Earth and Planetary Science Letters 376 (2013) 165–177

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Seismic observations of large-scale deformation at the bottom of fast-moving plates

Eric Debayle *, Yanick Ricard

Laboratoire de Géologie de Lyon: Terre, Planètes et Environnement, 2 rue Raphaël Dubois, Bâtiment Géode, 69622 Villeurbanne Cedex, France

A R T I C L E I N F O

Article history:
Received 8 February 2013
Received in revised form 12 June 2013
Accepted 15 June 2013
Available online 5 July 2013
Editor: P. Shearer

Keywords:
azimuthal anisotropy
surface waves
tomography
plate motion
present-day deformation
frozen-in anisotropy

A B S T R A C T

We present a new tomographic model of azimuthal anisotropy in the upper mantle, DR2012, and discuss in details the geodynamical causes of this anisotropy. Our model improves upon DKP2005 seismic model (Debayle et al., 2005) through a larger dataset (expanded by a factor ~ 3.7) and a new approach which allows us to better extract fundamental and higher-mode information. Our results confirm that on average, azimuthal anisotropy is only significant in the uppermost 200–250 km of the upper mantle where it decreases regularly with depth. We do not see a significant difference in the amplitude of anisotropy beneath fast oceanic plates, slow oceanic plates or continents. The anisotropy projected onto the direction of present plate motion shows a very specific relation with the plate velocity; it peaks in the asthenosphere around 150 km depth, it is very weak for plate velocities smaller than 3 $\mathrm{cm\,yr^{-1}}$, increases significantly between 3 and 5 $\mathrm{cm\,yr^{-1}}$, and saturates for plate velocities larger than 5 $\mathrm{cm\,yr^{-1}}$. Plate-scale present-day deformation is remarkably well and uniformly recorded beneath the fastest-moving plates (India, Coco, Nazca, Australia, Philippine Sea and Pacific plates). Beneath slower plates, plate-motion parallel anisotropy is only observed locally, which suggests that the mantle flow below these plates is not controlled by the lithospheric motion (a minimum plate velocity of around 4 $\mathrm{cm\,yr^{-1}}$ is necessary for a plate to organize the flow in its underlying asthenosphere). The correlation of oceanic anisotropy with the actual plate motion in the shallow lithosphere is very weak. A better correlation is obtained with the fossil accretion velocity recorded by the gradient of local seafloor age. The transition between frozen-in and active anisotropy occurs across the typical $\sqrt{\mathrm{age}}$ isotherm that defines the bottom of the thermal lithosphere around 1100 °C. Under fast continents (mostly under Australia and India), the present-day velocity orients also the anisotropy in a depth range around 150–200 km depth which is not deeper than what is observed under oceans.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

The first observations of seismic anisotropy date from the early sixties (Aki and Kanimura, 1963; McEvilly, 1964; Hess, 1964). Tomographic studies, at the end of the seventies and during the eighties, confirmed its presence at global scale in the oceanic and continental upper mantle (Forsyth, 1975; Lévêque and Cara, 1983; Tanimoto and Anderson, 1984; Regan and Anderson, 1984; Nataf et al., 1984; Montagner and Tanimoto, 1991). This anisotropy was attributed to the lattice preferred orientation of anisotropic crystals in minerals such as olivine or pyroxene (Nicolas and Christensen, 1987; Babuška and Cara, 1991).

Since the early nineties, the dramatic increase in the number of seismic stations and the development of automated approaches for analysis of very large datasets (Trampert and Woodhouse, 1995; van Heijst and Woodhouse, 1997; Debayle, 1999; Beucler et al., 2003; Lebedev et al., 2005) sharpened the details of the anisotropic structure of the upper mantle (Park and Levin, 2002; Trampert and Woodhouse, 2003; Debayle et al., 2005; Beucler and Montagner, 2006; Panning and Romanowicz, 2006; Lebedev and van der Hilst, 2008; Ekstrom, 2011). Current global tomographic models now resolve anisotropic lateral variations with wavelengths greater than 1000 km, compared to 5000 km in the early eighties.

Despite this tremendous progress, the origin of seismic anisotropy is still debated. Shear-wave splitting (SKS) observations are commonly used to study upper mantle anisotropy, especially beneath continents. SKS-type phases provide lateral resolution of a few tens of kilometers beneath a seismic station. However, they integrate the anisotropy over the whole mantle and have no depth resolution. This lack of vertical resolution has fueled a long debate on the origin of anisotropy beneath continents. Where fossil geological trends are parallel to present-day plate motions, like under South Africa, the same SKS anisotropic directions can either be interpreted as related to present-day plate motions (Vinnik et al., 1995), or as frozen-in within the lithosphere (Silver et al., 2001).

* Corresponding author.
E-mail address: Eric.Debayle@ens-lyon.fr (E. Debayle).

0012-821X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsl.2013.06.025

At global scale, shear-wave splitting (SKS) observations have also either been interpreted as frozen-in lithospheric anisotropy from past deformation processes (Silver and Chan, 1988, 1991), or as asthenospheric anisotropy resulting from present-day shear induced by plate motions (Vinnik et al., 1992).

Surface waves provide global coverage of the upper mantle, and allow to study anisotropy in oceanic areas where few seismic stations are available. They are sensitive to both radial and azimuthal anisotropy. In the range of periods commonly used for upper mantle studies (40–300 s) they constrain the anisotropy with a limited lateral resolution of several hundreds of kilometers, but with a much better vertical resolution of few tens of kilometers. Surface wave and SKS observations are therefore complementary.

Global models of surface wave azimuthal anisotropy display strong correlations of fast axes with plate motions at asthenospheric depths (Debayle et al., 2005; Ekstrom, 2011). This is certainly true under fast oceans (Smith et al., 2004; Maggi et al., 2006) or continents like Australia (Lévêque et al., 1998; Debayle, 1999; Debayle and Kennett, 2000b; Simons et al., 2002) or India (Debayle et al., 2005). This supports the idea that at least part of the anisotropy originates in the asthenosphere and reflects present-day shear induced by plate motions. This interpretation is substantiated by the general agreement between anisotropy and the global mantle flow that can be computed from geodynamic model (Becker et al., 2007; Long and Becker, 2010).

Resolving surface wave anisotropic directions at small scale and with a vertical resolution sufficient to identify frozen-in deformation within the continental lithosphere remains a challenge. In the shallowest 150 km of the Australian lithosphere, the anisotropy seems frozen-in and preserved since the Alice Spring orogeny (Debayle and Kennett, 2000b; Simons et al., 2002). Under South Africa (Adam and Lebedev, 2012) and North America (Marone and Romanowicz, 2007; Yuan and Romanowicz, 2010), a likely frozen-in anisotropy aligned with the surface geological trends is underlaid by the asthenosphere where fast anisotropic directions are coherent with the present-day plate motions. Beneath the Baltic Shield, the deep asthenospheric anisotropy does not appear to be related to the present motion of the craton (Pedersen et al., 2006).

Although a two-layer model for the anisotropy, fossil in the lithosphere and oriented by the flow in the asthenosphere, seems valid under various plates, this may not apply everywhere. First, large-scale plate-motion deformation within the asthenosphere may not be present everywhere (Debayle et al., 2005) and/or may be complicated by small-scale convection in a number of regions (Maggi et al., 2006; Pedersen et al., 2006; Yuan et al., 2011). Second, although lithospheric anisotropy has been compared locally with geological trends in a number of continental areas, there is a lack of quantitative comparison, especially at global scale in oceanic regions.

In this paper, we discuss the anisotropic part of DR2012, our new global SV-wave tomographic model of the upper mantle (Debayle and Ricard, 2012). DR2012 improves upon DKP2005, our previous azimuthal anisotropy model (Debayle et al., 2005), through a larger dataset (expanded by a factor ~ 3.7) and a new scheme that better extracts fundamental and higher-mode information. The dataset, new scheme and inversion procedure are presented in Debayle and Ricard (2012). Here, we study the agreement between fast anisotropic directions and Absolute Plate Motion (APM) or Fossil Accretion Velocity (FAV), which is recorded by the local age gradient in oceanic areas.

2. Data and tomographic inversion

Our dataset consists of $i = 374\,897$ path-average SV-wave depth dependent models (hereafter referred as "$\beta_v^i(z)$" models) obtained by waveform inversion of multimodes Rayleigh wave seismograms (Cara and Lévêque, 1987). The waveform inversion accounts for the fundamental and up to five higher Rayleigh modes in the period range 50–250 s. It has recently been automated by Debayle and Ricard (2012).

A 3D elastic model is obtained by combining the path-average $\beta_v^i(z)$ models in a tomographic inversion. Following Lévêque et al. (1998), we invert directly for the local distribution of shear velocity and azimuthal anisotropy. For each path i with length L_i, the path average slowness $1/\beta_v^i(z)$ can be seen as the integral at each depth z of the local slowness at geographical point (θ, ϕ) and for azimuth ψ, $1/\beta_v(z, \theta, \phi, \psi)$:

$$\frac{1}{\beta_v^i(z)} = \frac{1}{L_i} \int_i \frac{1}{\beta_v(z, \theta, \phi, \psi)} \, ds \tag{1}$$

The azimuthal variation of a long-period SV-wave propagating horizontally with velocity $\beta_v(z, \theta, \phi, \psi)$ can be approximated by:

$$\beta_v(z, \theta, \phi, \psi) = \beta_{v0}(z, \theta, \phi) + A_1(z, \theta, \phi)\cos(2\psi) + A_2(z, \theta, \phi)\sin(2\psi) \tag{2}$$

The inversion is performed at each depth for the isotropic shear velocity $\beta_{v0}(z, \theta, \phi)$ and the anisotropic parameters $A_1(z, \theta, \phi)$ and $A_2(z, \theta, \phi)$. We use a tomographic scheme based on the continuous regionalization formalism of Montagner (1986), extended for the analysis of massive surface wave datasets by Debayle and Sambridge (2004). Data weighting is discussed in Debayle and Ricard (2012). At each depth, we obtain a smooth model by imposing correlations between neighboring points using a Gaussian *a priori* covariance function. This covariance function is defined by a standard deviation σ controlling the amplitude of a component of the model perturbation, and by a horizontal correlation length L, controlling the horizontal smoothness. We use standard deviations of $\sigma = 0.05$ km s^{-1} and $\sigma = 0.005$ km s^{-1} for the isotropic and anisotropic components respectively. Increasing the anisotropic standard deviation by a factor of two produces anisotropy amplitudes that can locally exceed 15%, but does not affect the pattern of anisotropic directions (Fig. A.1). Such large amplitudes predict SKS delay times of up to 8 s that exceed the largest values expected from laboratory experiments or SKS measurements (Mainprice and Silver, 1993). The same horizontal correlation length is used for both isotropic and anisotropic components.

The isotropic part of the model ($\beta_{v0}(z, \theta, \phi)$) is discussed in details in Debayle and Ricard (2012). In the present paper, we focus on the anisotropic components A_1 and A_2. Using a correlation length $L = 400$ km, we obtain the SV-wave azimuthal anisotropy maps of the upper mantle depicted in Fig. 1. Increasing L leads to smoother tomographic images with higher amplitude anomalies, but the overall pattern of anisotropic anomalies remains unchanged (Fig. A.2).

The largest azimuthal anisotropy is observed in the upper 250 km of the mantle (Fig. 1). In this depth range, azimuthal anisotropy is in general perpendicular to the ridge axis, in agreement with previous global surface wave observations (Tanimoto and Anderson, 1984; Montagner and Tanimoto, 1991; Trampert and Woodhouse, 2003; Debayle et al., 2005; Beucler and Montagner, 2006; Becker et al., 2012). Azimuthal anisotropy maps are more complex at shallow depths (the first 100 km in oceanic regions, the first 150 km in continental regions). At 200 km beneath oceanic areas, azimuthal anisotropy organizes in a smooth, large-scale pattern within the asthenosphere. At depths greater

Download English Version:

https://daneshyari.com/en/article/6430109

Download Persian Version:

https://daneshyari.com/article/6430109

Daneshyari.com