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Crustal-scale shear zones and heterogeneous structure beneath the North Anatolian Fault Zone, Turkey, revealed by a high-density seismometer array

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ABSTRACT

Continental scale deformation is often localised along strike-slip faults constituting considerable seismic hazard in many locations. Nonetheless, the depth extent and precise geometry of such faults, key factors in how strain is accumulated in the earthquake cycle and the assessment of seismic hazard, are poorly constrained in the mid to lower crust. Using a dense broadband network of 71 seismic stations with a nominal station spacing of 7 km in the vicinity of the 1999 Izmit earthquake we map previously unknown small-scale structure in the crust and upper mantle along this part of the North Anatolian Fault Zone (NAFZ). We show that lithological and structural variations exist in the upper, mid and lower crust on length scales of less than 10 km and less than 20 km in the upper mantle. The surface expression of the NAFZ in this region comprises two major branches; both are shown to continue at depth with differences in dip, depth extent and (possibly) width. We interpret a <10 km wide northern branch that passes downward into a shear zone that traverses the entire crust and penetrates the upper mantle to a depth of at least 50 km. The dip of this structure appears to decrease west–east from ∼90° to ∼65° to the north over a distance of 30 to 40 km. Deformation along the southern branch may be accommodated over a wider (>10 km) zone in the crust with a similar variation of dip but there is no clear evidence that this shear zone penetrates the Moho. Layers of anomalously low velocity in the mid crust (20–25 km depth) and high velocity in the lower crust (extending from depths of 28–30 km to the Moho) are best developed in the Armutlu–Almacik block between the two shear zones. A mafic lower crust, possibly resulting from ophiolitic obduction or magmatic intrusion, can best explain the coherent lower crustal structure of this block. Our images show that strain has developed in the lower crust beneath both northern and southern strands of the North Anatolian Fault. Our new high resolution images provide new insights into the structure and evolution of the NAFZ and show that a small and dense passive seismic network is able to image previously undetectable crust and upper mantle heterogeneity on lateral length scales of less than 10 km.

1. Introduction

Major continental strike-slip faults, such as the North Anatolian fault Zone (NAFZ) in Turkey or the San Andreas Fault in the USA, are key elements in our understanding of plate tectonics. Such faults are clearly defined at the surface but considerable uncertainty surrounds their structure in the mid to lower crust and upper mantle, and specifically how deformation is focused in shear zones that are presumed to extend beneath seismically active fault planes (e.g., Handy et al., 2007; Platt and Behr, 2011). An understanding of such fault systems (e.g., Pollitz et al., 2001) requires characterisation of the structure and physical properties of the crust and upper mantle to constrain the rheological parameters that determine how stress is redistributed during the earthquake cycle (e.g., Hearn et al., 2009). Localised zones of relatively high or

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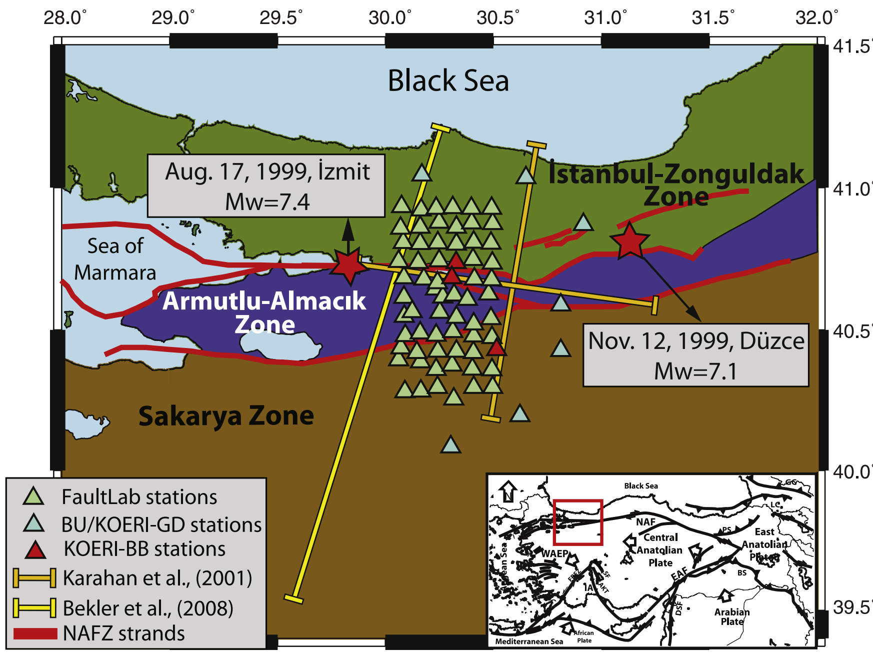

Fig. 1. Locations of seismometer stations for the DANA array (green triangles) and previous seismic refraction experiments (as indicated in the legend), segments of the North Anatolian Fault zone (red) and major tectonic terranes (IZ: Istanbul–Zonguldak zone; AA: Almatlu–Almacik zone; and SZ: Sakarya zone). The inset map shows the regional tectonic setting. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

low viscosity can have an important impact on this cycle (Yamasaki et al., 2014).

Modelling of geodetic deformation has provided some constraints on the physical variation of creep parameters (e.g., Bürgmann and Dresen, 2008; Hearn et al., 2009; Kenner and Segall, 2003; Wright et al., 2013), however, seismic imaging is the only method that can provide direct insights into the structure of the crust and the variation of elastic properties within it, albeit at length scales that are limited by the seismic wavelength. For instance, variations in Moho topography have been used to argue for both diffuse deformation within the crust (Wilson et al., 2004) and focused fault structure in the upper mantle (e.g., Wittlinger et al., 2004). Such arguments require careful control on the velocity variation within the entire crustal section (Schulte-Pelkum and Ben-Zion, 2012). While geodetic measurements reveal short-term strains caused by the current earthquake cycle, seismological imaging can reveal details of the geological structures created by the cumulative effect of many earthquake cycles.

In this study, we use teleseismic receiver functions (RFs) to image crust and upper mantle structure across part of the NAFZ using seismological data recorded by a rectangular array with a station interval of ∼7 km that was deployed for 18 months.

The NAFZ is a 1500 km-long right-lateral transform fault that separates a westward moving Anatolia from a relatively stationary Eurasian plate (Fig. 1). Subduction along the Hellenic trench and collision of the Arabian and Eurasian plates results in a general westward movement of Anatolia at rates of 20–30 mm/yr relative to Eurasia (e.g. Barka, 1996; McClusky et al., 2000; Reilinger et al., 2006), with strain focused on the NAFZ. Numerous major earthquakes have occurred during the last century (e.g. Barka, 1999); most recently in 1999 with epicentres at Izmit and Düzce (e.g. Barka et al., 2002; Fig. 1). We installed a dense network (DANA – Dense Array for Northern Anatolia) of temporary broadband seismic stations across the NAFZ in the region of the 1999 Izmit rupture in order to create exceptionally well-resolved images of NAFZ crustal structure.

2. Geological overview

The western NAFZ bisects a complex assembly of heterogeneous zones of differing crustal affinity, namely the continental fragments of the Istanbul–Zonguldak Zone (IZ) and the Sakarya Zone (SZ) (Fig. 1) that form part of what is commonly referred to as the Pontides (e.g. Okay and Tüysüz, 1999). The IZ has a late Precambrian crystalline basement (Chen et al., 2002; Yiğitbaş et al., 2004; Ustaömer et al., 2005) unconformably overlain by a continuous Ordovician–Carboniferous sedimentary succession (Görür et al., 1997; Dean et al., 2000). Carboniferous convergent deformation was followed by a Triassic marine transgression as the IZ formed part of the Laurasia passive continental margin (Okay, 2008) before Late Cretaceous back-arc spreading created the western Black Sea basin by rifting the present-day IZ southwards (Okay et al., 1994). The Intra-Pontide Ocean gradually closed by north-dipping subduction during Late Cretaceous–Early Eocene times (Okay and Tüysüz, 1999), forming the 400 km long east–west trending Intra-Pontide suture, which is now reactivated as the present-day trace of the NAFZ (e.g. Okay and Tüysüz, 1999; Sengor and Yilmaz, 1981; Okay, 2008). To the south, the basement of the SZ continental fragment consists of widespread subduction-accretion complexes of Triassic age (Şengör and Yilmaz, 1981; Okay and Tüysüz, 1999). A Jurassic–Eocene sequence of clastic sedimentary, carbonate and volcanic rocks unconformably rests upon the high-grade metamorphic basement (Okay et al., 1996; Pickett and Robinson, 1996; Okay and Tüysüz, 1999).

West of about 30.65°E, the NAFZ splits into northern (NNAF) and southern (SNAF) strands with ∼16 and ∼9 mm/yr slip, respectively (e.g. Stein et al., 1997). The Armutlu–Almacik crustal block (AA) lies between the NAFZ strands and is comprised of SZ pre-Jurassic basement (typically Triassic subduction/accretion units), SZ Jurassic–Eocene sedimentary sequences, a Cretaceous–Palaeocene accretionary complex and metamorphic rocks of unknown age and origin (possibly IZ; Sengor and Yilmaz, 1981; Okay and Tüysüz, 1999; Okay, 2008). The Sakarya River, offset in a right-lateral sense by the NAFZ, has incised the SZ and AA and has played a prominent role in erosion and deposition of sub-aerial