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Signature of slab fragmentation beneath Anatolia from full-waveform tomography

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ABSTRACT

When oceanic basins close after a long period of convergence and subduction, continental collision and mountain building is a common consequence. Slab segmentation is expected to have been relatively common just prior to closure of other oceans in the geological past, and may explain some of the complexity that geologists have documented in the Tibetan plateau also. We focus on the eastern Mediterranean basin, which is the last remainder of a once hemispherical neo-Tethys ocean that has nearly disappeared due to convergence of the India and Africa/Arabia plates with the Eurasia plate. We present new results of full-waveform tomography that allow us to image both the crust and upper mantle in great detail. We show that a major discontinuity exists between western Anatolia lithosphere and the region to the east of it. Also, the correlation of geological features and the crustal velocities is substantially stronger in the west than in the east. We interpret these observations as the imprint in the overriding plate of fragmentation of the neo-Tethys slab below it. This north-dipping slab may have fragmented following the Eocene (about 35 million years ago) arrival of a continental promontory (Central Anatolian Core Complex) at the subduction contact. From the Eocene through the Miocene, slab roll-back ensued in the Aegean and west Anatolia, while the Cyprus–Bitlis slab subducted horizontally beneath central and east Anatolia. Following collision of Arabia (about 16 million years ago), the Cyprus–Bitlis slab steepened, exposing the crust of central and east Anatolia to high temperature, and resulting in the velocity structure that we image today. Slab fragmentation thus was a major driver of the evolution of the overriding plate as collision unfolded.

1. Introduction

The mechanical interplay between subducting and overriding lithosphere changes considerably upon entrance of continental crust into a subduction zone. Crustal fragments on the subducting plate may delaminate and be transferred to the overriding plate. Alternatively, the slab may break off altogether. As continental crust commonly arrives asynchronously at the trench in a closing oceanic basin, it is likely that a once-continuous slab becomes laterally fragmented. However, closure of the Tethyan Ocean, the largest recently disappeared basin, can be traced in tomographic images of the Earth's mantle but the evidence for lateral slab fragmentation has been limited: the Tethys slab is probably fragmented beneath the Tibetan plateau (e.g., Liang et al., 2012) and Anatolia (De Boorder et al., 1998). What remains unclear in these regions is how slab fragmentation affected the evolution of the overriding plate. We exploit new results of full-waveform tomography for the Aegean–Anatolian region to address this question (Fig. 1). A main improvement of this new technique over classical methods is that it gives an unprecedented view of both the crust and upper mantle, allowing us to make the connection between different levels. We first try to connect the imaged structures to known geological features in the uppermost crust and upper mantle. Various new features arise from this. Many of these features can be explained by a regional plate tectonic evolution involving slab fragmentation that left a footprint in the overriding plate.

2. Tomographic method

While largely inaccessible to direct observation, the Earth's interior can be probed indirectly using seismic waves excited by earthquakes. As seismic waves encounter structural heterogeneities, their propagation velocity changes, scattering and reflec-

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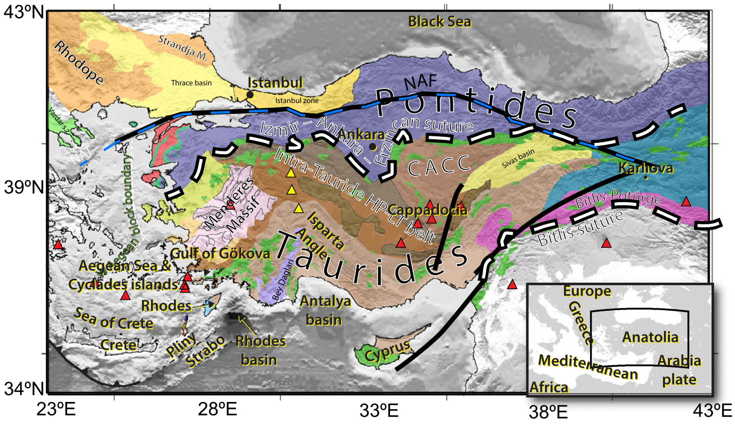

Fig. 1. Shaded relief map showing our study region, geographic names, and main tectonic units. We use "Anatolia" as a synonym for Asian Turkey. See Fig. 3 caption for details (colors in the web version of this article).

tions occur, and compressional and shear waves convert into each other. The combined effect of multiple heterogeneities produces a highly complex wave field recorded in the form of seismograms. Seismic tomography exploits the information contained in these wave field complexities to infer the structural heterogeneities from which they originated.

Advances in high-performance computing and numerical wave propagation allow us to exploit complete seismograms, including all the complexities induced by 3D-heterogeneity, using a variant of tomography often termed 'full-waveform inversion' (FWI) (e.g., Chen et al., 2007; Fichtner et al., 2009). FWI naturally combines body- and surface-wave tomography, and it accounts for the nonlinearity of the tomographic inverse problem through iterative improvements of an Earth model. New multiscale variants of FWI (Fichtner et al., 2013a) are able to jointly invert for the details of crustal and upper-mantle structure, yielding constraints in the depth interval from 10–100 km where crust–mantle interactions shape the nature of plate tectonics.

Here we offer a tectonic interpretation of a recent multi-scale FWI applied to Europe and western Asia, with a special focus on the Anatolian region where particularly dense coverage is available (Fichtner et al., 2013a). Our data set consists of 16,837 three-component seismograms, corresponding to 113 M5.0-6.8 earthquakes that occurred between 2005 and 2011 along the tectonically active margins of the Eurasian plate. Within the Anatolian region, complete seismograms are modeled and inverted in the period range from 8–200 s, ensuring that crustal and mantle structures are jointly constrained.

In the following sections, we present our tomographic model in terms of the isotropic shear velocity V_s, computed from the (Voigt) average of the elastic tensor over all angles. In terms of the SH-velocity V_{sh} and the SV-velocity V_{sv}, the isotropic velocity can be computed as $V_s^2 = 2/3V_{sh}^2 + 1/3V_{sv}^2$ (Babuska and Cara, 1991). The reference frequency in the visco-elastic model is 1 Hz. The attenuation model is QL6 (Durek and Ekström, 1996). Quantitative resolution analyses (Fichtner et al., 2013b) indicate that structures with a lateral extent of 25 km or more are resolved from the surface to around 50 km depth. Below 50 km depth, lateral resolution length increases gradually, but structures wider than 50 km are generally reliably imaged. Based on the comparison with receiver function studies, vertical resolution within the upper 50 km is estimated to be around 10 km.

To place our model into a wider context, we provide comparisons to the global lithospheric model LITHO1.0 (Pasyanos et al., 2014). We estimate that uncertainties due to anisotropy and attenuation are on the order of 0.1–0.2 km/s. These errors are, however, too small to affect our main results.

3. Results

Fig. 2 shows the tomographic result at selected depths. By using grey tone contours we attempt to maximize an objective evaluation with a level of detail that agrees with the tomographic resolution (Appendix A in Supplementary material).

3.1. *Isotropic S-wave speeds in the upper mantle*

We start our discussion of the results at 100 km depth because this allows us to connect our results to earlier studies. Fig. 2h displays V_s at 100 km depth. Large-scale features agree with the results from previous combined body and surface wave tomographies (e.g., Legendre et al., 2012). Much like Zhu et al. (2015), we resolve considerably more regional detail. The Aegean slab in the southwest is visible as a relatively high velocity anomaly that was identified also in previous studies (Bijwaard et al., 1998; Piromallo and Morelli, 2003) and that is coincident with the regional Wadati–Benioff zone. The sequence of horizontal slices in Movie 1 (Auxiliary Materials) demonstrates the northeastward dip of the slab in the depth range from 100 to 300 km. It also shows that the slab edge roughly aligns with the Pliny–Strabo "trenches" at the surface, supporting the interpretation of this plate boundary as a STEP fault (Govers and Wortel, 2005; Özbakır et al., 2013).

A second, separate, high velocity anomaly is visible in the depth range 25–150 km near the Turkish southwest coast. At 25 km it is located below the Gulf of Gökova, and below the Rhodes Basin in the depth range 100–150 km. The anomaly coincides with a Wadati–Benioff zone (Gessner et al., 2013). The Rhodes Basin is a very young (post-Miocene) and unusually deep basin. Özbakır et al. (2013) propose that Africa–Aegean relative motion is partly accommodated by NW directed thrusting here. This high velocity anomaly may thus correspond to a gravitational instability that developed recently along the STEP fault as was predicted by Baes et al. (2011) based on geodynamic model experiments.

In the depth range 60–160 km (Movie 1), a relatively fast anomaly is located beneath the Antalya basin and Isparta Angle. It corresponds roughly with a NE dipping Wadati–Benioff zone. Similar anomalies have been imaged in previous tomographic studies (Biryol et al., 2011). Biryol et al. (2011) interpret this anomaly as the west Cyprus slab. Their eastern segment connects all the way up to the trench to the south of Cyprus, is not expressed in the uppermost 150 km of our results. Below 270 km depth, S-wave velocities higher than 4.65 km/s are interpreted as signatures of a deeper slab that is also imaged by Biryol et al. (2011), and that they interpret as the Cyprus slab. Biryol et al. (2011) argue that the shallow Cyprus slab became fragmented recently. Relative