Physics of the Earth and Planetary Interiors 219 (2013) 11–20

Contents lists available at SciVerse ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Separating intrinsic and apparent anisotropy

Andreas Fichtner [a,*], Brian L.N. Kennett [b], Jeannot Trampert [c]

[a] Department of Earth Sciences, Swiss Federal Institute of Technology, Zurich, Switzerland
[b] Research School of Earth Sciences, The Australian National University, Canberra, Australia
[c] Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

ARTICLE INFO

Article history:
Received 4 July 2012
Received in revised form 10 March 2013
Accepted 27 March 2013
Available online 6 April 2013
Edited by G. Helffrich

Keywords:
Seismic anisotropy
Apparent anisotropy
Intrinsic anisotropy
Seismic tomography
Mantle convection
Lattice-preferred orientation

ABSTRACT

Seismic anisotropy plays a key role in studies of the Earth's rheology and deformation because of its relation to flow-induced lattice-preferred orientation (LPO) of intrinsically anisotropic minerals. In addition to LPO, small-scale heterogeneity produces apparent anisotropy that need not be related to deformation in the same way as intrinsic anisotropy. Quantitative interpretations of observed anisotropy therefore require the separation of its intrinsic and apparent components.

We analyse the possibility to separate intrinsic and apparent anisotropy in media with hexagonal symmetry – typically used in surface wave tomography and SKS splitting studies. Our analysis is on the level of the wave equation, which makes it general and independent of specific data types or tomographic techniques.

We find that observed anisotropy can be explained by isotropic heterogeneity when elastic parameters take specific combinations of values. In practice, the uncertainties of inferred anisotropy are large enough to ensure that such a combination is always within the error bars. It follows that commonly observed anisotropy can always be explained completely by a purely isotropic laminated medium unless *all* anisotropic parameters are known with unrealistic accuracy. Most importantly, minute changes in the poorly constrained P wave anisotropy and the parameter η can switch between the possible or impossible existence of an isotropic equivalent.

Important implications of our study include: (1) Intrinsic anisotropy over tomographically resolved length scales is never strictly required when reasonable error bars for anisotropic parameters are taken into account. (2) Currently available seismic observables provide weak constraints on the relative contributions of intrinsic and apparent anisotropy. (3) Therefore, seismic observables alone are not sufficient to constrain the magnitude of mantle flow. (4) Quantitative interpretations of anisotropy in terms of mantle flow require combined seismic/geodynamic inversions, as well as the incorporation of additional data such as topography, gravity and scattered waves.

1. Introduction

Over the past few decades, work on seismic anisotropy has taken a prominent role in studies of the Earth because of the potential relation to geodynamic processes. In the field and in laboratory experiments, flow of geological materials leads to lattice-preferred orientations (LPO) of intrinsically anisotropic crystals, such as olivine in ophiolites. LPO produces materials with seismically observable anisotropy via the directional dependence of wavespeeds (e.g., Turner and peridotites, 1942; Verma, 1960; Hess, 1964; Zhang and Karato, 1996; Mainprice et al., 2005; Raterron et al., 2009). The consequence of such intrinsic seismic anisotropy is differences in wavespeed properties depending on polarisation: with shear-wave splitting in SKS waves accumulated along the path, and differences in the behaviour of Love and Rayleigh wave dispersion that cannot be explained by simple isotropic models. Analysis of observed seismic anisotropy has often concentrated on simple scenarios with nearly homogeneous media, so that all measures of observed seismic anisotropy represent model-based inferences rather than direct observations of material properties. The results have been taken up in geodynamic modelling, where observed seismic anisotropy – translated into Earth models via the solution of an inverse problem – has often been assumed to be entirely intrinsic, and thus represent a direct indicator of flow patterns (e.g., Ribe, 1989; Chastel and Dawson, 1993; Becker et al., 2006; Becker, 2008).

It was early recognised that many facets of observed seismic anisotropy can be mimicked by heterogeneous isotropic media, when the wavelengths employed are much larger than the scales of variation of the heterogeneity (e.g., Backus, 1962; Levshin and Ratnikova, 1984; Babuška and Cara, 1991; Fichtner and Igel,

* Corresponding author.
E-mail address: andreas.fichtner@erdw.ethz.ch (A. Fichtner).

0031-9201/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.pepi.2013.03.006

2008; Guillot et al., 2010; Capdeville et al., 2010a, in press). The shape-preferred orientation (SPO) of small fluid inclusions or cracks, for instance, can produce such apparent anisotropy (e.g., Babuška and Cara, 1991; Blackman and Kendall, 1997). Similarly, a finely stratified medium will appear transversely isotropic (equivalent to hexagonal crystal symmetry) and will display shear-wave birefringence with a separation of pulses of different polarisation. Consequently, observed anisotropy may be used to infer the presence of small-scale isotropic heterogeneity, including cracks (e.g., Crampin and Chastin, 2003) and melt pockets (e.g., Bastow et al., 2010).

The similarity of small-scale heterogeneity and large-scale anisotropy has profound consequences for seismic tomography that typically aims to find smooth models with as few parameters as possible. Small-scale structure that cannot be resolved by a finite amount of bandlimited data is suppressed from the outset via regularisation. This leads to tomographic models that are long-wavelength equivalents of potentially smaller-scale structure that cannot be resolved (Capdeville et al., in press). While regularisation is often a technical necessity, a smooth anisotropic model may also require less parameters or be statistically more plausible than a rough isotropic model that explains the data equally well (Montagner et al., 1988; Trampert and Woodhouse, 2003). This provides additional intuitive justification for this approach, because it seems in accord with Occam's razor, or the law of parsimony. While being useful formalisations of human intuition, neither statistics nor Occam's razor are fundamental laws of nature, and therefore unresolvable heterogeneity may map into large-scale apparent anisotropy. In surface wave tomography, for instance, the unknown details of crustal structure can produce apparent anisotropy in the mantle (Bozdağ and Trampert, 2008; Ferreira et al., 2010).

Evidence for structural heterogeneities capable of producing apparent anisotropy has grown rapidly, via sample analysis, studies of scattering, and seismic tomography. The Earth is undoubtedly heterogeneous on all scales with quasi-fractal behaviour over some scale ranges. Parts of this heterogeneity will appear as apparent anisotropy when interrogated by longer wavelength seismic waves. Furthermore, the heterogeneity itself will have been generated by geodynamic processes.

Thus, when we look at the interior of the Earth from the surface, we are faced with a situation where clear indications of anisotropy could arise from intrinsic effects such as LPO, or be apparent, representing averages through fine-scale heterogeneity – which itself could be anisotropic. To improve geodynamic understanding, we need to resolve the anisotropic components and, in particular, recognise the intrinsic component directly related to flow.

At the present time, the problem of separating intrinsic and apparent anisotropy is too complex in full generality. We can, however, examine simpler and illustrative problems. We here restrict attention to the case of transverse isotropy, where properties are symmetric about a preferred axis, equivalent to a crystal with hexagonal symmetry about this axis. We then ask if, given a set of transversely isotropic properties, do we need intrinsic anisotropy, or is there some equivalent combination of isotropic materials?

While it is well known that a small-scale isotropic model has a long-wavelength isotropic equivalent, the reverse problem considered here has, to the best of our knowledge, only been addressed by Backus (1962) – despite its outstanding geodynamic relevance. It is, a priori, not obvious which anisotropic models can be represented by an isotropic equivalent. The mere fact that one can go from any small-scale isotropic model to one anisotropic model does not imply that the opposite is true as well, i.e., that one can go from any anisotropic model to one small-scale isotropic model.

We will see that the solution to this problem is surprisingly complex, and that in many circumstances we cannot discriminate between intrinsic and apparent anisotropy. Where we can, the distinction depends on very precise controls on certain properties of the materials such as the P wavespeeds or the anisotropic parameter η that can hardly be determined from seismic observations.

This paper is organised as follows: following the definitions of apparent, intrinsic and observed anisotropy, we provide a brief review of the upscaling relations for finely layered media. We then discuss the set of inequalities that an anisotropic medium must satisfy to be representable by an equivalent finely layered isotropic medium. In Section 3.2, these inequalities are illustrated for the specific case of a vertical symmetry axis. A more detailed analysis in Section 4 confirms that small variations in elastic parameters can switch between existence and non-existence of isotropic equivalents. It follows, that isotropic equivalents can generally be found unless all elastic parameters are known with unrealistic accuracy. A detailed discussion of this result is provided in Section 6.

2. Structure-induced apparent anisotropy in layered media

To reduce the complexity of our analysis to a tractable level, we restrict ourselves to layered, transversely isotropic media described in terms of density and the elastic parameters a, c, f, l and n (Love, 1927). In this paragraph we briefly review the concept of structure-induced apparent anisotropy in layered media, as introduced by Backus (1962). This is intended to set the stage for subsequent developments. In the interest of a transparent terminology, we consider the case of a vertical symmetry axis. This allows us to use the notion of plane waves with horizontal or vertical polarisation and propagation directions. The formal development, however, applies to any orientation of the symmetry axis, including horizontal orientation relevant for the analysis of SKS splitting (e.g., Silver and Chan, 1988; Babuška and Cara, 1991).

We assume the stratified medium to vary appreciably over a length scale $\updownarrow$. When the wavelength is much longer than $\updownarrow$, wave propagation through the finely stratified medium is identical to wave propagation through a smoothed equivalent medium, the elastic parameters of which are given by the upscaling equations

$$A = \langle a - f^2 c^{-1} \rangle + \langle c^{-1} \rangle^{-1} \langle f c^{-1} \rangle^2, \quad C = \langle c^{-1} \rangle^{-1}, \quad F = \langle f c^{-1} \rangle \langle c^{-1} \rangle^{-1},$$
$$L = \langle l^{-1} \rangle^{-1}, \quad N = \langle n \rangle. \tag{1}$$

The symbol $\langle . \rangle$ represents the vertical average $\langle \phi \rangle (z) = \int w(\xi - z)\, \phi(\xi)\, d\xi$, where ϕ is any function, and the smoothing window w is required to be positive. The effective medium described in terms of A, C, F, L and N is referred to as a smooth, transversely isotropic, long-wavelength equivalent (STILWE). In the special case where the original layers are isotropic with $a = c = \lambda + 2\mu, f = \lambda$ and $l = n = \mu$, the effective parameters are given by

$$A = \langle 4\mu(\lambda+\mu)(\lambda+2\mu)^{-1} \rangle + \langle (\lambda+2\mu)^{-1} \rangle^{-1} \langle \lambda(\lambda+2\mu)^{-1} \rangle^2, C = \langle (\lambda+2\mu)^{-1} \rangle^{-1},$$
$$F = \langle (\lambda+2\mu)^{-1} \rangle^{-1} \langle \lambda(\lambda+2\mu)^{-1} \rangle, \quad L = \langle \mu^{-1} \rangle^{-1}, \quad N = \langle \mu \rangle. \tag{2}$$

Unless λ and μ are constant, we find $A \neq C$ and $L \neq N$, meaning that isotropic layering induces apparent anisotropy when wavelengths much longer than $\updownarrow$ are observed. This phenomenon is illustrated in Fig. 1.

Eqs. (1) and (2) gain special relevance in the context of structural inverse problems that are generally under-determined due to the finite amount of independent seismic data. Under-determinacy implies the need for regularisation, i.e., the enforcement of smoothness that prevents the appearance of small-scale features (e.g., fine layers) that cannot be resolved (e.g., Trampert et al., 2013). It follows that seismic inverse problems produce long-wavelength equivalents with at least some degree of apparent anisotropy – the only exception being the unlikely case where