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Review Article

Global radially anisotropic mantle structure from multiple datasets: A review, current challenges, and outlook

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ABSTRACT

Since the 1960s seismologists have mapped anisotropy in the uppermost mantle, the mantle transition zone, and the D″ region. When combined with constraints from mineral physics and geodynamics, anisotropy provides critical information on the geometry of mantle flow. Here we review the theory, early work, recent tomographic models, and experimental constraints on radial anisotropy. We discuss current challenges in resolving radial anisotropy seismically. In particular, we show that it is highly beneficial to use multiple datasets in inversions for anisotropy, notably short-period group velocity data with strong sensitivity to the crust. We present a new whole-mantle model of radial anisotropy, based on surface-wave and body-wave travel time data, along with incorporated Moho perturbations. Our whole-mantle model shares common features with previous global models and is consistent with results from several high-resolution regional studies.

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1. Introduction

Single-crystal olivines and pyroxenes, the main constituents of the Earth's upper mantle, are highly anisotropic. For example, shear-wave velocity in an olivine crystal can vary up to 20% depending on the axis of symmetry (e.g., Kumazawa and Anderson, 1969; Mainprice, 2007). However, in order to develop macro-scale seismic anisotropy large-strain deformation must align the minerals. Mantle flow can deform and align anisotropic minerals in a so-called lattice-preferred orientation (LPO). Therefore, the orientation, symmetry, and strength of seismic anisotropy can be extremely useful to constrain mantle convection.

Many studies have provided seismic evidence for azimuthal and radial anisotropy in the Earth's interior. Azimuthal anisotropy, where wave speed depends on the azimuth of propagation, was first recognized by Hess (1964) and is often studied through shear-wave splitting measurements. It is also referred to as horizontal transverse isotropy, given a horizontal symmetry axis in hexagonal symmetry. Azimuthal anisotropy and shear-wave splitting results have been reviewed by Silver (1996), Savage (1999), and Long (2013). In this review, we focus mainly on radial anisotropy in the Earth's mantle.

Radial anisotropy was first observed by Anderson (1961, 1965), Aki and Kaminuma (1963), and McEvilly (1964), who recognized that Rayleigh and Love wave dispersion cannot be explained by isotropic velocity profiles. Radial anisotropy is also known as polarization anisotropy or vertical transverse isotropy. Since there was a consensus on the presence of radial anisotropy in the uppermost mantle, the Preliminary Reference Earth Model (PREM; Dziewoński and Anderson, 1981), one of the most widely used 1-D seismic velocity models, incorporates radial anisotropy between the Moho (at 24.4 km depth) and a seismic discontinuity at 220 km depth. There have been some attempts to constrain the 3-D radially anisotropic structure of the mantle (e.g., Ekström and Dziewoński, 1998; Ferreira et al., 2010; Gung et al., 2003; Kustowski et al., 2008; Lekić and Romanowicz, 2011; Montagner and Tanimoto, 1991; Nataf et al., 1984; Panning and Romanowicz, 2006; Shapiro and Ritzwoller, 2002; Visser et al., 2008; Zhou et al., 2006) since the development of seismic tomography in the late 1970s (Aki et al., 1977; Dziewoński et al., 1977; Woodhouse and Dziewoński, 1984). However, large discrepancies still persist among the various 3-D radially anisotropic mantle models, in contrast with global 3-D isotropic models, which show a good level of agreement at least for long-wavelength structure in the upper mantle. The relatively slow progress in anisotropic tomography reflects the subtle effects of anisotropy on seismic waveforms, which cannot be easily separated from the effects of isotropic structure, notably in the crust and in the lowermost mantle (e.g., Ferreira et al., 2010; Kustowski et al., 2008; Panning et al., 2010).

In this paper, we review the theoretical background, the implications of radial anisotropy for interpretations based on mineral physics, and the development of 3-D radially anisotropic mantle models. We also compare results from regional studies of radial anisotropy with global 3-D radially anisotropic models and discuss synthetic tests to determine the sensitivities of various seismic data types to radial anisotropy. In particular, we explore current challenges and new strategies to better resolve radial anisotropy in the Earth's mantle. We present a new 3-D global radially anisotropic model, where we reduce the impact of the crust on the imaging of radial anisotropy in the mantle by incorporating short-period surface-wave group-velocity data as well as phase velocity and body-wave travel time data.

2. Theoretical background

Seismic anisotropy can be represented by an elastic tensor, which relates an applied stress to the resulting strain via Hooke's law as follows (e.g., Aki and Richards, 1980),

$$\tau_{ij} = c_{ijpq}\epsilon_{pq}, \tag{1}$$

where τ_{ij}, ϵ_{pq}, and c_{ijpq} are the stress, strain, and elastic tensor, respectively. Due to the following symmetries, the elastic tensor has 21 independent coefficients:

$$c_{jipq} = c_{ijpq}\left(\text{since}\,\tau_{ji} = \tau_{ij}\right) \tag{2}$$

$$c_{ijqp} = c_{ijpq}\left(\text{since}\,\epsilon_{qp} = \epsilon_{pq}\right) \tag{3}$$

$$c_{pqij} = c_{ijpq}. \tag{4}$$

The Eq. (4) is due to the first law of thermodynamics that the rates of mechanical work and heat flux are balanced with the increase rate of kinetic and internal energies; refer to Aki and Richards (1980) for its derivation. While all 21 coefficients are required to describe a medium with triclinic symmetry, the number of independent coefficients can be reduced if the medium itself is symmetric. Various symmetry classes are presented in Fig. 1. If the medium is isotropic, that is, a medium without variation of elastic parameters with direction, there are only two elastic coefficients (the Lamé constants: λ and μ) related to the compressional wave speed V_P and shear wave speed V_S by $(\lambda + 2\mu) = \rho {V_P}^2$ and $\mu = \rho {V_S}^2$, where, ρ is density.

A radially anisotropic medium has hexagonal symmetry with a vertical symmetry axis. This medium can be described by five independent elastic coefficients, which are traditionally called Love coefficients: A, C, F, L, and N (Love, 1927). They are related to seismic velocities as follows:

$$A = \rho V_{PH}^2 \tag{5}$$

$$C = \rho V_{PV}^2 \tag{6}$$

$$L = \rho V_{SV}^2 \tag{7}$$

$$N = \rho V_{SH}^2 \tag{8}$$

$$F = \frac{\eta}{A{-}2L}, \tag{9}$$

where, ρ is density, V_{PH} and V_{PV} are horizontally and vertically polarized *P* wave velocities, respectively, and V_{SH} and V_{SV} are horizontally and vertically polarized *S* wave velocities, respectively. η is a parameter relating