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 motivation for the proposed study is threefold. First, the Arabian-Eurasian plate boundary is an excellent place for the study of continent-continent collision processes. It is geologically younger and smaller than the much-studied India-Asian collision zone. Second, in the past several years the number of high quality seismic stations has increased significantly because of new and expanded networks in Oman, Kuwait, Saudi Arabia, Iran, Azerbaijan, and others. These provide high-quality P and S wave travel-time data. Third, observations show that wave propagation varies significantly with small changes in path across the suture zone, indicating rapid spatial changes in the crust and mantle properties. To obtain an accurate structural model of the region, high-resolution tomographic studies are required.

The tomography is done in two steps. First, 3-D P and S velocity structures are determined by regional travel-time tomography. Next, teleseismic body-wave tomography is carried out for upper mantle and transition zone structure. Preliminary tomographic results show a complex crust and upper mantle structures and evidence of subduction both in the north (South Caspian Sea) and the Makran zone in the south.

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 Indian Ocean. 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.

The 3-D velocity structure from this study will improve event location accuracy in the region. While several individual countries in the area prepare their own earthquake bulletins, no single comprehensive catalog of well-located earthquakes exists for the whole region. This study would utilize these individual event bulletins to provide an extensive database of relocated events. Additionally, the high resolution body wave travel-time tomographic models will aid in the calculation of model-based station corrections.

A number of unanswered questions remain about the structure and processes in the upper mantle beneath the collision zone. The fate of the Neo-Tethys 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., 2005b). 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), 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.

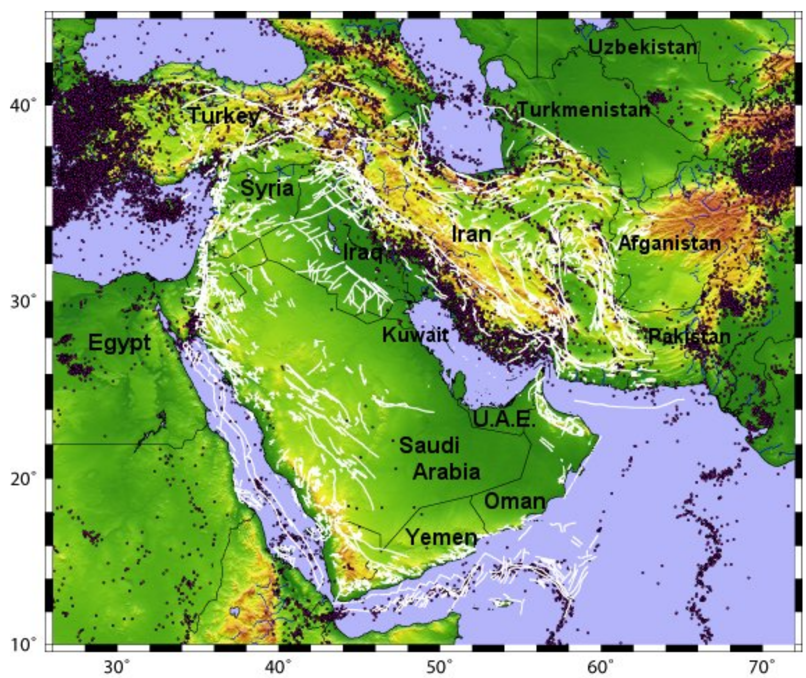

Figure 1. Topographic map of the Middle East and surrounding regions. White lines denote the location of known faults, while the black dots represent the epicenter locations of earthquakes in the region.

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 Neo-Tethys Sea was subducted beneath Eurasia (Bird, 1978; Şengör and Yılmaz, 1981; Jackson and McKenzie, 1984; Dewey et al., 1986). Several tectonic features were formed as a result of the deformation associated with the collision, such as the Bitlis Suture Zone, the Zagros fold and thrust belt, and the strike-slip East Anatolian fault that mark the Arabian-Eurasian plate boundary. Other tectonic features, such as the Caucasus Mountains and the Iranian and Anatolian Plateau, also formed as a result of the plate collision. Additionally, extensive basaltic volcanism occurred in Anatolia beginning around 8 Ma, though most of the volcanics are younger than 3 Ma (Pearce et al., 1990). The deformation and the seismicity surrounding the Arabian-Eurasian collision zone are similar to, but less intense than that of the Indian-Eurasian collision zone (Gülen, 1989). The Arabian-Eurasian convergence deformation patterns are shown in a simplified map in Figure 1.

Pre-, syn-, and post-collision tectonics have produced very complex structures in the region. The complex structure extends far beyond the collision zone into Iran, the Caucasus, and Anatolia. The Arabian Plate consists of a Late Proterozoic shield in the southwest, and a Phanerozoic platform in the north and northeast (Bird, 1978; Seber and Mitchell, 1992; Rodgers et al., 1999; Al-Damegh et al., 2005). Structural complexity in the Arabian Plate increases to the north and along the western boundary along the Red Sea and the Dead Sea Fault Zone. The geological features are obscured by the thick sediment cover on the Arabian plate to the southwest of the Zagros fold and thrust belt under the Caspian Sea.

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. Seismic velocities in the uppermost mantle are low beneath Arabia, Turkey, Iran, and the western part of the Arabian plate and are faster than those beneath the Eastern Arabian Platform and Caspian Sea regions (Pasyanos and Walter, 2002; Shapiro and Ritzwoller, 2002; Pasyanos et al., 2001; Villasenor et al., 2001; Ritzwoller and Levshin, 1998). Regional scale surface wave tomographic studies further highlight the complexity of the collision zone (Maggi and Priestley, 2005; Mohktar et al., 2001; Rodgers et al., 1999; Mindevalli and Mitchell, 1989) showing a thickened crust under the Caucasus and Zagros, and low shear velocity beneath the Turkish and Iranian plateaus.

Ritzwoller et al. (1998), Hearn and Ni (1994), and Al-Lazki et al. (2003; 2004), found slow Pn velocities ($\leq$ 8 km/s) beneath the Anatolian plateau, northwestern Iran, the Greater Caucasus, and northwestern 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). The Lg wave propagation is 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; however, Lg propagates efficiently across the Arabian Plate.

The Sn wave, which propagates in the uppermost mantle, is sensitive to mantle lid rheology. Sn is strongly attenuated in Anatolia and northwest Iran (Rodgers et al., 1987; Gök et al., 2000; 2003; Sandvol et al., 2001; Ritzwoller et al., 2002; Al-Damegh et al., 2004).

The conclusions that can be derived from these examples are that the seismic properties of the Zagros-Bitlis suture zone and surrounding areas are extremely heterogeneous and require high resolution studies to elucidate. Data from the high density of seismic stations that have become available provide opportunity for such a study.

Pn Tomography in the Middle East Region

Pn travel time residuals are inverted for the lateral velocity variation and anisotropy within the mantle lid following Hearn's approach and computation method (Hearn, 1996). The preliminary results are shown in Figure 2 and they indicate significant lateral variations in Pn velocity, especially in the Caucasus and surrounding regions. Generally areas of thicker continental crust show lower velocities, while oceanic crust under the Black Sea, Southern Caspian Sea, and Azerbaijan show high velocities with respect to the reference uppermost mantle Pn velocity of 7.9 km/s.

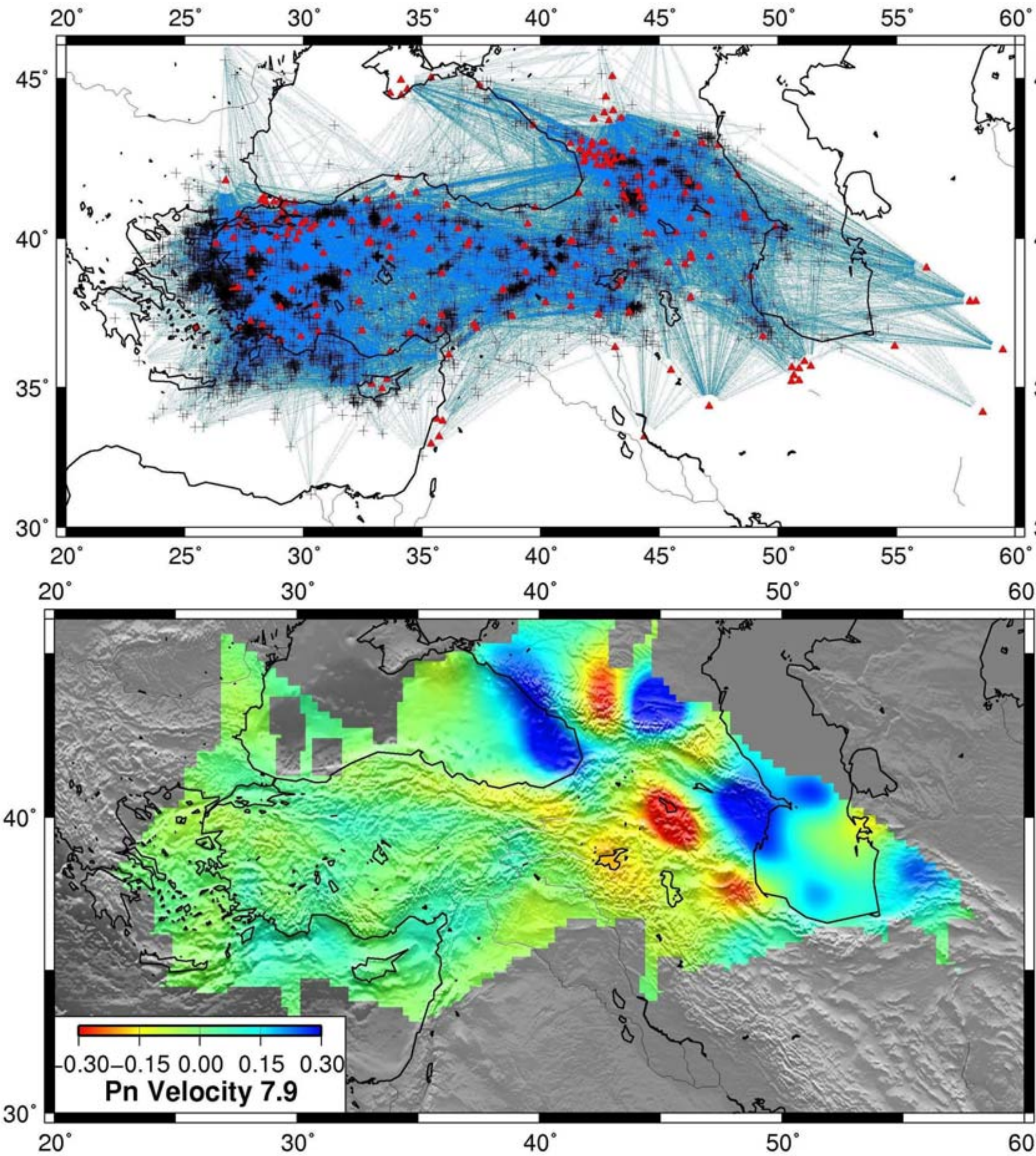

Figure 2. (a) Ray paths for Pn travel times. From 5465 events recorded by 245 stations (red triangles), 41,682 Pn rays were obtained (black crosses). (b) Pn velocity lateral variations. Average Pn velocity is 7.9 km/s. Lower velocities are shown in red, and higher velocities are shown in blue.

P-Wave Travel-time Tomography of the Middle East Region

Data and method

The data most relevant to this study for P-wave teleseismic travel-time tomography come from three sources: (1) picked arrival times from regional (temporary) seismic arrays; (2) the EHB (**E**ngdahl, van der **H**ilst, and **B**uland, 1998) datasets, reprocessed from the International Seismological Center (ISC) between 1964 and 2004; and (3) the global PP-P differential travel-time dataset.

Array data: We manually picked P-wave arrivals from local, regional, and teleseismic earthquake recorded at ~50 seismometers in Ethiopia and Saudi Arabia (yellow triangles in Figure 3). Travel time residuals are then computed by subtracting travel time calculated based on the *ak135* reference model (Kennett et al., 1995). The database will be continually expanded by obtaining data from networks in Oman, Kuwait, Saudi Arabia, and others.

Global EHB catalog: The second part of our data comes from the global EHB catalog. We use about 10 million P, Pg, pP, Pn, and PKP phases from 1964 to 2004. About 750 stations of the EHB are located within the Middle East region (red triangles in Figure 3) and they provide key constraints on the subduction along the Zagros-Bitlis suture zone.

Global PP-P data: We use the differential times of PP-P, accurately measured by waveform cross-correlation from digital seismogram (Woodward and Masters, 1991), to resolve structures in the upper mantle region with few earthquakes and stations.

To mitigate effects of uneven data coverage we use an adaptive parameterization, in which the size of grid block is based on the sampling density of the high frequency data (Li et al., 2006). To reduce the crustal anomaly smearing due to strong crustal heterogeneity along P-wave paths with small incidence angle, we use an a priori crustal model for the crustal correction by means of regularization (Li et al., 2006). We invert the whole mantle structure to avoid the errors caused by the anomalies elsewhere and the results presented here are a subset of the P-wave global model.

Upper mantle structure beneath the Middle East

In Figure 4 we present P-wave velocity variations beneath the Middle East in map view with the coast lines and plate boundary. In Figure 5 we illustrate the subduction along the Zagros and Makran by means of vertical cross sections.

Our model reveals an intriguing low velocity anomaly beneath Ethiopia from 100 km down to 500 km depth (Figure 4). Also, another low velocity anomaly is located beneath the northwestern part of the Arabian plate from 100 km to 300 km depth (Figure 4). These low velocity anomalies spread out at the lower mantle, suggesting that the hotspot may be the surface manifestation of a broad mantle upwelling connected to the African Super Plume in the lower mantle beneath southern Africa (Benoit et al., 2006).

High velocity anomaly is visible down to ~100 km depth beneath Azerbaijan. This result is consistent with our Pn tomography and indicates that the oceanic lithosphere beneath the Southern Caspian extends westward beneath Azerbaijan.

The subduction along the Zagros suture zone is well imaged (Figure 4; section A in Figure 5). Pronounced high velocity anomalies with a southward dip angle are detected in the upper mantle (above 410 km discontinuity) and earthquakes are confined above 150 km depth in the fast structures. The south-dipping slabs in the upper mantle (section A in Figure 5) may a result that Arabian plate has overridden itself during the post-collision between Arabian and Eurasian plates, like what we have observed at the Indian and Eurasian collision (Li et al., 2006). Slabs in the upper mantle seem to disconnect with the fast structures in the lower mantle, which can be interpreted at Mesozoic Neo-Tethys plate (section A in Figure 5). This is evidence for the brake-off of the slabs during the continental collision (Molinaro et al., 2005).

No slabs are observed along the Makran suture zone at the shallow depth (Figure 4; section B in Figure 5). Sparse earthquakes are confined in the crust beneath the Makran suture (section B in Figure 5). Slabs are detected from 410 km discontinuity down to the lower mantle, which are a part of the subducted Neo-Tethys oceanic slabs. These observations suggest that after the cessation of the Mesozoic Neo-Tethys subduction there is no significant collision between Arabian and Eurasian plates along the Makran suture.

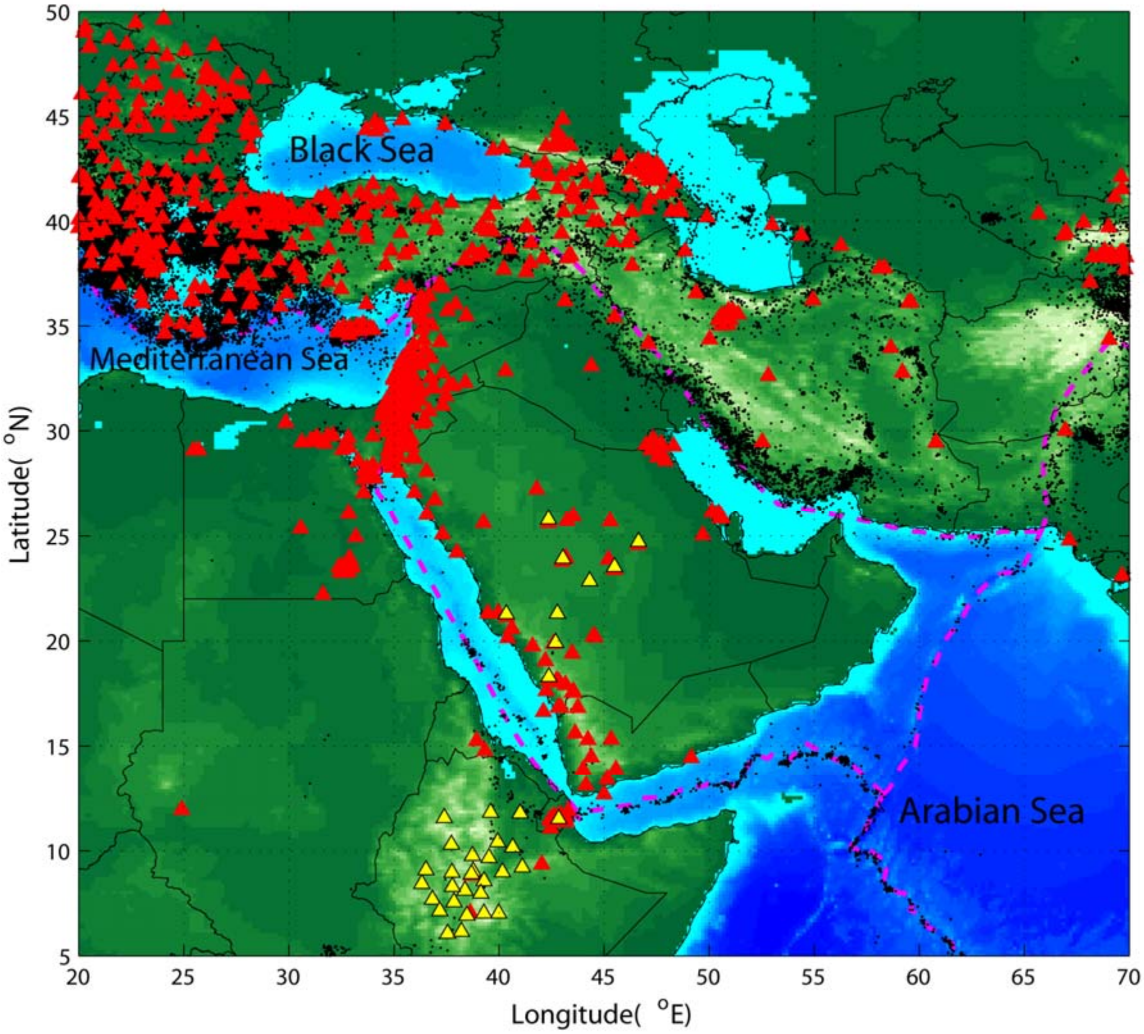

Figure 3. The distribution of seismic stations and earthquakes (black dots) in the Middle East region. The earthquake data are from the updated EHB catalog (Engdahl et al., 1998). The red triangles indicate the stations that are included in the ISC catalog. The yellow triangles are the stations from a temporay seismic network in Africa (Benoit et al., 2006) and the Saudi Arabian stations.

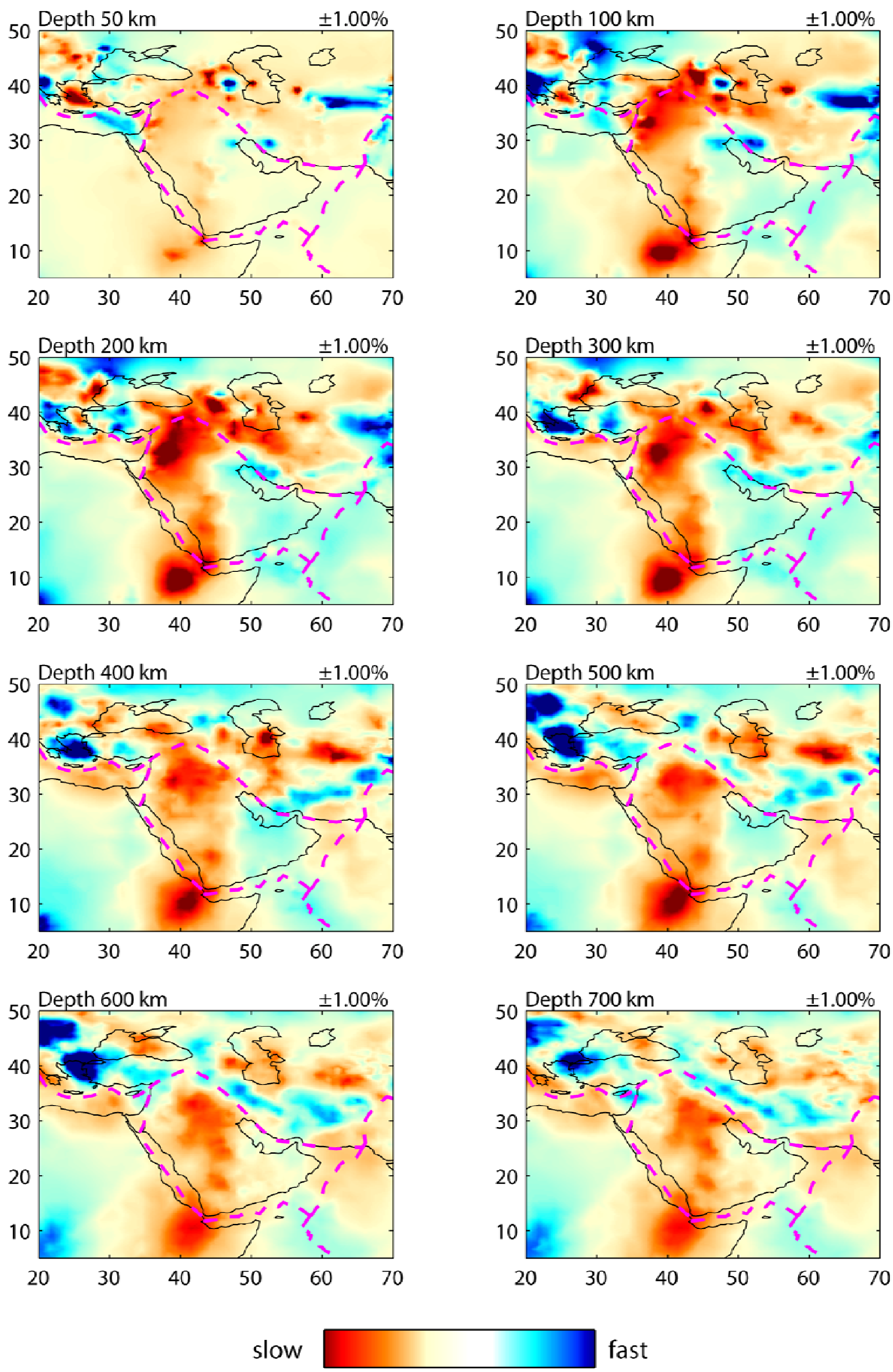

Figure 4. P-wave anomalies beneath the Middle East at different depths as indicated on the left upper corner in each subplot. The blue and red represent high and low velocity anomalies respectively. The dashed purple lines are the plate boundaries, and the black lines are the coastlines.

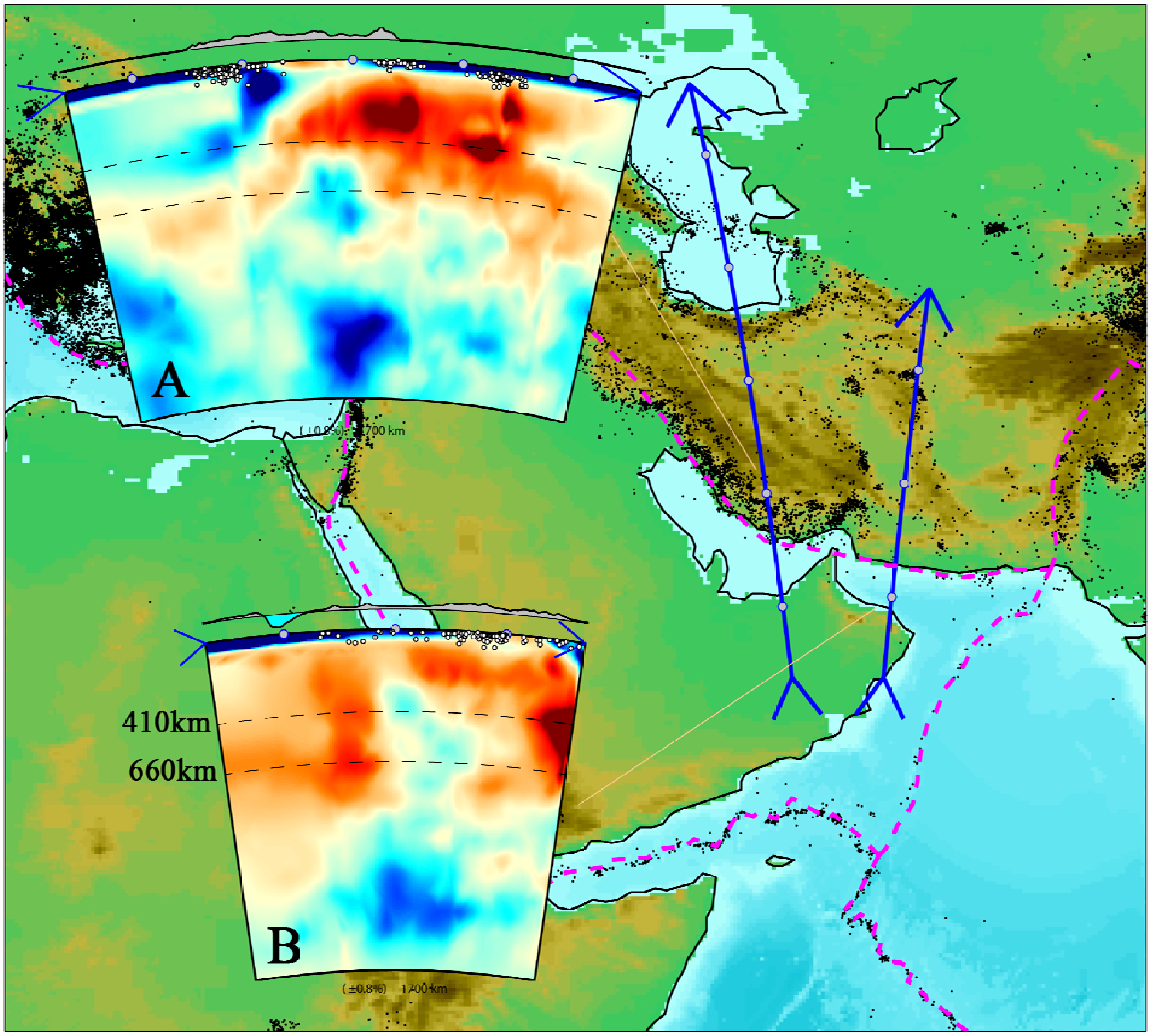

Figure 5. Vertical cross-sections showing the P-wave velocity anomalies down to 1700 km depth. As in Figure 4, the color scale indicates 0.8% deviations with respect to the 1-D *ak135* model. The dashed lines indicate the 410 km and 660 km mantle discontinuities. The topography is shown on the top of the cross-section.

CONCLUSIONS AND RECOMMENDATIONS

The preliminary tomographic results obtained in the Middle East region show a complex crust and upper mantle structure. Pronounced low velocity anomalies have been delineated beneath Ethiopia and northwestern part of the Arabian plate. These anomalies appear to emanate from the African Super Plume in the lower mantle beneath southern Africa. A high velocity anomaly is visible down to ~100 km depth beneath Azerbaijan which is consistent with our Pn tomography results that indicate the presence of oceanic lithosphere beneath Southern Caspian Sea and Azerbaijan. Pronounced high velocity anomalies with southward dip angles are detected beneath the Zagros and the Makran Suture Zones indicating that the Arabian plate has overridden itself during the post-collision between the Arabian and the Eurasian Plates. The tomographic models will be refined by applying crustal corrections and with the inclusion of local network data from Oman, Kuwait, Saudi Arabia, Turkey and others.

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