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Pronounced zonation of seismic anisotropy in the Western Hellenic subduction zone and its geodynamic significance

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ABSTRACT

Many subduction zones exhibit significant retrograde motion of their arc and trench. The observation of fast shear-wave velocities parallel to the trench in such settings has been inferred to represent trench-parallel mantle flow beneath a retreating slab. Here, we investigate this process by measuring seismic anisotropy in the shallow Aegean mantle. We carry out shear-wave splitting analysis on a dense array of seismometers across the Western Hellenic Subduction Zone, and find a pronounced zonation of anisotropy at the scale of the subduction zone. Fast SKS splitting directions subparallel to the trench-retreat direction dominate the region nearest to the trench. Fast splitting directions abruptly transition to trench-parallel above the corner of the mantle wedge, and rotate back to trench-normal over the back-arc. We argue that the trench-normal anisotropy near the trench is explained by entrainment of an asthenospheric layer beneath the shallow-dipping portion of the slab. Toward the volcanic arc this signature is overprinted by trench-parallel anisotropy in the mantle wedge, likely caused by a layer of strained serpentine immediately above the slab. Arcward steepening of the slab and horizontal divergence of mantle flow due to rollback may generate an additional component of sub-slab trench-parallel anisotropy in this region. Poloidal flow above the retreating slab is likely the dominant source of back-arc trench-normal anisotropy. We hypothesize that trench-normal anisotropy associated with significant entrainment of the asthenospheric mantle near the trench may be widespread but only observable at shallow-dipping subduction zones where stations nearest the trench do not overlie the mantle wedge.

1. Introduction

Seismic anisotropy in the Earth's upper mantle is commonly attributed to the preferred alignment of olivine crystals caused by finite strain field associated with viscous flow (McKenzie, 1979). Anisotropy is measurable by quantifying the birefringence of shear waves that propagate vertically through an anisotropic layer and accumulate a time offset δt between a fast component polarized in a vertical plane of azimuth ϕ, and an orthogonal slow component (Silver and Chan, 1991). At subduction zones, two domains of anisotropy are frequently observed: a domain of trench-parallel fast directions between the trench and volcanic arc, and a domain of trench-normal directions over the back-arc (e.g., Russo and Silver, 1994; Long and Becker, 2010). Trench-normal anisotropy is commonly attributed to the lattice-preferred orientation (LPO) of A-type olivine crystals induced by back-arc corner flow. By contrast, at subduction zones exhibiting significant slab advance or retreat, trench-parallel anisotropy is often inferred to represent trench-parallel flow driven by the trench-normal motion of the slab (Russo and Silver, 1994; Long and Silver, 2009). Such a pattern of flow, often termed toroidal, in which sub-slab mantle is forced to escape around the retreating slab and into the mantle wedge (in the case of slab retreat), has been inferred from laboratory (Buttles and Olson, 1998; Kincaid and Griffiths, 2003; Schellart, 2004; Funiciello et al., 2006) and numerical (Piromallo et al., 2006; Stegman et al., 2006; Schellart et al., 2007) experiments. However, in many of those studies, toroidal flow is confined to the region near and beyond the slab edge, and it is unclear how pervasive trench-parallel flow might be beneath and above the interior portion of the slab.

Alternatively, mechanisms that do not require rollback-driven, trench-parallel sub-slab flow have been proposed to explain trench-parallel anisotropy. These mechanisms place the source of trench-parallel anisotropy within the slab or in the overlying

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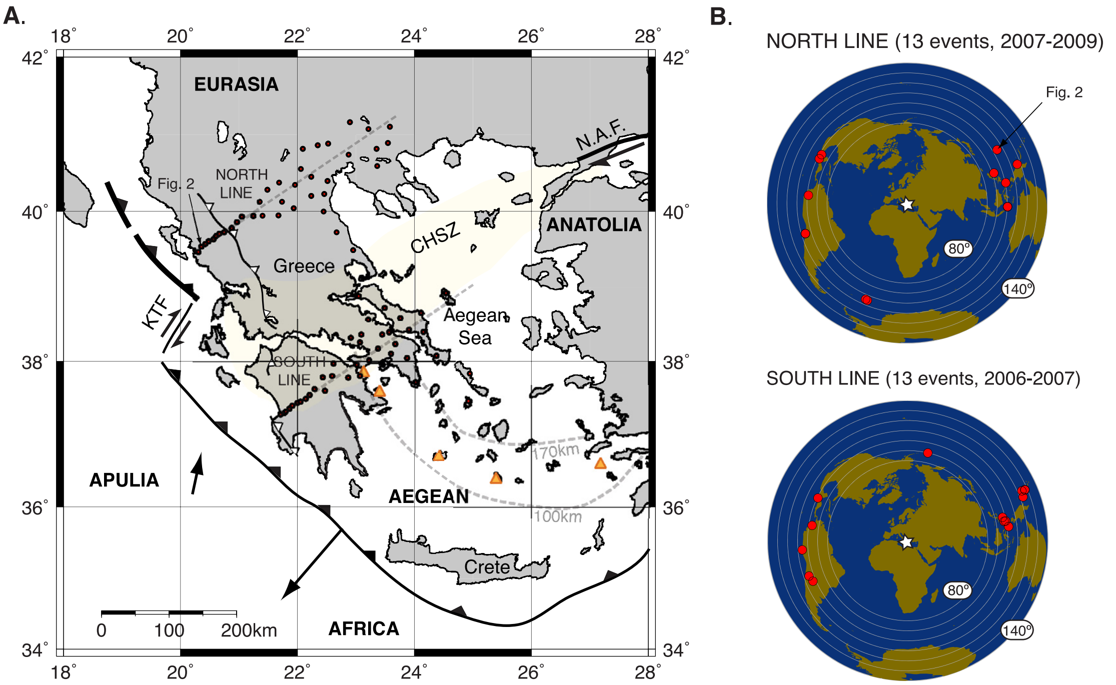

Fig. 1. A. Study area and location of the MEDUSA stations (dots). Dashed gray lines indicate the projections of the North and South lines shown on Fig. 4. The black line with barbs marks the trench in the northern segment. The thinner black line in the southern segment indicates the bathymetric trench, which is distinct from the deformation front (not shown) further to the southwest (Royden and Papanikolaou, 2011). Dashed gray curves indicate the depth to the Wadati–Benioff Zone in the Southern segment (Papazachos et al., 2000). Other major tectonic features include (Royden and Papanikolaou, 2011): the Kefalonia Transform Fault (KTF), the Central Hellenic Shear Zone (CHSZ, yellow shading), the North Anatolian Fault (NAF), the front of the internal Pindos ophiolite (thin black line with open barbs), and the active volcanic arc (orange triangles). The trench retreat velocity is indicated in a hotspot reference frame (Hatzfeld et al., 2001). The motion of Apulia in an absolute reference frame (Pérouse et al., 2012) is indicated with a black arrow. B. Teleseismic events used for SKS splitting measurements along both seismic lines. Circles are plotted every 10° of angular distance from Central Greece. The station (N002) and event (2008130) associated with the measurement shown in Fig. 2 are outlined in A and B.

fore-arc mantle wedge. Examples of such mechanisms are: serpentine-filled cracks in the downgoing slab (Faccenda et al., 2008), B-type olivine fabrics in the cold, hydrated mantle wedge nose (Jung and Karato, 2001), 3D convective instabilities (Behn et al., 2007), and flow driven by slab curvature (Kneller and van Keken, 2008). Distinguishing between these various models requires reliable constraints on the depth-distribution of the anisotropic sources, which shear-wave splitting from teleseismic arrivals does not easily provide. Splitting of local S-waves generated along the Wadati–Benioff Zone or in the slab has proven to be an effective tool to discriminate between wedge and sub-wedge anisotropy when compared with teleseismic shear wave splitting. Using this methodology, Long and Silver (2009) established that ~90% of subduction zones exhibit trench-parallel anisotropy in the sub-slab mantle. Notable exceptions featuring sub-slab trench-normal anisotropy include Cascadia (Currie et al., 2004) and Central Alaska (Christensen and Abers, 2010).

A successful model for subduction zone anisotropy must therefore account for this variability in addition to properly explaining the spatial distribution of anisotropy at the scale of individual subduction systems. It is likely that subduction zone anisotropy reflects a combination of several of the mechanisms listed above, rather than a single ubiquitous process. In particular, the geometry of a given subduction zone influences where each of these mechanisms is best expressed in measurements of seismic anisotropy, and how the anisotropy associated with these mechanisms constructively and/or destructively interferes with one another.

In this study, we attempt to isolate different sources of anisotropy based on shear-wave splitting in the Western Hellenic Subduction Zone, a subduction system experiencing significant retrograde motion of the slab (Fig. 1). Previous seismic anisotropy studies in the region include: Pn-wave tomography (Hearn, 1999), shear-wave splitting (Hatzfeld et al., 2001; Evangelidis et al., 2011), and surface wave anisotropy (Endrun et al., 2011). These have revealed significant trench-parallel anisotropy along the Hellenic arc, as well as fast-directions parallel to the retreat of the Hellenic trench correlating well with extensional deformation throughout the back-arc domain (Jolivet et al., 2009). Here we focus on seismic anisotropy closer to the trench using a station network of unprecedented density. We show that this relatively small-scale subduction system displays pronounced zonation of anisotropy that can be attributed to the juxtaposition of several sources—each relatable to mantle flow or known subduction processes. We discuss our results in terms of the global variability in subduction zone anisotropy and speculate on the geodynamic implications for coupling between surface plates and the sub-asthenospheric mantle.

2. Methods

2.1. Study area: The Western Hellenic Subduction Zone

The Western Hellenic Subduction Zone (Fig. 1) is one of the small-scale (<1000 km), rapidly evolving mobile belts accommodating the slow convergence between the European and Nubian plates (Molnar, 1988; Hyndman et al., 2005; Faccenna and Becker, 2010). It displays many classical features of subduction, including a northeastward dipping slab that increases in dip from 20° to ~45° around ~100 km depth (Papazachos et al., 2000; Piromallo and Morelli, 2003; Suckale et al., 2009; Pearce et al., 2012), as well as an active volcanic arc in its southern portion. The Western Hellenic Subduction Zone is characterized by rapid southwestward retreat of the arc and trench since the late