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Topography of Mantle Transition Zone beneath the Middle East by Receiver function stacking

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Abstract
We use a dense seismic data set to provide an image of the mantle transition zone (MTZ) beneath the Middle East. We applied Common Conversion Point (CCP) stacking of P-wave receiver functions to study the topography on the 410-km and 660-km discontinuities defining the upper and lower boundaries of the MTZ. Our results show significant topography on the MTZ discontinuities and corresponding variations in the MTZ thickness. The MTZ topography is broadly consistent with seismic tomography implying the presence of both cold thermal anomalies imparted by detached Tethyan slabs and lithospheric segments and hot thermal anomalies induced by upwelling of lower mantle material. The MTZ topography in the northern Middle East is dominated by the presence of segments of cold material that are intermittently separated by regions of 'hot' to 'normal' MTZ. Our results suggest that the Tethyan slab in the Middle East is segmented. The southern Middle East is dominated by the mantle upwelling beneath the Afar depression. Our results imply that the lower mantle material enters the MTZ beneath the Afar depression and then spreads out northeastward beneath the western Arabia flowing within the MTZ and in the upper mantle.

Key words:: Tethyan Slab, Mantle Transition Zone, Receiver Function

Introduction
The mantle transition zone (MTZ) is defined as the region between the Earth's upper and lower mantle and is assumed to play a central role in the mantle dynamics (e.g. Yuen et al., 1994). The top and bottom boundaries of the MTZ are marked by two global seismic discontinuities laying at depths around 410 and 660 km in spherical velocity models (Helffrich, 2000). We hereafter refer to these discontinuities as the '410' and '660'. Pressure-induced isochemical mineral phase transformations are commonly assumed to be the most plausible explanation for the '410' and '660' discontinuities (Ringwood, 1970; Helffrich, 2000). The exact depth at which the phase transformation occurs at each discontinuity depends on the pressure-temperature conditions at the relevant boundary. The lateral variation in depth to the '410' and '660' discontinuities and the MTZ thickness is typically taken as a signature of the lateral variation in thermal structure of the MTZ. The mineral phase changes across the MTZ discontinuities yield pronounced seismic contrast, which results in partitioning of energy of seismic waves crossing the boundaries of the MTZ. The depth and sharpness of the MTZ discontinuities can therefore be imaged by observing seismic waves travelling across them. The P-to-S (Ps) converted waves generated at the '410' and '660' discontinuities are among the most common seismic observations to constrain the depth of these discontinuities (e.g. Schmandt, 2012).
The Middle East is an important region that incorporates all known types of plate boundaries (Figure 1a) which accommodates the relative motions within the Africa-Arabia-Eurasia system (e.g. Le Pichon and Kreemer 2010). Geochemical data, seismic tomography imaging and numerical modelling (e.g. van de Zedde and Wortel, 2001; Hafkenscheid et al., 2006; Agard et al., 2011; Bijwaard et al., 1998; Biryol et al., 2011) suggest a diachronous nature of the events that have occurred along the southern edge of the Eurasian plate, including the initiation of subduction of the Tethyan slab, the onset of continental collision and slab detachment. The current depth extent and position of the detached slab and segments of lithosphere have important implications for the relationship between the mantle dynamics and active tectonics. The detached slabs and continental materials can be distributed at different depths depending upon the timing of detachment and sinking rate of the detached segments in the uppermost mantle. Results of numerical modelling (e.g. Goes et al., 2017) suggest that cold subducting materials can reside in the MTZ for a few tens of millions of years before they destabilize and flush into the lower mantle. Seismic tomography revealed the presence of positive velocity anomalies at different depths beneath the northern Middle East (Bijwaard et al., 1998; Biryol et al., 2011; Simmons et al., 2015). Hafkenscheid et al., (2006) interpreted the positive anomalies at depths of the MTZ as segments of the stagnant

slabs, while the positive anomalies in lower mantle are considered as segments of the old subducted Tethyan slab penetrated into the lower mantle.

In this.study, for the first time, we investigate the topography of the mantle transition zone across the most of the Middle East using CCP stacking of a large dataset of PRFs. The study area encompasses the Iranian Plateau, the Zagros mountains, the Arabian Shield and Platform, the Anatolian Plateau, the Caucasus and the eastern end of the Aegean Sea

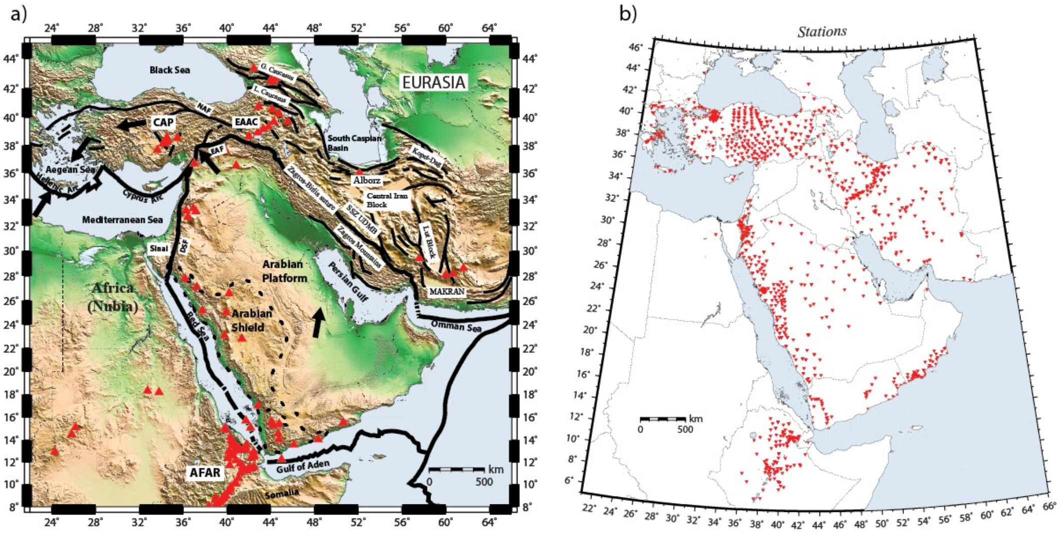

Figure 1. a) A topographic map superimposed with the major tectonic features of the Middle East. The major faults are depicted with black solid lines. The red triangles present the location of quaternary volcanism. The main continental boundary fault zones and tectonic units are abbreviated on the map and described here: CAP: Central Anatolian Plateau, EAAC: East Anatolian Accretionary Complex, NAF: Northern Anatolian Fault, EAF: Eastern Anatolian Fault, DSF: Dead Sea Fault, SSZ: Sanandaj-Sirjan Zone, UDMA: Urumieh-Dokhtar magmatic arc. b) Locations of 1114 broadband seismic stations used for receiver function imaging.

Data, Method and Results

We collected and analyzed P-waveforms from teleseismic events with magnitudes greater than 5.6 at epicentral distances between 34° and 95° that have been recorded during the past two decades by a dense network of 1114 broad-band stations across the Middle East (Figure 1b). We computed receiver functions to image '410' and '660' discontinuity topography beneath the network of stations. After the inspection of receiver functions, we end up with a total of 39600 usable receiver functions. We then follow the approach similar to Cottaar and Deuss (2016) to create Common Conversion Point (CCP) image of the mantle from the distribution of the PRFs amplitudes in a 3-D volume.

Vertical cross-sections were extracted from the 3-D CCP volume to follow the track of the mantle discontinuities across different tectonic units. In Figure 2 we show vertical cross-sections along latitudes and longitudes.

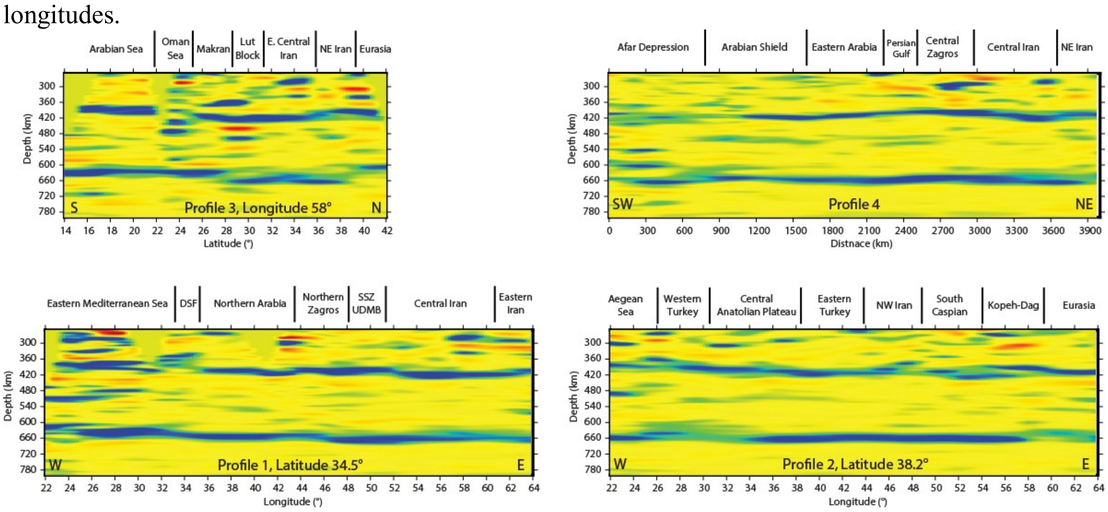

Figure 2. Examples of vertical cross-sections of the stacked CCP amplitudes. The locations of different profiles are shown in Figure 3c

The uniformly sampled 3-D CCP volume also allows us to extract maps of the depth to the ‘410’ and ‘660’ discontinuities. In Figure 3 we show maps of the ‘410’ and ‘660’ topography as well as a map of the MTZ thickness.

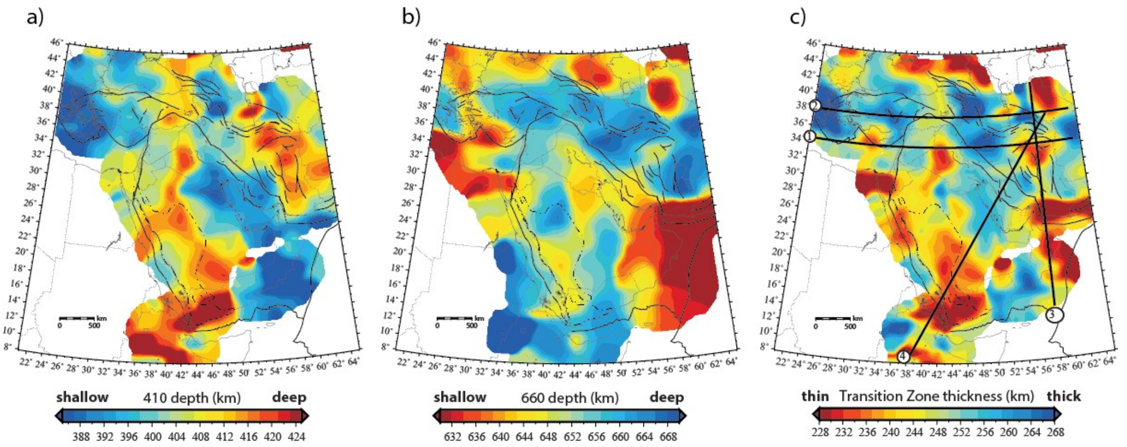

Figure 3. Maps showing the topography of the 410-km and 660-km discontinuities (a and b) and thickness of the mantle transition zone (c). Thin dashed lines delineate political boundaries. Thick solid lines show the main faults and tectonic boundaries.

Discussion and Conclusion

The CCP stacking of the PRFs provided images that exhibit significant topography of the MTZ discontinuities beneath the Middle East. This topography is consistent with large lateral temperature variations in the mantle transition zone. In summary, we highlight the following main conclusions from the seismic image acquired from the CCP stacking of receiver functions.

Regions of thickened MTZ are observed beneath the Middle East, which are separated by regions of thin or normal MTZ. This observation implies that the Tethyan slab subducted beneath the Arabia/Africa-Eurasia collision zone is strongly segmented. The segmentation of the subducted slab can have occurred during or following break-off from the continental lithosphere. Two main regions of the absence of slab-related bodies in the MTZ are observed beneath the western and eastern Anatolia, where the upper mantle is also devoid of large slab bodies. These regions can represent an important gap in the Tethyan subduction. We classify these regions as the western slab window between the Aegean and Cyprean slabs (currently beneath the Isparta Angle, the Cyprean-Hellenic intersection) and the eastern window between the paleo-Cyprean and Neo-Tethyan slabs (currently beneath the eastern Anatolian plateau). A region of thinned MTZ is observed beneath Central Iran that is mainly due to a downward deflection of the 410-km discontinuity. This implies that local flow of hot material can exist in the upper mantle beneath this region.

Our results suggest that the hot lower mantle material is upwelling beneath the Afar depression and then spreads northward as a channeled flow in the upper mantle beneath the Arabian Shield and Platform. This channeled flow extends further north beneath Iraq to reach the eastern Turkey. This wide-spread channeled flow has important implication for the geodynamic evolution and plate tectonics of the Arabia-Eurasia collision system.

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