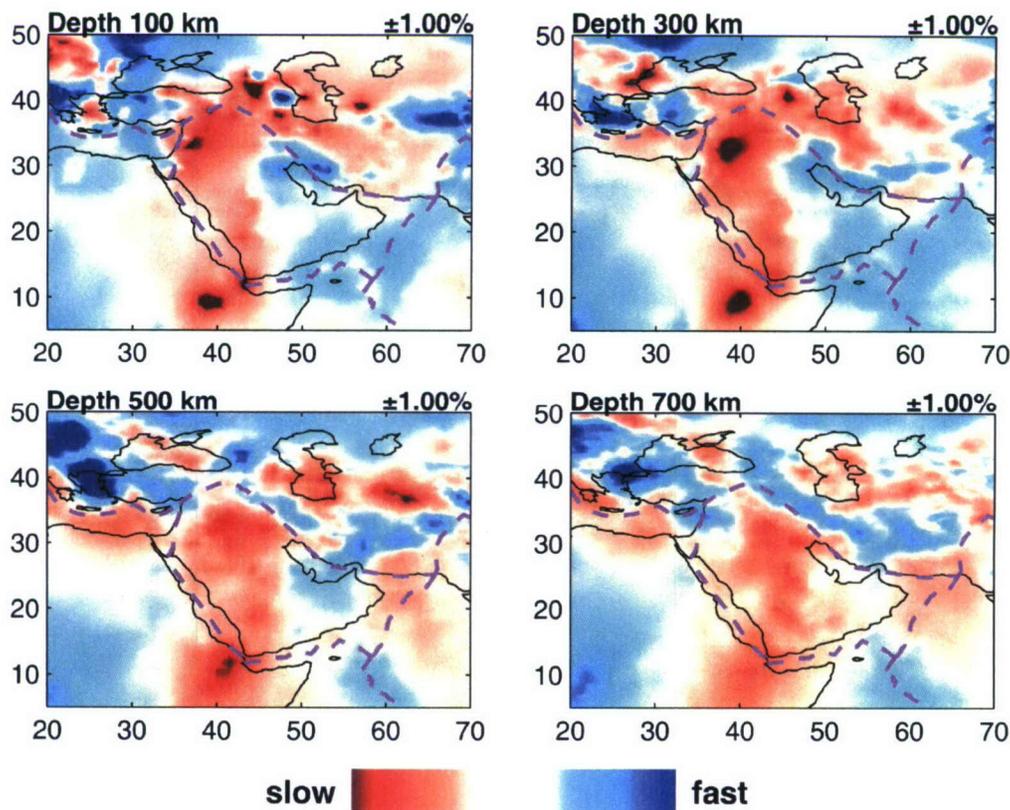


Figure 7. P-wave anomalies beneath the Middle East at different depths as indicated on the left upper corner in each subplot. The blue and red represent high and low-velocity anomalies, respectively. The dashed purple lines are the plate boundaries, and the black lines are the coastlines.

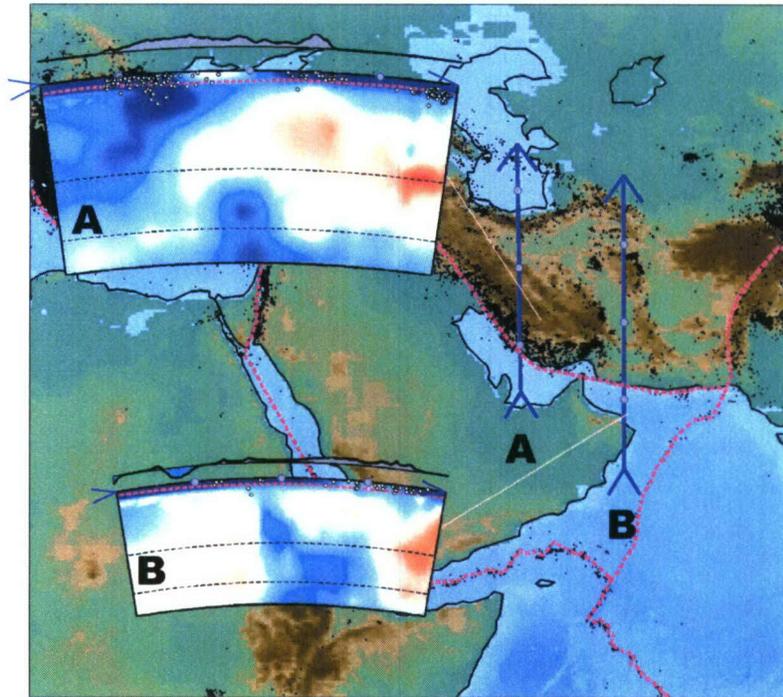


Figure 8. Vertical cross sections showing the P-wave velocity anomalies down to 700 km depth. The color scale indicates 0.8% deviations with respect to the 1-D *ak135* model. The dashed lines indicate the 410 km and 660 km mantle discontinuities. The topography is shown on top of the cross section.

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 50 stations in Iran. Altogether, 160,000 Pn arrivals and 100,000 Sn arrivals were used to do a seamless tomography of the uppermost mantle on the Arabian Eurasian collision zone, and to obtain both the Pn and Sn velocities. The main features of the velocity models are as follows:

1. Pn and Sn velocities are similar in general. Measurable differences exist in some regions.
2. Pn (and Sn) velocities are lowest under eastern Anatolia, northwest Iran, and the southern Caucasus. Velocities under the Anatolian and Iranian plateaus are low.
3. Velocities are lower under Anatolia than under the Iranian plateau.
4. There are isolated low-velocity zones under the northern Dead Sea Fault.
5. Pn and Sn velocities are high under the Arabian Platform and under regions surrounding the Iranian and Anatolian plateaus (e.g. Persian Gulf, Black Sea, South Caspian, and Kyzyl Kum and Kara Kum basins).
6. Upper mantle velocities obtained with regional and teleseismic arrival time data clearly delineate images of the subducted Neotethys slab.
7. Slab geometry varies significantly in different parts of the convergence zone. It is a typical oceanic subduction under Makran but becomes more complex under the northern parts of the collision zone.

Future work in the project will concentrate on obtaining travel-time data from additional stations, generating 3-D P and S wave velocity models for the crust, and redoing the upper mantle tomography with the new 3-D crustal model included. Evaluating the effects of velocity heterogeneities on the waveforms over local and regional distances will be an important part of the effort, as well as model evaluation with selected ground truth events.

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