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Intrinsic *versus* extrinsic seismic anisotropy: Surface wave phase velocity inversion

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The precise determination and interpretation of anisotropy are relatively difficult because the apparent anisotropy is usually a mixture of intrinsic and extrinsic anisotropy, which might partly hide the true properties of the medium investigated. The artificial anisotropy can be due to the fact that seismic waves do not 'see' the real details of a medium, but a 'filtered' (or 'upscaled') version of the Earth model. This can be due to a bad quality of the data coverage, to limited frequency band effects, or to errors in the approximate theory. With the limitation to layered Earth models, through comparisons of the results of the homogenization method with those of the periodic isotropic two-layered model as an analytical solution, we illustrate that the Backus theory for the long wavelength equivalent effect can be extended to calculate the extrinsic anisotropy, due to upscaling effects at discontinuities for the general isotropic layered model, when its spatial scale is much less than or equal to the seismic wavelength. We find that the extrinsic radial S-wave anisotropy produced by the vertical heterogeneities in the upper mantle of the Earth can be as large as 3% (about 30% extrinsic anisotropy of the 10% radial anisotropy). To better recover information from seismic data, we propose a surface wave phase velocity inversion method based on the first-order perturbation theory. We show that resolution at discontinuities can be improved by adding overtone modes of surface wave data. For more general layered models, the homogenization method could be considered, which can flexibly adapt the scale of the model to seismic wavelengths. However, the periodic isotropic two-layered model can also help to analytically quantify the amount of extrinsic radial, and possibly azimuthal anisotropy produced by the tilted fine layering.

1. Introduction

At a global scale, the Earth has many discontinuities, such as the Mohorovicic discontinuity, as the discontinuities in the mantle at 220 km and 400 km (Dziewonski and Anderson, 1981). The Earth also has some lateral or vertical heterogeneities at different scales that are related to the change in the physical or chemical properties (e.g., phase changes, partial melting) in the lithosphere and mantle, and even in the inner core (Anderson, 2006; Ben-Zion and Lee, 2006; Vidale and Earle, 2000). Seismic waves will show different levels of artificial anisotropy when they propagate

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through these discontinuities and heterogeneities, which will depend on their spatial scales and the seismic wavelength. Indeed, much information on the structure of the Earth is 'filtered' away when seismic waves pass through these discontinuities and heterogeneities, especially at high frequencies. Therefore, artificial anisotropy exists in seismic data due to this upscaling (filtering) process. This kind of extrinsic (artificial) anisotropy can misguide us in the exploration and explanation of the anisotropic properties of the Earth in the crust, upper mantle and transition zone. One possibility is to quantify the upscaling effect, although this is not a simple question. For a simply layered model like the periodic isotropic two-layered (PITL) model, we can calculate analytically its effective anisotropic model (or more accurately, the vertical transversely isotropic [VTI] model with radial anisotropy) based on the Backus long-wavelength equivalent theory (Backus, 1962; Postma, 1955; Wang et al., 2013). For more general layered models, the homogenization method (Capdeville and Marigo, 2007; Capdeville et al., 2010; Guillot et al., 2007) provides us with a good tool to quantitatively estimate the upscaling effect, as it can adapt the scale of the model to seismic wavelengths. As the upscaling effect introduces artificial anisotropy, this makes the explanation of anisotropy in seismic data more difficult and non-unique.

Due to the lack of information in seismic data, such as the finite period or limited frequency band, bad data coverage, the error related to approximate theory, and theoretical errors of inversion methods, we can also obtain some extrinsic anisotropy in tomographic Earth models. An accurate inversion method can help us to better retrieve anisotropy in seismic data, and further help us analyze its original mechanisms. The inverse problem deals with the relationship between the model parameter space and the data space, which are related through the forward problem. Different theories can be used to construct the forward operator. When the spatial scale of heterogeneity λ_S is much larger than the seismic wavelength λ_W, we can use ray theory, in the form of the geometrical optics approximation (Gilbert and Helmberger, 1972; Keller, 1963; Sambridge and Snieder, 1993). When the heterogeneity scale is the same as that of the seismic wavelength ($\lambda_S \approx \lambda_W$), we can use the scattering theory based on the Born approximation, which takes finite frequency effects into account (Born and Wolf, 1964; Hudson and Heritage, 1981; Zhou et al., 2005). The first-order perturbation theory is applied when the perturbations in anisotropy or heterogeneity are small (Crampin, 1984; Jech and Pšenčík, 1989; Montagner and Jobert, 1981; Smith and Dahlen, 1973). The forward problem can then be solved by many sophisticated methods, which include analytical solutions, such as the normal mode summation method (Saito, 1988; Takeuchi and Saito, 1972; Woodhouse, 1988; Woodhouse and Girnius, 1982), numerical solutions, such as finite difference methods (Dablain, 1986; Kelly et al., 1976), finite element methods (Johnson, 1990; Turner et al., 1956), and spectral element methods (Komatitsch and Tromp, 2002; Komatitsch and Vilotte, 1998; Patera, 1984).

Solving of the inverse problem is usually equivalent to minimizing different kinds of misfit functions, including the travel-time misfit, amplitude misfit, and waveform misfit (Bozdağ et al., 2011; Dahlen et al., 2000; Lailly, 1983; Tarantola, 1984; Tarantola and Valette, 1982; Tromp et al., 2005). Many methods can be used to minimize the misfit function. Gradient methods can be applied easily, such as the steepest descent algorithm, the conjugate gradient method, and the quasi-Newton method (Tarantola, 2005). Similarly for adjoint tomography, which can be implemented in the framework of finite frequency (Fichtner et al., 2006a, 2006b; Tarantola, 1984; Tromp et al., 2005; Zhu et al., 2012). The full waveform inversion goes beyond traditional tomographic approaches that are typically based only on travel-time or phase velocity data. This has been widely studied in both the time domain (Rickers et al., 2013; Sears et al., 2008; Shipp and Singh, 2002; Tape et al., 2007; Virieux and Operto, 2009) and the frequency domain (Bleibinhaus et al., 2007; Brossier et al., 2009; Pratt, 1999). Statistical and probabilistic searching methods, such as the Monte-Carlo method (Khan et al., 2000; Press, 1968; Sambridge and Mosegaard, 2002), genetic algorithms (Carbone et al., 2008; Mallick, 1995), and the simulated annealing method (Kirkpatrick et al., 1983; Ryden and Park, 2006), are also widely used today. Compared with other inversion methods, these searching methods avoid computation of partial derivatives, although they usually need more storage space and computational time to find the most likely solution.

The apparent anisotropy obtained from seismic data using different kinds of inversion techniques is usually interpreted as the sum of intrinsic and extrinsic anisotropy (Fichtner et al., 2013; Kawakatsu et al., 2009; Wang et al., 2013). Distinction and interpretation of intrinsic and extrinsic anisotropy was discussed by Wang et al. (2013) for investigations into radial anisotropy in reference Earth models, by Fichtner et al. (2013) for surface wave tomography of the Australian plate, and by Bodin et al. (2014) for joint exploration of 1D Earth models using surface wave and receiver functions. Therefore, the interpretation of apparent anisotropy is not unique and deserves further investigation. As a first step, we must estimate the anisotropy that results from the inversion technique itself. To better extract intrinsic anisotropy from the seismic data, we propose an accurate phase velocity inversion method that is based on first-order perturbation theory, and we explore different causes of uncertainties in the inverted anisotropy. We derive different tests that start with the continuous smooth isotropic 1066A model (Gilbert and Dziewonski, 1975), for which there is no upscaling effect. Then considering the isotropic and anisotropic preliminary reference Earth model (PREM; Dziewonski and Anderson, 1981) with several seismic discontinuities, we show the validity of our inversion method for quantification of the effects of upscaling. At the stage of the interpretation of radial anisotropy, we discuss the quantification of extrinsic anisotropy of the general isotropic layered model that is due to the upscaling effect, and investigate the amount of extrinsic anisotropy that is produced by the isotropic petrological layered model in the upper mantle of the Earth.

2. Inversion of surface wave data

Our phase velocity inversion method is based on classical first-order perturbation theory (Crampin, 1984;