Earth and Planetary Science Letters 429 (2015) 101–109

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Robust constraints on average radial lower mantle anisotropy and consequences for composition and texture

R.W.L. de Wit*, J. Trampert

Department of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD, Utrecht, The Netherlands

A R T I C L E I N F O

Article history:
Received 26 February 2015
Received in revised form 20 July 2015
Accepted 26 July 2015
Available online 13 August 2015
Editor: J. Brodholt

Keywords:
mantle anisotropy
radial Earth structure
normal modes
uncertainty estimation
thermochemical structure

A B S T R A C T

Seismic anisotropy has been observed in the upper mantle (<660 km depth) and the lowermost ∼150–250 km of the mantle (the D″ region), while the remainder of the lower mantle is believed to be isotropic. Here, we used centre frequencies for spheroidal and toroidal normal modes together with a neural-network-based technique to infer probability density functions for the average radial anisotropy in the lower mantle. We show, for the first time, a robust observation that the average lower mantle is anisotropic (mainly in the parameter η) below 1900 km depth, challenging the consensus that this part of the mantle is isotropic. The mass density also shows a well-constrained positive deviation from existing models at the same depths. Using existing mineral physics data, our results are compatible with an average lower mantle that is about 100–200 K colder than commonly-assumed adiabats and that consists of a mixture of about 60–65% perovskite and 35–40% ferropericlase containing 10–15% iron. If further a crystal alignment mechanism is assumed, the observed anisotropy can constrain the orientation of the two minerals and suggests a new window to study the nature of flow in the lower mantle.

1. Introduction

Seismic anisotropy, the direction-dependence of elastic wave propagation, can be a key indicator of mantle flow, deformation and consequently mantle dynamics (Montagner, 1994; McNamara et al., 2002; Panning and Romanowicz, 2004). It is commonly interpreted as lattice-preferred orientation (LPO) or shape-preferred orientation (SPO) of the mineral crystals that constitute the mantle (Karato, 2008; Fichtner et al., 2013). LPO refers to the alignment of intrinsically anisotropic minerals, such as olivine, while SPO relates to (long-wavelength) apparent anisotropy that is observed as a result of a specific configuration of isotropic material, e.g. a stack of thin alternating layers with contrasting elastic properties, melts or cracks (Backus, 1962).

Seismic anisotropy has been observed in the upper mantle (above the 660 km discontinuity) and the lowermost ∼150–250 km of the mantle (Montagner and Kennett, 1996; Panning and Romanowicz, 2004; Beghein et al., 2006; Visser et al., 2008; Chang et al., 2014). By contrast, the current consensus is that the remainder of the lower mantle is isotropic, although both experimental and modelling studies have shown that lower mantle minerals are intrinsically anisotropic (Meade et al., 1995; Mainprice et al., 2000). Karato et al. (1995) explained the absence of lower mantle anisotropy by super-plastic flow, since the associated diffusion creep does not lead to the development of LPO of mantle minerals. There are also no viable candidates known for SPO in the lower mantle.

Most seismically anisotropic earth models suffer from several limitations. Firstly, there is a well-documented trade-off between anisotropy in the crust and in the mantle (Bozdağ and Trampert, 2008; Panning et al., 2010). Secondly, seismological inverse problems are notoriously non-unique. Thirdly, a certain scaling is often imposed between chosen model parameters to simplify the seismological inverse problem and reduce the number of free parameters, which may lead to biased models (Beghein et al., 2006; Panning and Romanowicz, 2006; Kustowski et al., 2008). Finally, regularisation is commonly applied to stabilise the inverse problem, which can have a significant effect on the final solution (Beghein and Trampert, 2003; de Wit et al., 2012). These issues call for a quantitative assessment of model uncertainties. Nonetheless, most models come without error bars, which makes it impossible to quantify the discrepancies between existing models.

We assessed anisotropy in the lower mantle (>660 km depth) in a fully quantitative manner, i.e. we solved the inverse problem and estimated uncertainties without imposing any scaling between parameters. We adopted a Bayesian framework, in which any inference made about a model is the result of the conjunction of our current (*prior*) knowledge and the ability of the model to explain

---

* Corresponding author. Tel.: +31 (0)30 253 5135.
E-mail address: ralphdewit@gmail.com (R.W.L. de Wit).

http://dx.doi.org/10.1016/j.epsl.2015.07.057
0012-821X/© 2015 Elsevier B.V. All rights reserved.

the observations (Tarantola and Valette, 1982). The updated (*posterior*) knowledge on the model — that is, after observing the data — represents the new degree of belief in the model, expressed by a probability density function (pdf). We only consider the marginal posterior pdfs for single earth model parameters, averaged over a certain depth range. Such a 1-D marginal posterior pdf, hereafter referred to as 'marginal', represents the information on a single model parameter, given the data and the possible variations in all other model parameters. We employed machine learning techniques to learn relationships between data and model based on samples of the prior model space. To obtain marginals, we used a Mixture Density Network (MDN, Bishop, 1995; de Wit et al., 2013; Käufl et al., 2014), which takes the seismic data as input and outputs the marginal for the earth model parameter of interest. Our inversion method is designed to provide a flexible tool for hypothesis testing, which allows us to assess the probability of a certain statement or hypothesis. The flexibility enables us to focus on averages of any parameter of interest over an arbitrary depth range (de Wit et al., 2014), rather than focus on the parameters at a given depth, as used by the forward calculation, which are difficult to resolve by the data used. In this study, we used splitting function measurements for spheroidal (Deuss et al., 2013; Koelemeijer et al., 2013; Koelemeijer, 2014) and toroidal (Reference Earth Model, 2001) modes. We focus here on the radial (1-D) seismic structure of the lower mantle and show that this region is indeed anisotropic.

Firstly, we briefly describe the earth model parametrisation, the neural network methodology and the normal mode data. Secondly, we 'invert' the centre frequency measurements using MDNs and construct 1-D marginal posterior pdfs for the radial averages of P-wave (V_P) and S-wave (V_S) velocities, density (ρ) and three parameters describing radial anisotropy in six layers in the lower mantle. Finally, we assess whether the observed elasticity, as represented by the 1-D marginals for the seismic parameters in each layer, can be explained by a simple thermochemical lower mantle model, given currently available mineral physics data.

2. Model parametrisation

The radial structure of the Earth is parametrised in terms of wavespeeds, density and bulk and shear attenuation ($1/Q_\kappa$ and $1/Q_\mu$, respectively). We allowed for radial anisotropy in the whole mantle and inner core, while the outer core was isotropic. The radial anisotropy was parametrised by the velocities of vertically and horizontally propagating P-waves (V_{PV} and V_{PH}), the velocities of vertically and horizontally polarised S-waves propagating horizontally (V_{SV} and V_{SH}) and the fifth anisotropic parameter η, similar to the parametrisation of the Preliminary Reference Earth Model (*PREM*, Dziewoński and Anderson, 1981). We used a finely layered parametrisation with depth on a discrete set of 185 points (similar to the models used in the Mineos package Masters et al., 2011) and allowed the depths of the discontinuities to vary. No correlations between physical parameters were imposed, i.e. velocity, density ρ, η and attenuation profiles were constructed independently from each other. We introduced correlations between adjacent depth points, based on randomly perturbed *PREM*-gradients, to exclude physically implausible models and restrict the size of the model space. In addition, similar to *PREM*, we imposed constraints on the mass and moment of inertia of the earth models (Chambat and Valette, 2001).

We generated 100 000 synthetic models, which were randomly drawn from the prior model distribution. The prior for the velocities, density and anisotropic parameters was centred on *PREM*, but spans a wide range of values (Supplementary Figure A.1). In general, wave velocities, density and η were allowed to vary with respect to *PREM* by ±5% in the upper mantle and ±3% in the lower mantle and core. The prior ranges for discontinuity depths included deviations from *PREM* of several tens of kilometres and the prior for attenuation parameters spanned multiple orders of magnitude. The exact prior ranges for all earth model parameters and further details on the parametrisation and the implementation of the correlation between depths points can be found in de Wit et al. (2014).

A radially anisotropic medium can be described by hexagonal symmetry with a vertical (radial) symmetry axis, density and the five independent Love coefficients A, C, N, L and F (Love, 1927). Three parameters are commonly used to describe the radial anisotropy: the P-wave anisotropy ($\phi = \frac{C}{A} = \frac{V_{PV}^2}{V_{PH}^2}$), the shear-wave anisotropy ($\xi = \frac{N}{L} = \frac{V_{SH}^2}{V_{SV}^2}$) and $\eta = \frac{F}{A-2L}$, which corresponds to anisotropy at intermediate incidence angles. In addition to the three anisotropic parameters, we studied the density and the isotropic equivalents of the P- and S-wave velocities, which are given by the Voigt averages (Babuska and Cara, 1991; Panning and Romanowicz, 2006),

$$V_P = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} \tag{1}$$

and

$$V_S = \sqrt{\frac{G}{\rho}}, \tag{2}$$

where the Voigt average bulk and shear moduli, K and G respectively, are defined as

$$K = (C + 4A - 4N + 4F)/9 \tag{3}$$

and

$$G = (C + A + 6L + 5N - 2F)/15. \tag{4}$$

with the five independent Love coefficients A, C, N, L and F. We note that our results are not affected by the choice between a parametrisation in terms of the Love coefficients or wave velocities and η, as our method is derivative-free. It is straightforward to extract the five Love coefficients from the polarised wave velocities and η in an earth model and calculate the corresponding ϕ, ξ and Voigt average isotropic wave velocities (Equations (1)–(4)).

Rather than focusing on the individual depth points of the original earth model parametrisation, which we could not resolve with the data used, we estimated the radially averaged η, ϕ, ξ, ρ and the Voigt average equivalent isotropic V_P and V_S in six lower mantle layers. The bulk of the lower mantle was divided into five layers of roughly equal thickness, which had approximate depth ranges 670–1027, 1027–1456, 1456–1884, 1884–2313 and 2313–2741 in kilometres. The sixth and deepest layer (2741–2891 km) represents the D″ region, which is well-known to be anisotropic (see Nowacki et al., 2011; Chang et al., 2014 for reviews). Note that the depths of the three discontinuities enclosing the lower mantle and the D″ region, i.e. the top of the lower mantle (670 km), the top of the D″ region (2741 km) and the core–mantle boundary (CMB, 2891 km), were allowed to vary by ±20–30 km between the earth models (de Wit et al., 2014). For each model, the depths of the remaining boundaries of the five lower mantle layers were determined by linearly interpolating between the new depths of the discontinuities at 670 and 2741 km.

Note that all other parameters in the model, i.e. parameters describing bulk and shear attenuation, core and upper mantle structure, are also allowed to vary within our prior model distribution (Supplementary Figure A.1). We further emphasise that we did