Physics of the Earth and Planetary Interiors 254 (2016) 12–24

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

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

Imaging the inner core under Africa and Europe

J.C.E. Irving

Department of Geosciences, Princeton University, Princeton, NJ, USA

ARTICLE INFO

Article history:
Received 2 November 2015
Received in revised form 1 March 2016
Accepted 3 March 2016
Available online 14 March 2016

Keywords:
Inner core
Anisotropy
PKPdf
Hemisphere boundary

ABSTRACT

The inner core under Africa is thought to be a region where the nature of inner core texture changes: from the strongly anisotropic 'western' part of the inner core to the weakly anisotropic, or isotropic 'eastern' part of the inner core. Additionally, observations of a difference in isotropic velocity between the two hemispheres have been made. A very large new dataset of simultaneous PKPdf and PKPbc observations, on which differential travel times have been measured, is used to examine the upper 360 km of the inner core under Europe, Africa and the surrounding oceans. Inversion of the differential travel time data for laterally varying inner core anisotropy reveals that inner core anisotropy is stronger under central Africa and the Atlantic Ocean than under the western Indian Ocean. No hemispherical pattern is present in Voigt isotropic velocities, indicating that the variation in anisotropy is due to differing degrees of crystal alignment in the inner core, not material differences. When anisotropy is permitted to change with depth, the upper east-most part of the study region shows weaker anisotropy than the central and western regions. When depth dependence in the inner core is neglected the hemisphere boundary is better represented as a line at 40°E than one at 10°E, however, it is apparent that the variation of anisotropy as a function of depth means that one line of longitude cannot truly separate the more and less anisotropic regions of the inner core. The anisotropy observed in the part of the inner core under Africa which lies in the 'western' hemisphere is much weaker than that under central America, showing that the western hemisphere is not uniformly anisotropic. As the region of low anisotropy spans a significant depth extent, it is likely that heterogeneous heat fluxes in the core, which may cause variations in inner core anisotropy, have persisted for several hundred million years.

1. Introduction

Seismic anisotropy in the inner core causes variation in body wave travel times (Morelli et al., 1986; Shearer and Toy, 1991; Creager, 1992; Song and Helmberger, 1995) and body wave attenuation (Souriau and Romanowicz, 1996; Cormier et al., 1998) as well as normal mode splitting functions (Woodhouse et al., 1986; Tromp, 1993; Ishii et al., 2002a; Beghein and Trampert, 2003) and spectra (Durek and Romanowicz, 1999; Irving et al., 2008). In addition to the presence of inner core anisotropy, a 'hemispherical pattern' has been detected using body wave observations of the inner core, where the 'eastern' and 'western' parts of the inner core have differing isotropic velocities, strength of anisotropy and attenuation (for example Tanaka and Hamaguchi, 1997; Creager, 1999; Garcia, 2002a; Oreshin and Vinnik, 2004; Yu and Wen, 2006b; Sun and Song, 2008; Lythgoe et al., 2014). The presence of hemispherical structure in the inner core has not been supported by all investigations, with the influence of mantle structure on travel time observations (Bréger et al., 1999; Bréger et al., 2000; Ishii et al., 2002b), possible structure in the outer core's tangent cylinder (Romanowicz et al., 2003) and both a complex lower mantle and inner core (Tkalčić, 2010) all having been put forward as alternative causes for the observed travel time anomalies. A second, supporting line of evidence for hemispherical inner core structure comes from Earth's normal mode oscillations. Normal modes are sensitive hemispherical anisotropic structure in the inner core (Irving et al., 2009) and observations of coupled normal modes (Deuss et al., 2010) support the presence of distinct eastern and western hemispheres in the inner core. In the western hemisphere, possibly below an uppermost isotropic layer, the presence of anisotropy causes polar rays, which travel close to parallel to Earth's rotational axis, to experience higher velocities than equatorial rays, which travel close to parallel to Earth's equatorial plane. Conversely below the uppermost isotropic layer the eastern hemisphere continues to be isotropic (e.g. Tanaka and Hamaguchi, 1997; Garcia and Souriau, 2000) or displays only weak seismic anisotropy (for example Creager (1999) and Leykam et al. (2010)).

Despite the growing consensus that anisotropy in the inner core is laterally varying, the nature of the transition region between two

E-mail address: jirving@princeton.edu

http://dx.doi.org/10.1016/j.pepi.2016.03.001

hemispheres is poorly understood. A sharp boundary between two regions with different isotropic velocities was imaged by Waszek et al. (2011), which is not easy to reconcile with some models of inner core dynamics and mineral physics (Geballe et al., 2013). The inner core under Africa is likely to host one of the two boundary region between the two hemispheres. Hemisphere boundaries are normally modeled as a line of constant longitude, though there is some evidence that approximation is too simplistic, at least for the boundary under the Pacific Ocean (Miller et al., 2013; Irving and Deuss, 2015).

A range of locations have been proposed for the boundary between the two hemispheres under Africa (Fig. 1) using observations of several different core-sensitive seismic phases (Fig. 2). Tanaka and Hamaguchi (1997), in the first study of the hemispherical pattern of the inner core, defined the boundaries after expanding the differential travel time residuals of equatorial paths using spherical harmonics. Creager (1999) inspected PKPbc–PKPdf and PKPab-PKPdf differential travel time residuals and found hemisphere boundaries which separated small and large traveltime anomalies for polar paths.

Best-fitting boundaries were located by Irving and Deuss (2011) by systematically seeking the boundary locations which gave the lowest residual error when fitting independent eastern and western hemisphere anisotropy curves to a global dataset of PKPbc–PKPdf and PKPab–PKPdf differential travel times. In a similar way, Lythgoe et al. (2014) used data from absolute PKPdf travel times to find the hemisphere boundary location. As that study contained many rays turning within 550 km of the center of the inner core in addition to rays turning higher in the inner core, their location should be regarded as an average across the entire inner core radius. Modeling the inner core as an anisotropic central body overlain by an isotropic layer of varying thickness, Garcia and Souriau (2000) used absolute PKPdf and PKPbc–PKPdf differential travel times to find the edges of a deeper isotropic region in the inner core. In the resulting eastern hemisphere, an isotropic layer may extend up to 400 km below the inner core boundary (ICB). Miller et al. (2013) selected a preferred boundary location on the basis of forward modeling of equatorial PKPbc–PKPdf seismic data.

A number of other studies have used alternative phases or techniques to seek the hemisphere boundary locations. Several studies used the seismic phase pair of PKPdf and PKiKP to locate the boundary (Niu and Wen, 2001; Wen and Niu, 2002; Garcia, 2002a). The same phase pair has also been used to find independent hemisphere boundaries for three different depth layers in the upper 106 km of the inner core (Waszek and Deuss, 2011).

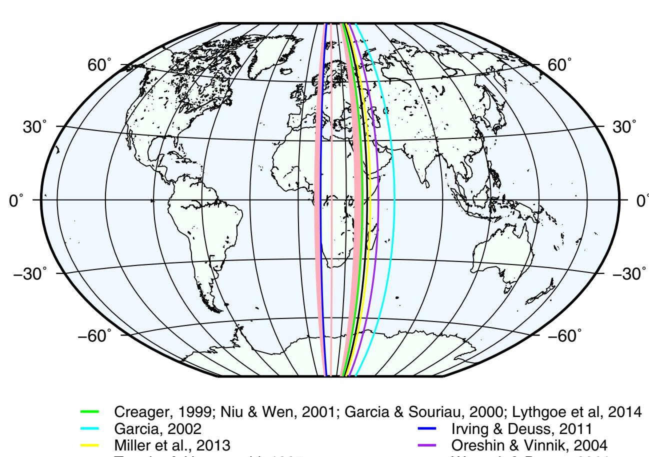

Fig. 1. Locations proposed for the boundary between the 'western' (left) and 'eastern' (right) hemispheres under Africa.

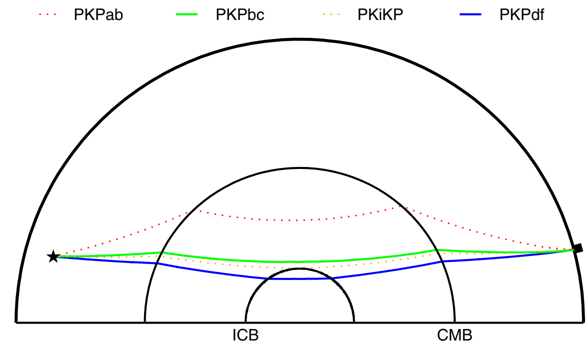

Fig. 2. Raypaths for phases PKPdf and PKPbc (solid lines), which are used in this study, as well as PKiKP and PKPab (dotted lines). Paths are shown those generated by an earthquake at depth of 600 km (black star) traveling to a seismometer at an epicentral distance of 150° (black box).

The hemisphere boundary locations shift eastwards as a function of depth over this relatively small depth range. Differences in the degree of attenuation of PKPdf between the two hemispheres was investigated by Oreshin and Vinnik (2004), who sampled the inner core to a depth of 850 km below the ICB. They found that attenuation in the western hemisphere is anisotropic but isotropic in the eastern hemisphere. As with Lythgoe et al. (2014) the large range of inner core turning depths mean that this boundary should be treated as an average over the upper two thirds of the inner core's radius.

It is likely then, based on multiple studies, that one of the two inner core hemisphere boundaries is located somewhere under Africa, with the modal reported location at 40°E. Some depth variation of the hemisphere boundary is possible, whether it is a true shift in boundary location (Waszek et al., 2011), a change in isotropic layer thickness (e.g. Garcia and Souriau, 2000) or a step-shaped velocity anomaly for equatorial paths (Miller et al., 2013). The inner core translation models of Alboussiere et al. (2010) and Monnereau et al. (2010) would suggest a smooth change in isotropic velocity between the two hemispheres, though the implications of those models for inner core anisotropy are more difficult to predict. Here, a very large new dataset is used to image the isotropic and anisotropic velocity structure under this region to better understand the properties of the inner core close to the transition between the two hemispheres.

2. Data and methods

2.1. Data

PKPbc–PKPdf differential travel times are used to investigate velocity variations in the inner core. PKPdf is a compressional body wave which travels from an earthquake, through the mantle, outer core and inner core. PKPbc takes a similar path, but reaches its deepest point in the outer core (Fig. 2) and arrives several seconds after PKPdf. Using PKPbc–PKPdf differential travel times negates much of the effect of upper mantle structure and earthquake mis-location as PKPdf and PKPbc travel through very similar paths in the shallow Earth, are generated by the same source and recorded at the same station.

Seismograms recorded after selected earthquakes between the beginning of January 1998 to the end of February 2015 were collected from the IRIS DMC (Incorporated Research Institutions for Seismology Data Management Center); for some events these were supplemented by data from the ODC (Observatories and Research Facilities for European Seismology Data Center). The inner core under Africa and surrounding areas is the target of this study. Thus,