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Mid mantle seismic anisotropy around subduction zones

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ABSTRACT

There is increasing evidence for mid mantle seismic anisotropy around subduction zones whose interpretation remains elusive. In this study I estimate the strain-induced mid mantle fabric and associated seismic anisotropy developing in 3D petrological-thermo-mechanical subduction models where the slab is either stagnating over the 660 km discontinuity or penetrating into the lower mantle. The modelling of synthetic lattice-preferred-orientation (LPO) development of wadsleyite and perovskite has been calibrated with results from deformational experiments and ab-initio atomic scale models, and the single crystal elastic tensor of the different mineral phases is scaled by local P–T conditions. The lower transition zone (ringwoodite + garnet) is assumed to be isotropic. Mid mantle fabric develops in proximity of the subducting slab where deformation and stresses are high, except at depths where upwelling or downwelling material undergoes phase transformations, yielding to LPO reset. The upper transition zone (wadsleyite + garnet) is characterized by weak transverse isotropy (2–3%) with symmetry axes oriented and fast S wave polarized dip-normal. A slightly stronger transverse isotropy develops in the lower mantle (perovskite + periclase), where the symmetry axes, the polarization of the fast S wave and the maximum Vp and dVs are parallel to the slab dip and subduction direction. For stagnating slab models this translates into negative and positive radial anisotropy in the upper transition zone and lower mantle back-arc, respectively, minimum delay times for vertically travelling shear waves and large shear wave splitting for waves propagating horizontally in the lower mantle. These results may help in reconciling the seismic anisotropy patterns observed in some subduction zones with subduction-induced deformation, such as those measured in the mid mantle between the Australian plate and the New Hebrides–Tonga-Kermadec trenches that I interpret as related to stagnating portions of the subducted Pacific plate.

1. Introduction

Convection controls the chemical and thermal evolution of the Earth's mantle and detailed studies of mantle flow geometries are needed to better understand the dynamics of the planetary interiors. The patterns of mantle convection can be determined by measuring seismic anisotropy caused by deformation and interpreted as resulting from either strain-induced shape-preferred orientation (SPO) of elastically heterogeneous materials or strain-induced lattice-preferred orientation (LPO) of homogeneous material (McNamara et al., 2002). Seismic anisotropy is commonly observed in boundary layers where deformation and stresses are greatest (Montagner, 1998). The dominant seismic anisotropy is detected under tectonic plates in the upper mantle (0–410 km, UM), while secondary contributions are identified in the mid mantle (410–900 km) and at the bottom of the lower mantle (D″). In particular, the nature of the mid mantle, composed by the transition zone (TZ) and the uppermost lower mantle (ULM), is controversial because it appears to act as a (partially permeable) barrier dividing the mantle, in average, in two convective systems, the upper mantle and the lower mantle (Montagner and Kennett, 1996; Montagner, 1998; Deschamps et al., 2011). Seismic tomographies show cold anomalies in proximity of subduction zones that are either stagnanting above the 660 km discontinuity or penetrating into the lower mantle (Grand et al., 1997; Bijwaard et al., 1998; Karason and van der Hilst, 2000), suggesting that the 660 km discontinuity hamper, but do not completely block material across the TZ.

There is increasing evidence for seismic anisotropy in the mid mantle around subduction zones that, if interpreted correctly, may shed light on the dynamics of such boundary layer (Fig. 1). At global scale, normal mode, surface wave overtone and body wave data indicate that the mid mantle is characterized in average by a weak (1–2%) radial ($\xi = (V_{SH}/V_{SV})^2$, where V_{SH} and V_{SV} are the velocities of the horizontally and vertically polarized shear waves) and azimuthal (ϕ, azimuthal variation of a given seismic wave)

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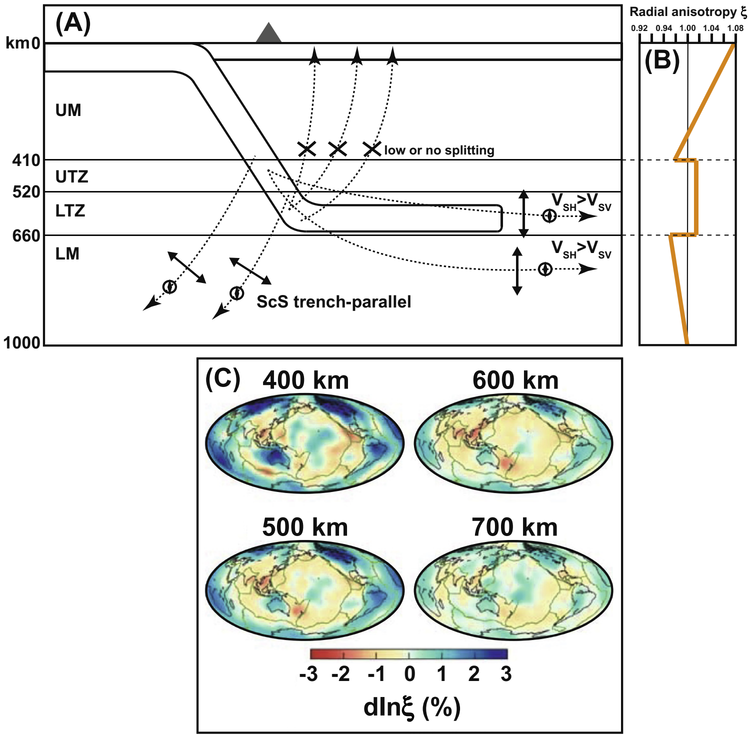

Fig. 1. (A) Cartoon summarizing mid mantle seismic anisotropy observed at subduction zones from S-waves generated by local earthquakes. (B) Global average upper and mid mantle radial anisotropy (adapted from Montagner and Kennett (1996)). (C) Radial anisotropy at 400–700 km depths from S-wave tomography (Panning and Romanowicz, 2006).

anisotropy (e.g., (Montagner and Kennett, 1996; Trampert and van Heijst, 2002; Panning and Romanowicz, 2006; Visser et al., 2008)). By using eigenfrequency data, (Montagner and Kennett, 1996) showed that in average the TZ and ULM exhibit positive and negative ξ, respectively (Fig. 1B). S-wave tomography studies found negative ξ perturbations ($V_{SH} < V_{SV}$) associated with subduction zones (Panning and Romanowicz, 2006) (Fig. 1C). At a regional scale, the measurement of local and teleseismic shear wave splitting allows for a more detailed analysis of the mantle fabric. The observations indicate that strong anisotropy is present all around subducting slabs down to the ULM (Chen and Brudzinski, 2003; Wookey and Kendall, 2004; Foley and Long, 2011; Di Leo et al., 2012) (Fig. 1A). For example, at Tonga subduction zone, probably one of the best studied convergent margin in terms of upper and mid mantle anisotropy, significant trench-parallel anisotropy is measured below the Pacific slab in the upper and mid mantle (Foley and Long, 2011). In the Tonga back-arc strong $V_{SH} > V_{SV}$ is found in the TZ and ULM between the Tonga-Kermadec–New Hebrides and Australian plate for horizontally propagating waves (Chen and Brudzinski, 2003; Wookey and Kendall, 2004), while vertically propagating SKS waves yield null splitting for the mid mantle (Fisher and Wiens, 1996). More in general, by comparing SWS in vertically propagating S phases from local earthquakes and teleseismic SKS waves, (Fisher et al., 1998) found that the Pacific subduction zone back-arcs are characterized by isotropic lower transition zone (LTZ, 520–660 km) and lower mantle, with the exception of the upper transition zone (UTZ, 410–520 km) beneath the southern Kurils that appears to contain weak anisotropy. It is worth to note that the negative radial anisotropy found by Panning and Romanowicz (2006) in the Tonga back-arc mid mantle appears to be in contrast with the $V_{SH} > V_{SV}$ measured in the TZ by Chen and Brudzinski (2003), potentially because this last observation is more related to the subducting slab than with the surrounding mantle.

The extrapolation of the mantle flow from seismological observations is not always warranted and is, in fact, complicated by several mechanisms. The primary source of anisotropy is considered to be the LPO of anisotropic minerals developing during deformation, although other mechanisms such as tilted laminated structures or even organized pockets of fluid inclusion are often invoked as plausible models for the anisotropy in the TZ (Karato, 1998; Trampert and van Heijst, 2002). Laboratory experiments indicate that the strain-induced LPO patterns vary as a function of the deformation history, temperature, deviatoric stress and water content conditions (e.g., (Karato et al., 2008)). It follows that the interpretation of seismic anisotropy in terms of the mantle flow is neither simple nor unique, especially at subduction zones where complex and non-steady-state 3D flow patterns may establish.

In order to reduce the number of possible interpretations that can explain a given anisotropy dataset, a promising approach is to compare seismic measurements with predictions of numerical and experimental flow models (Long et al., 2007). The development of strain-induced LPO has been modelled mostly for the upper mantle (Hall et al., 2000; Becker et al., 2012; Faccenda and Capitanio, 2013), but few studies have been devoted to deeper levels. For instance, (McNamara et al., 2002) used dynamic 2D models of subduction with a composite Newtonian and power-law creep rheology, showing that lower mantle fabric can be produced in proximity of subducting slabs where stresses are relatively high and dislocation creep becomes predominant. Lately, the same flow models were used in combination with polycrystal plasticity models of lower mantle minerals aggregates (Wenk et al., 2006). However, these studies focused mainly on the LPO development at the Core-Mantle-Boundary. (Nippress et al., 2004) used instantaneous 2D flow solutions of a slab lying over the 660 km discontinuity and found that large deviatoric stresses and significant amounts of finite strain in the ULM below a viscosity increase at the 660 km discontinuity could produce a fabric responsible for the seismic anisotropy observed in the ULM (e.g., (Wookey and Kendall, 2004)).