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Seismic anisotropy in central north Anatolian Fault Zone and its implications on crustal deformation

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ABSTRACT

We investigate the crustal seismic structure and anisotropy around the central portion of the North Anatolian Fault Zone, a major plate boundary, using receiver function analysis. The characterization of crustal seismic anisotropy plays a key role in our understanding of present and past deformation processes at plate boundaries. The development of seismic anisotropy in the crust arises from the response of the rocks to complicated deformation regimes induced by plate interaction. Through the analysis of azimuthally-varying signals of teleseismic receiver functions, we map the anisotropic properties of the crust as a function of depth, by employing the harmonic decomposition technique. Although the Moho is located at a depth of about 40 km, with no major offset across the area, our results show a clear asymmetric distribution of crustal properties between the northern and southern blocks, divided by the North Anatolian Fault Zone. Heterogeneous and strongly anisotropic crust is present in the southern block, where complex intra-crustal signals are the results of strong deformation. In the north, a simpler and weakly anisotropic crust is typically observed. The strongest anisotropic signal is located in the first 15 km of the crust and is widespread in the southern block. Stations located on top of the main active faults in the area indicate the highest amplitudes, together with fault-parallel strikes of the fast plane of anisotropy. We interpret the origin of this signal as due to structure-induced anisotropy, and roughly determine its depth extent up to 15–20 km for these stations. Away from the faults, we suggest the contribution of previously documented uplifted basement blocks to explain the observed anisotropy at upper and middle crustal depths. Finally, we interpret coherent NE-SW orientations below the Moho as a result of frozen-in anisotropy in the upper mantle, as suggested by previous studies.

1. Introduction

As an intercontinental dextral strike-slip fault with significant strain localization, the 1600-km-long North Anatolian Fault Zone (NAFZ) represents a major plate boundary between the Eurasian plate in the north and the Anatolian plate in the south. Although collision between the Arabian and Eurasian plates (in the east) was initially thought to be the main driving force for the westward motion of the Anatolian plate (e.g. Dewey and Şengör, 1979), recent advances in high-resolution GPS data have revealed a clear role of the southwest-trending rollback of the Hellenic subduction zone in the south Aegean Sea for the rapid deformation of the Aegean-Anatolian region (e.g. McClusky et al., 2000; Reilinger et al., 2006). In this respect, the deformation history of the rocks at various depth ranges remains enigmatic within the crust and mantle of this complex tectonic setting. A detailed sketch of the Anatolian tectonic setting can be found in Fig. 1.

The determination of the directional dependence of seismic wave speed, also known as seismic anisotropy, plays a fundamental role in the elucidation of the complicated deformation regimes induced by plate interaction along such plate margin.

Crustal seismic anisotropy is generally attributed to the alignment of joints or microcracks, to lattice preferred orientation (LPO) of anisotropic minerals, or to highly foliated metamorphic rocks (e.g., Sherrington et al. 2004). In the upper crust, possible sources of seismic anisotropy can be either stress-induced or structure-induced (Boness and Zoback, 2006). Stress-induced anisotropy can be generated either by the extensive dilatancy of fluid-filled microcracks (Crampin, 1987) or by the preferential closure of fractures by the in situ stress field (Boness and Zoback, 2006). In the latter case, the orientation of fast waves of vertically propagating shear waves aligns parallel to the maximum horizontal stress (SH_{max}). When structure-induced mechanisms are dominant, seismic anisotropy may be associated to the

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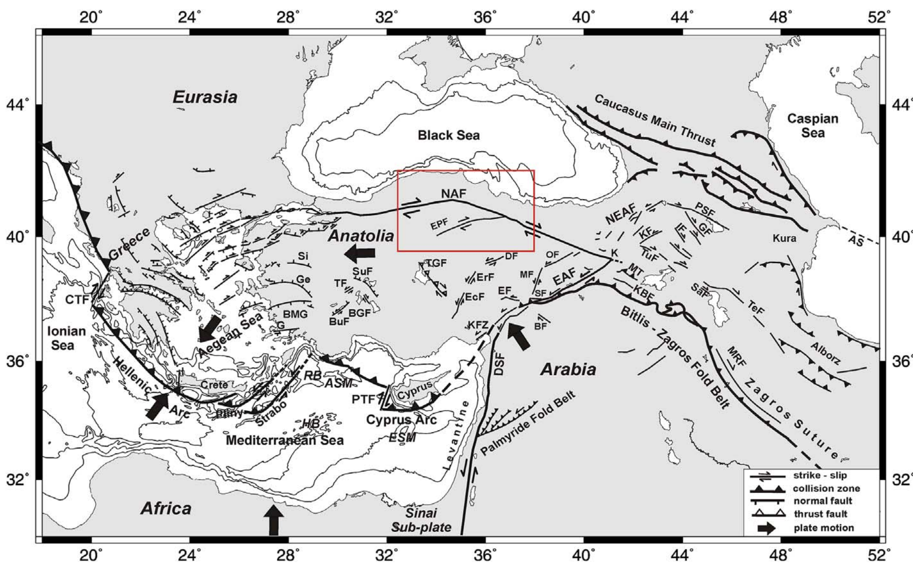

Fig. 1. A sketch map of active tectonic boundaries in the study area and surroundings. For the source of compiled data, please see Taymaz et al. (1990, 1991, 2004, 2007a,b), Yolsal-Çevikbilen and Taymaz (2012) and references therein. Abbreviations: AS: Apşeron Sill, ASM: Anaximander Sea Mountains, BF: Bozova Fault, BGF: Beyşehir Gölü Fault, BMG: Büyük Menderes Graben, BuF: Burdur Fault, CTF: Cephalonia Transform Fault, DSF: Dead Sea Transform Fault, DF: Deliler Fault, EAF: East Anatolian Fault, EcF: Ecemiş Fault, EF: Elbistan Fault, EPF: Ezine Pazarı Fault, ErF: Erciyes Fault, ESM: Eratosthenes Sea Mountains, G: Gökova, Ge: Gediz Graben, GF: Garni Fault, HB: Herodotus Basin, IF: Iğdır Fault, KBF: Kavakbaşı Fault, KF: Kağızman Fault, KFZ: Karataş-Osmaniye Fault Zone, MF: Malatya Fault, MRF: Main Recent Fault, MT: Muş Thrust, NAF: North Anatolian Fault, NEAF: North East Anatolian Fault, OF: Ovacık Fault, PSF: Pampak-Savan Fault, PTF: Paphos Transform Fault, RB: Rhodes Basin, SaF: Salmas Fault, Si: Simav Graben, SuF: Sultandağ Fault, TeF: Tebriz Fault, TF: Tatarlı Fault, TGF: Tuz Gölü Fault. Black arrows exhibit relative plate motions with respect to Eurasia (McClusky et al., 2003; Reilinger et al., 2006).

alignment of macroscopic features due to shear-induced deformation near active faults (Zhang and Schwartz, 1994; Zinke and Zoback, 2000; Tadokoro et al., 2002), sedimentary bedding planes (Kern and Wenk, 1990), and preferred mineral alignments (Sayers, 1994).

Local shear waves splitting analyses, performed over detected micro-seismic earthquakes along various segments of the NAFZ, have indicated a spatial correlation between the fast polarization directions (FPDs) and station distance from the fault (e.g. Tadokoro et al., 2002; Peng and Ben-Zion, 2004; Hurd and Bohnhoff, 2012; Eken et al., 2013). Lateral variations of the FPDs inferred from local shear waves implied the presence of both stress- and structure induced mechanisms causing seismic anisotropy in the upper 8–10 km of the crust. In addition, these local splitting studies have highlighted the structural control of the complex geologic and tectonic environment along the western segments of the NAFZ on the spatial variation of FPDs.

For the deeper part of the crust, i.e. > 20–25 km, several studies have shown that aligned minerals are the most likely cause of anisotropy (Sherrington et al., 2004, and references therein) and that hexagonal anisotropy with a unique slow symmetry axis can explain seventy percent of the observations (Brownlee et al., 2017). In particular, the alignment of micas along the plane of foliation is often the primary cause of bulk anisotropy in this depth range (Sherrington et al., 2004; Audet 2015).

Over the last decade, receiver function (RF) data have been widely used for the characterization of seismic anisotropy. RFs are time series that represent the impulse response of the near receiver structure in terms of P-to-S conversions contained in the P-coda of teleseismic events (Vinnik, 1977; Langston, 1979). After deconvolution of the vertical trace from the horizontal ones, P-to-SV and P-to-SH converted phases are isolated on the Radial (R) and Transverse (T) components of the RFs, respectively. In particular, P-to-SH conversions are generated from the rotation of the energy out of the source-receiver plane induced by anisotropy and/or dipping velocity contrasts at depth (Sherrington et al., 2004; Maupin and Park, 2007; Piana Agostinetti and Chiarabba, 2008; Schulte-Pelkum and Mahan, 2014a). The analysis of the azimuthally varying characteristic of the P-to-S conversions (amplitudes and delay times) can provide robust information about the location of anisotropy at depth (e.g. Rümpker et al., 2014; Licciardi and Piana Agostinetti, 2016). RFs provide complementary depth-dependent information about seismic anisotropy that is difficult to obtain with other common seismological data (e.g. shear wave splitting and surface waves dispersion), since RFs are strongly sensitive to the depth of contrasts in anisotropic properties.

More in detail, the RF harmonic decomposition technique (Bianchi et al., 2010; Park and Levin, 2016) has proven to be effective to quantify seismic anisotropy in various geodynamical settings over the last decade and at different scales of investigation (Piana Agostinetti et al., 2011; Bianchi et al., 2015; Olugboji and Park (2016); Vinnik et al., 2016) including the shallow crust (Licciardi and Piana Agostinetti, 2017; Piana Agostinetti et al., 2017). In particular, RF harmonics have been used to map the depth-dependent distribution of seismic anisotropy in areas of intense crustal deformation, e.g., around the San Andreas Fault (SAF) (Audet 2015), the Tibetan Plateau (Liu et al., 2015), the Cyclades (Cossette et al., 2016), the Canadian Cordillera (Tarayoun et al., 2017) and the Appennines (Bianchi et al., 2010; 2016).

In this work, we analyse RF harmonics using data from the North Anatolian Fault passive seismic experiment ([dataset]Beck and Zandt, 2005; Biryol et al., 2010), in order to delineate the first-order seismic structure of the crust and to map crustal anisotropy as a function of depth. In particular, our main objectives are to elucidate i) orientation and strength of deformation in the crust at various depth ranges ii) how much the strain fields within crust and upper mantle are coupled iii) possible link between lateral variation of crustal anisotropy parameters and existing lithology contrast across the NAF. These results yield insight into the poorly known role of crustal seismic anisotropy in the area.

2. Geological setting of North-Central Anatolia

The study region is located in an important area of orogenic amalgamation of Anatolia, a transition zone between compressional-deformed eastern Anatolia and extensional western Anatolia. There are numerous key structures developed under the complex deformation, such as the Ezine Pazarı – Sungurlu Fault, the İzmir – Ankara – Erzincan (IAESZ) and Intra – Pontide Suture Zones, the İstanbul Zone, the Sakarya Continent, the Central Pontides, the Kırşehir Massif and the Çankırı Basin (Okay and Tüysüz, 1999; Fig. 2). It is reported that some of these structures (e.g., the Istanbul Zone; Şengör, 1979) were parts of Eurasia, while other fragments were separated from the Arabian-African Plate. Görür et al. (1998) further inform that the major basins in Central Anatolia were formed on continental units; i.e., the Sakarya Continent and the Kırşehir Massif adjacent to the suture zones. These structures have significant importance on understanding the tectonic evolution of the region. For example, the İzmir–Ankara–Erzincan suture zone (IAESZ) is a remnant of the Neo-Tethys Ocean and hence consists of ophiolitic units (Rojay, 2013). It separates the Pontides to the north from the Anatolide–Tauride and the Kırşehir blocks to the south