Physics of the Earth and Planetary Interiors 245 (2015) 103–116

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

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

Global scale observations of scattered energy near the inner-core boundary: Seismic constraints on the base of the outer-core

J.M.-C. Adam [a,*], B. Romanowicz [a,b,c]

[a] Institut de Physique du Globe, 1 rue Jussieu, 75238 Paris Cedex 05, France
[b] Collège de France, 11 Place Marcelin Berthelot, 75005 Paris, France
[c] Berkeley Seismological Laboratory, 215 McCone Hall # 4760, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 10 February 2015
Received in revised form 4 June 2015
Accepted 4 June 2015
Available online 11 June 2015

Keywords:
PKP scattering
Outer-core
PKPbc
PKPbc-diff

ABSTRACT

We have collected a global dataset of several thousands of high quality records of PKPdf, PKPbc, PKPbc-diff and PKPab phase arrivals in the distance range [149–178°]. Within this collection, we have identified an energy packet that arrives 5–20 s after the PKPbc (or PKPbc-diff) and represents a phase that is not predicted by 1D reference seismic models. We use array analysis techniques to enhance the signal of these scattered phases and show that they originate along the great-circle path in a consistent range of arrival times and narrow range of ray parameters. We therefore refer to this scattered energy the "M" phase. Using the cross-correlation technique to detect and measure the scattered energy arrival times, we compiled a dataset of 1116 records of this M phase. There are no obvious variations with source or station location, nor with the depth of the source. After exploration of possible location for this M phase, we show that its origin is most likely in the vicinity of the inner-core boundary. A tentative model is found that predicts an M-like phase, and produces good fits to its travel times as well as those of the main core phases. In this model, the P velocity profile with depth exhibits an increased gradient from about 400 km to 50 km above the ICB (*i.e.* slightly faster velocities than in AK135 or PREM), and a ~50 km thick lower velocity layer right above the ICB.

1. Introduction

Since its discovery in 1936 by Lehmann (Lehmann, 1936), the inner-core has been the focus of many studies (*e.g.* see recent reviews by Souriau, 2007; Deguen, 2012). The fascination for this small and solid body that is surrounded by the liquid outer-core is due, in particular, to the significant role it may play for the generation and stabilization of the earth's magnetic field.

Seismological studies have shown evidence that the inner-core is anisotropic, with seismic waves traveling faster along the direction of the earth's rotation axis (Morelli et al., 1986; Woodhouse et al., 1986; Creager, 1992; Song and Helmberger, 1992; Bréger et al., 1999). Morelli et al. (1986) suggested that this anisotropy can be explained by cylindrical anisotropy and might be due to preferred orientation of iron crystals. Also, there is evidence for hemispherical variations in anisotropy and isotropic P-velocity, with higher amplitudes of anisotropy and smaller isotropic P-velocities in the western hemisphere than in the eastern hemisphere (Niu and Wen, 2001; Cao and Romanowicz, 2004; Irving and Deuss, 2011; Waszek and Deuss, 2011; Tanaka, 2012). To explain this dichotomy Alboussière et al. (2010) and Monnereau et al. (2010) recently proposed a model of inner-core melting and freezing by permanent eastward translation of the inner-core. This model would both explain the inner-core anisotropy and hemispherical dichotomy. It is however difficult to reconcile with the most recent estimates of thermal conductivity of the core (*e.g.* Pozzo et al., 2012; de Koker et al., 2012).

While the presence of heterogeneities in the inner-core has been accepted for decades, it is usually assumed that the liquid outer-core is homogeneous because of its low viscosity (Stevenson, 1987), which could not sustain density variations large enough to be detected by seismological methods. However, the homogeneity of the outer-core has been debated. At the top of the outer-core, there may be compositional stratification with higher than average concentration of light elements (*e.g.* Fearn et al., 1981; Eaton and Kendall, 2006; Helffrich and Kaneshima, 2010). Likewise, the last 200 km at the base of the outer core exhibit a reduced P-velocity gradient with depth (Souriau and Poupinet, 1991; Song and Helmberger, 1992; Yu and Wen, 2005; Zou et al., 2008). This region, denoted F-layer by K.E. Bullen in the 1940s may be the site of complex dynamics (*e.g.* Gubbins

* Corresponding author.
E-mail address: adam@ipgp.fr (J.M.-C. Adam).

http://dx.doi.org/10.1016/j.pepi.2015.06.005
0031-9201/

et al., 2008). In addition, seismologists have been investigating the seismic detectability of structure in the bulk of the outer-core from P wave tomography (*e.g.* Soldati et al., 2003), and the presence of faster than average P-velocities inside the tangent cylinder to the inner core has been proposed as a possible alternative to inner core anisotropy (Romanowicz and Bréger, 2000; Romanowicz et al., 2003). While this possibility has been questioned (*e.g.* Souriau et al., 2003; Ishii and Dziewonski, 2005; Yu and Wen, 2005), evidence for hemispherical variations of structure at the base of the outer core has also been proposed (*e.g.* Song and Helmberger, 1992; Yu and Wen, 2005; Zou et al., 2008).

Significant scattering has been documented previously in the coda of the PKPbc-diff phase (*e.g.*Nakanishi, 1990; Tanaka, 2005). From the wide distribution of slownesses of PKPbc-diff investigated using array data, Tanaka (2005) suggested that the small slownesses (smaller than 2 s/°) could be explained by the trapping of seismic waves by ICB topography. Other studies have also suggested the presence of significant short wavelength topography at the ICB (*e.g.* Morita, 1987; Cao et al., 2007). On the other hand, Nakanishi (1990) suggested that the PKPbc-diff coda phases with high slownesses (between 2 and 4 s/°) could be scattered PKP phases at the core-mantle boundary (CMB).

To investigate the velocity structure at the base of the outer-core, Zou et al. (2008) measured PKPbc-diff travel-times and amplitudes with respect to PKPdf and modeled synthetic seismograms for a variety of F-layer models. They searched for a model that would best fit their observations. They were able to explain the relative travel-time measurements by introducing a low velocity layer at the base of the outer-core. However, they failed to predict the PKPbc-diff/PKPdf amplitude ratios and proposed that either ICB topography or a layer of high attenuation at the base of the outer-core might be required to fit their measurements. In a recent paper, Souriau (2015) used a large dataset of PKPbc travel-time residuals from seismological bulletins and analyzed the velocity profile at the base of the outer-core. Her results suggest that a heterogeneous patch with P-velocity perturbations up to 0.5% may exist in the eastern hemisphere in the deep outer-core, right above the F-layer. If confirmed, this would show that the base of the outer-core may not be homogeneous and that heterogeneities could be detectable using seismological tools.

In this study, we collect a global dataset of more than a thousand PKPdf, PKPbc, PKPbc-diff and PKPab waveforms. We document the presence of significant scattering in the coda of the PKPbc and PKPbc-diff phases. Scattering in seismic wave codas is usually very complex and expected to be due to short wavelength structure (Vidale and Earle, 2000). However, we easily identify isolated scattered phases that are well above the noise and with waveforms that are comparable to those of PKPdf and PKPbc core phases. We use array analysis techniques to enhance the signal of the scattered phases and consider the possible explanations for these observations. We argue that the scattering must originate near the ICB.

2. Data collection and identification of scatterers

We have collected a high quality dataset of vertical component broad-band records of core phases: PKPdf, PKPbc, PKPbc-diff and PKPab (Fig. 1) at IRIS, Orfeus and F-net data centers corresponding to 435 worldwide earthquakes from January 1998 to November 2013. We only considered events with depth greater than 100 km, to avoid contamination of the core phases with depth phases, and with mb magnitude between 5.1 and 6.8, to avoid source complexity in the waveforms. Event parameters are from the relocated EHB catalog (Engdahl et al., 1998; Bondár and Storchak, 2011), or from the ISC bulletin (International Seismological Centre, 2012) when EHB parameters are not available. Instrument response is removed and high-pass and low-pass filters are applied between the frequencies 0.2–0.7 Hz and 1.5–2.6 Hz, respectively. The cut-off and corner frequencies have been tested and this bandpass filter seems to best highlight the core phases.

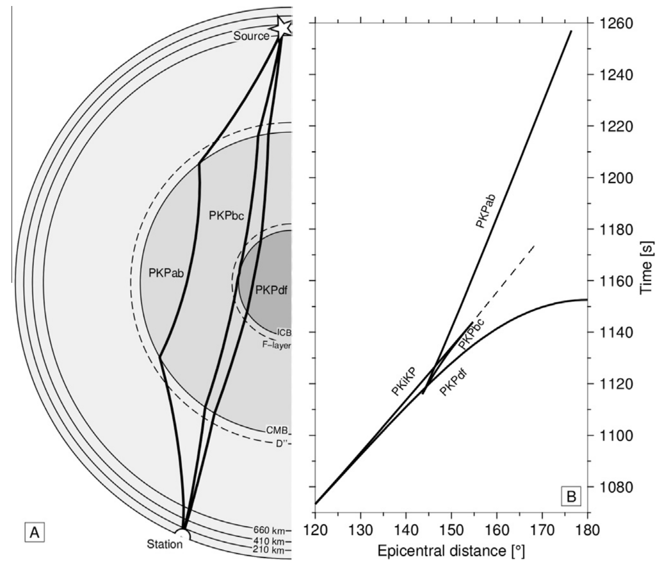

Fig. 1. Raypaths of PKPdf, PKPbc, PKPbc-diff (dashed line) and PKPab for a 500 km depth event at an epicentral distance of 154.7°.

Upon examining the collected waveforms, we identified an energy arrival about 5–20 s after the PKPbc or PKPbc-diff arrivals (Adam and Romanowicz, 2013) that is not predicted by reference 1D Earth models (Fig. 2 and Table 1). In order to further investigate the origin of this energy, we systematically analyzed our dataset for events in the south American and Fiji Islands subduction zones, in the north Pacific area, and for one deep event in Spain. We selected the data for which we detected scattering in the PKPbc (or PKPbc-diff) coda (see Section 4 for more information about the detection of the scattered phases). We mainly focused our study on these subduction zones because of the good geographical distribution of earthquakes and available stations, although the scattered phases are also observed in other regions (Fig. 6).

We note that the scattered energy can be individually isolated in the seismograms (Fig. 2), in contrast to other types of scattered energy, such as precursors to PKPdf which appear as a continuum of energy, best modeled using an envelope-based approach (*e.g* Shearer and Earle, 2008). Also, the amplitude of the scattered phase can sometimes be almost as large as that of the PKPbc and stronger than that of PKIIKP. We call this scattered phase “M”.

3. Array analysis

We used the Phase Weighted Stack (PWS) technique (Schimmel and Paulssen, 1997) on small aperture arrays to enhance the scattered signal and better constrain its arrival time and slowness. We combined this technique with a beamforming analysis in order to detect the direction of arrival of the signal and determine whether the energy propagates along the great-circle path. Stations within each array were chosen such that the epicentral distance and azimuth ranges did not exceed 5° and 10° respectively. This was to avoid wave front distortions due to heterogeneities beneath the stations that would reduce the coherency of the signal. The PWS is computed with a time resolution of 0.05 s, slowness resolution of 0.1s/° and azimuth resolution of 10°.