Dissimilarity of the Earth's inner core surface under South America and Southeastern Asia revealed by core reflected phases

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Abstract

Resolving topography of the inner core boundary (ICB) and the structure and composition of the nearby region is key to improving our understanding of solidification of the Earth’s inner core (IC). Observations of travel times and amplitudes of short-period seismic phases of PKiKP and PcP reflected, respectively, off the inner and outer boundary of the liquid core, provide essential constraints on the properties of this region. In recent decades, for the whole IC surface there have been published just several hundred high-quality joint PKiKP/PcP observations mostly in the distance range 15 to 60 degrees and only a handful below 10 degrees. We revisit heterogeneities of ICB using a total of more than 1300 new differential travel times and amplitude ratios of PKiKP and PcP measured at 3.2 – 35.2 degrees and reflected off the core’s boundaries under Southeastern Asia and South America. We observe a statistically significant systematic bias between the measurements collected in western and eastern hemispheres. We carefully examine its origin in terms of contributions by various Earth’s shells and find that most of variance in PKiKP-PcP differential travel times measured above the epicentral distance of 16 degrees can be accounted for by mantle corrections evaluated with respect to LLNL-Earth3D model. We find the liquid western hemisphere can be 1–3 km thicker than the liquid eastern, and the ICB density jump under Southeastern Asia is about 0.3 g/cm$^3$, which is three times as small as under South America. The findings are interpretable either as evidence for IC hemispherical asymmetry whereby crystallization dominates in the West and melting in the East (not vice versa), or in terms of two disconnected mosaic patches with contrasting properties.

1. Introduction

It is widely accepted that the Earth’s crystalline iron inner core (IC) has formed by gradual freezing and accretion, and its nature is determined by processes in the transition from liquid to solid core. At the Earth’s radii of about 1220 km, the temperature falls below the
solidus of the Fe-Ni alloy of the outer core (OC) and IC freezes (Jacobs, 1953). The up-to-date description of this outward crystallisation is way far from complete and admits a number of scenarios including formation of slurry, dendritic and non-dendritic morphologies etc (Loper and Roberts, 1978; Fearn et al., 1981; Tian and Wen, 2017). It was shown that interfacial heat flux at either boundary of the OC has a significant effect on solidification regime and IC texture formation, so the cooling rate during phase transition is not uniform throughout the inner core boundary (ICB) and may give rise to multi-scale heterogeneities (Aubert et al., 2008; Gubbins et al., 2011). From daylight surface, such heterogeneities may look like compositional and thermal mosaic of the IC exterior (Krasnoshchekov et al., 2005) and even dissimilar hemispheres (Aubert et al., 2008; Aloussier et al., 2010; Monnereau et al., 2010). Were pressure and temperature in the transition not about 350 GPa and 6000 K, respectively, constraining physical parameters and spatial heterogeneities in the top of the IC would be a metallurgic task replicable in normal practice. Experiments with Diamond Anvil Cells and Laser Heating are about to allow in situ observations of processes under ultrahigh temperature and pressure at small scales (Tateno et al., 2010), but seismic probing of the ICB is still the most reliable source of experimental data on its properties.

Most of seismological constraints on ICB structure and parameters have been obtained using body waves reflected from it (the seismic phase of PKiKP) and the Earth’s free oscillation eigen-frequencies. The approaches invoke, respectively, the body waves with periods of about 1 s and the standing waves two to four orders of magnitude as long. Certain peaks of the Earth’s normal mode spectrum after a large earthquake can be inverted for radial distribution of density or seismic velocity in the core, but cannot be used to constrain fine-scale and regional lateral heterogeneities like IC texture or surface mosaic. For instance, an integrated estimate of the ICB density jump (about 0.6 g/cm³) by normal modes is currently accepted by standard Earth models (Dziewonski and Anderson, 1981; Kennett et al., 1995).

Studies of ICB and its vicinity by short-period PKiKP waves normally involve a reference seismic phase whose path (in an ideal case) coincides with the one of PKiKP in crust and mantle. Differential travel times and amplitudes of PKiKP and the reference phase measured on a record of one and the same event are less contaminated with out-of-core effects and, consequently, yield insights into the ICB structure. PKiKP waveforms are routinely observed in the group of first arrivals beyond the epicentral distance of about ~110° where they are post-critical. The relevant studies usually use the shallow IC refracted phase of PKIKP as a reference. They find regional and local variation in seismic velocity and attenuation in the top of
the IC (e.g. (Godwin et al., 2018)), but their interpretation can be conflicting like, for example, a highly controversial (Aubert et al., 2008) feature of hemispherical difference in the IC freezing rate. It was initially suggested on the base of PKiKP–PKIKP differential measurements (Monnereau et al., 2010), and then questioned (Ivan et al., 2018) on the base of analysis of an enhanced dataset that provided somewhat better core coverage.

Yet the pre-critical PKiKP waveforms seem to be the best tool to map fine-scale and regional heterogeneities at ICB, where the seismic phase of PcP reflected off the core-mantle boundary (CMB) is used as a reference. Technically, the pair of PKiKP and PcP yields adequate resolution, and close proximity of their crust and mantle paths cancels the influence of heterogeneities localized outside the Earth’s core (especially in narrow-angle reflections). It is these waveforms that produce the main evidence that the IC surface is mosaic (Krasnoshchekov et al., 2005) or rough (deSilva et al., 2018), and enable localized estimates of the ICB density jump (Boltand Qamar, 1970). However, the results of studies of pre-critical PKiKP waveforms sometimes may not match the outputs from normal modes or teleseismic PKiKP. For instance, their ICB density jump estimates are usually larger (up to 1.8 g/cm³), and hemispherical pattern in ICB properties is not confirmed (Waszek and Deuss, 2015) by pre-critical reflections.

Part of the discrepancies can be attributed to severe lack of differential measurements of steeply reflected PKiKP and PcP. Detection of these waveforms is tricky because they are subtle and always hidden in seismic coda formed by intensive reverberations in crust and mantle. In practice, PKiKP–PcP differential measurements are usually too few in number, yield sparse sampling, and exhibit large differences over small lateral length scales. On average, the observed PKiKP/PcP amplitude ratios should scatter around the ‘true’ amplitude ratio, and the best way to resolve concerns as to usability (Buchbinder et al., 1973) and uncertainties (Tkalčić et al., 2009) of such data and related estimates is to increase the number of measurements. This, however, may be difficult because the chief factor governing observability of steeply reflected PKiKP and PcP waveforms on daylight surface hasn’t been established yet, despite efforts to examine various effects of seismic source, CMB (Tkalčić et al., 2010) and ICB (Krasnoshchekov et al., 2005). Over the years, for the whole IC surface there have been published just few hundred high-quality joint PKiKP/PcP observations mostly in the distance range 15°–60° and only about a dozen measurements below 10°. Statistically, such datasets may be prone to misinterpretation, because even if both PKiKP and PcP are observable in 100% of cases, some data still can be rejected due to randomness, wherein the rejected data percentage depends on the chosen significance level.
From pure statistical point of view, poor sampling by pre-critical PKiKP and PcP waveforms may undermine the relevant interpretations, especially if considered in terms of replication of such studies and reproducibility of their results. Repeating such studies by using the same procedures but with a different sample can be difficult and may fail to reproduce the original findings not because of changeable nature of the object of interest, but due to non-availability of more PKiKP or PcP waveforms. In this context, the answer to the question whether the findings can be generalised to the population (i.e. whether the interpretation reflects the studied specifics at the ICB or any its patch) rather than applying only to the specific sample can be ambiguous. In general, this reflects the common concern that small sample sizes mitigate the use of inferential statistics and decrease the generalization power of the findings. Thus, in the problem of sampling the ICB with PKiKP, where the coverage and number of samples are extremely limited, enhancing the dataset is of chief importance to improve the level of accuracy and confidence in the observations. Here we revisit heterogeneities of ICB using the newly presented (Krasnoshchekov and Ovtchinnikov, 2018) database of a total of more than 1300 new differential travel times and amplitude ratios of PKiKP and PcP measured at 3.2°–35.2° and reflected off two spots in the western and eastern hemispheres of the Earth’s core.

2. Data and methods

2.1 Raw data and measurements of PKiKP and PcP waveforms

The analysed database includes records of broadband and short-period digital seismic channels of temporal and permanent arrays installed in South America and Eastern Asia. Steeply reflected core phases are less reliably detected in non-array data because a pulse from a random process may be interpreted as a PKiKP waveform around its expected arrival time in the record of standalone three-component station. In order to prevent false PKiKP and PcP waveform interpretation, here we analyse only records of arrays or networks where the sought arrivals can be simultaneously observed and tracked within the relevant aperture. The list of earthquakes and arrays with references to parameters of seismic channels is given in Table 1.

The used broadband and short-period seismometers have a common feature of flat velocity response at frequencies higher than 1 Hz (see details for each network online by the relevant DOI given in Table 1). To uniform the analysed dataset and increase signal-to-noise ratio of PKiKP and PcP waveforms, vertical components (with record mean and instrument response removed) were bandpass frequency filtered between 1.1 and 7 Hz. The filtering took out the intensive crust and mantle reverberations and accentuated the detected pulse-shaped
waveforms of PcP and PKiKP on vertical components. The revealed PKiKP and PcP waveforms look much alike, exhibit low slowness predicted by standard Earth models, and build a characteristic reflected phases’ hyperbolic travel time curve observable across the aperture of the array or network (Fig. 1). After filtering, both PKiKP and PcP waveforms may dominate on the time interval tens of seconds long around the predicted arrival time and exhibit signal-to-noise ratios well above 2.5, which makes their picking straightforward and well defined (either by cross-correlation or manually). Absolute travel times and amplitudes of pre-critical PKiKP and PcP are highly variable due to crust and mantle heterogeneities, but their influence can be mitigated by using PKiKP–PcP differential measurements.

We measured PKiKP/PcP peak-to-peak amplitude ratio and the respective PKiKP waveform time delay relative to PcP. To exclude outliers in measurements, before picking, we visually inspected the obtained stacks of filtered vertical seismograms and rejected all faulty or glitchy traces. Picking was performed automatically in Seismic Analysis Code (Goldstein et al., 2003) by cross-correlation of PKiKP and PcP waveforms. About 10% of measured peak-to-peak amplitudes and PKiKP-PcP differential travel times were then manually re-measured to check for possible bias between the automatic and manual measurements. No discrepancy was found.

2.2 Reconstruction of non-uniformly sampled curves

Previous studies of experimental differential characteristics of PKiKP and PcP waveforms (e.g. Buchbinder et al., 1973; Tkalčić et al., 2009) repeatedly stress tremendous scatter of such measurements (especially PKiKP/PcP amplitude ratios). The scatter is usually not confined to theoretical curves on the base of reasonable physical parameters of ICB and CMB, and persists almost all through the range of pre-critical reflection. Practical measurements are usually not abundant and available only at a limited set of epicentral distances. The large scatter makes interpreters average the data, which results in just a few measurements with wide confidence intervals. Thus robust reconstruction of distance dependence can be statistically not reliable. Our dataset features the total of 1338 differential measurements of PKiKP and PcP in two compact groups. This number and density of sampling datapoints allow us to make use of advanced methods for curve reconstruction from a point cloud and get robust dependencies of differential time and amplitude measurements on, for example, distance.

α-shape (Edelsbrunner et al., 1983) is a classical computational geometry tool for restoring the curve out of a point cloud. Its generalization to k-order α-shape was shown to be extremely effective for datasets featuring samples with outstanding error, extreme values, noise
or even non-relevant data (Krasnoshchekov and Polishchuk, 2014). Here we apply k-order α-shape in conformity with the algorithm (Nikkilä et al., 2014) developed for processing seismic data. We use its flexibility in selection of quality measure, and in absence of noise do not split data into training and validation sets. Specifically, we estimate successive alpha-shapes of growing order k until the output shape’s standard deviation is on the order of magnitude of the modelled residuals.

2.3 Theoretical estimates of PKiKP and PcP differentials

The differential travel time of PKiKP-PcP is the most sensitive tool to study the geometrical configuration consisting of two reflecting boundaries of ICB and CMB and the liquid OC between them. Trade-offs between contribution of each element of the configuration into the measured differential travel time make it difficult to discern actual parameters of CMB, OC or ICB. Yet in general, the PKiKP–PcP differential travel time residual with respect to a standard axial Earth model \((t_{PKiKP} - t_{PcP})_{\text{measured}} - (t_{PKiKP} - t_{PcP})_{\text{model}}\) directly constrains the OC thickness (unless being interpreted in terms of complex velocity variations). Once the effects of out-of-core heterogeneities are taken into account (e.g. by using 3-D tomographic model of the Earth), it is OC thickness or differential topography between the ICB and CMB that lies behind the residuals. Shen et al. (2016) have diligently considered accruements of PKiKP-PcP differential travel time along the PcP and PKiKP raypaths under various scenarios and found that ‘a 1-s residual corresponds to a 4–5 km thickness variation between ICB and CMB’. Here we do not speculate about possible effects of ICB topography and/or other structural and velocity heterogeneities of the specific geometrical configuration of the Earth’s core below Asia and South America, but use estimate by Shen et al. (2016) to robustly establish the OC thickness undulation at the two spots of the Earth’s core in the western and eastern hemispheres.

To model PKiKP/PcP amplitude ratios we used the method (Bolt and Qamar, 1970) that requires calculation of the upper side reflection coefficients at CMB and ICB, P-wave transmission coefficient at CMB, the geometrical spreading factor for PKiKP and PcP, and the standard quality factor of 10000 for evaluation of PKiKP attenuation in the liquid core (Cormier and Richards, 1976). The effect of attenuation factor in the Earth’s mantle is neglected because narrow-angle PKiKP and PcP raypaths almost coincide. The PKiKP/PcP amplitude ratio arises in the joint system of equations resulting from application of boundary conditions (zero tangential stress and continuity of normal displacement and normal stress) at CMB and ICB. The three triads can then be solved simultaneously for the ratio, if the unknown shear velocity in the top of
the IC and the ICB density jump are fixed. Tkalčić et al (2009) provide detailed formalism of the method as well as analysis of numerous sources of biases and potential trade-offs in PKiKP/PcP amplitude ratio estimate. Almost all previous studies of measured PKiKP/PcP amplitude ratios tend towards giving interpretation in terms of ICB density jump, although the resulting constraints can be cast in terms of, say, body wave velocity too. In order to collate our outputs with previously published results, we interpret the amplitude data in terms of ICB density jump. The relevant velocity constraints can be easily secured on the base of universal relations and specific conditions in the Earth’s core.

Before interpreting, we also compared the obtained purely algebraic theoretical estimates of PKiKP/PcP amplitude ratios with measurements performed on numerical synthetic PKiKP and PcP waveforms evaluated by Direct Solution Method (Kawai et al., 2006) (Fig. 1). Comparison of analytical and numerical ratio estimates yields two-fold effect. First, it makes certain there is no interference with other seismic phases. Second, it enables us to reveal and reject cases where the influence of focal depth and mechanism, as well as configuration of the relevant propagation path is essential.

3. Results
3.1 Detection and coverage

The reflection points of the analysed dataset provide good sampling of two IC spots of about 125 x 240 km² under Bolivia and to the southeast of Sakhalin Island (Fig. 2). Each spot is probed by hundreds of ray traces with incident angles from 2° to 20°, which is unprecedented and enables statistically significant and robust estimates. In general, observability of pre-critical PKiKP and PcP phases can be associated with favourable seismic energy radiation pattern at source and focusing along the propagation paths. Indeed, all four focal mechanisms of the analysed events including the one in Okhotsk Sea feature domination of vertical forces and faulting. The PKiKP and PcP incidence angles in such mechanisms are not far from maxima in the P-wave radiation pattern, which encourages observation of PKiKP and PcP waveforms. On the other hand, 300 km away to the North, 9 hours before the analysed event in Okhotsk Sea, there had occurred an M7.3 earthquake with essentially similar focal depth and mechanism, but no PKiKP or PcP waveforms were observed in its records by the same set of stations. As a matter of fact, PKiKP and PcP from these two nearby consecutive events propagate in the same geological settings through the Earth’s shells, but are distinct after the analysed second one, and not observable in the records of the first one in the whole distance range of 3°–35°. This
obviously questions significant influence of focusing on PKiKP and PcP ray paths assumed, for example, by Waszek and Deuss (2015), and suggests a closer look into the sources’ mechanism favoured by Cao and Romanowicz (2004).

To estimate radiation from given seismic source, we use the radiation pattern formulae of Ou (2008) for shear-tensile source model (STSM) and global CMT catalogue (Dziewonski et al., 1981; Ekström et al., 2012). Selection of source solution does not significantly influence the conclusions, since decompositions of seismic moment tensor by independent agencies for the analysed strong events are essentially similar. Evaluation of correction coefficient for given takeoff angle and azimuth requires specifying the strike, dip, and slip rake along the fault plane, as well as two additional parameters — tensile angle and Poisson ratio. The tensile angle is measured between the vector along the slip direction projected on the fault plane and the actual direction of the fault movement. For simplicity, we set the tensile angle to zero to reduce the radiation from the STSM to the classical shear source, but essentially similar results can be obtained within the full STSM (with non-zero tensile angle in a wide range of values of Poisson ratio). P and S radiation patterns can then be used to assess the energy flux at a station and radiated energy partitioning — \( E_S/E_P \) ratio between the radiated energy in the S and P waves (Boore and Boatwright, 1984; Boatwright and Fletcher, 1984).

Figure 3 presents P and S radiation patterns along with PKiKP and PcP details for earthquakes from Table 1 and the above mentioned event under Okhotsk Sea after which either phase was not observed. It is clearly seen that the PKiKP and PcP take-off angles in the four analysed events are way far from nodes and close to maximum in P-wave radiation pattern. The PKiKP and PcP take-off angles differ by just a few degrees and the relevant directivity effects are about two orders of magnitude as small as the reflection coefficient. This confirms an earlier conclusion (see, e.g. (Koper and Dombrovskaya, 2005; Tkalčić et al., 2009)) that accounting for source effects when evaluating distance dependence of narrow-angle PKiKP/PcP amplitude ratio is unnecessary.

Comparison of source mechanisms of two consecutive nearby events in Okhotsk Sea (four lower diagrams in Figure 3) yields not so trivial results. These two events obviously exhibit essentially similar downward oriented radiation pattern favourable for observation of PKiKP and PcP phases, but different relative intensity of S-waves. As evidenced in Figure 3 by P and S energy radiation patterns, the earlier, stronger main event features large \( E_S/E_P \) ratio characteristic for shear sources in a Poissonean solid. The aftershock with its low \( E_S/E_P \) ratio can be interpreted as tensile fracture or shear fracture combined with significant tensile component enriching the P
radiation (e.g., Vavryčuk, 2001; Ou, 2008). This can be one of the reasons for observing core reflected phases after the aftershock, and absence of PKiKP and PcP waveforms in the records of the main event. This suggestion is indirectly confirmed by the fact that PKiKP waveforms are frequently observed after powerful underground nuclear explosions known for their isotropic radiation pattern and low intensity of S-waves (Krasnoshchekov et al., 2005). Furthermore, Castro and Ben-Zion (2013) find enhanced high-frequency P-wave radiation from aftershocks of $M_w 7.2$ earthquake that may reflect isotropic radiation generated by rock damage in the source region. Interestingly, in CMT inversions the diagonal elements of the moment tensor are constrained to be equal zero (i.e. $M_{rr} + M_{00} + M_{q0} = 0$) (Ekström et al., 2012). It corresponds to the assumption that the moment tensor has no volumetric component, but in case of an event with focal depth of about 600 km, mechanics of the seismic source is strongly affected by chemical phase transitions taking place at the relevant depth. More detailed study of seismic sources as well as possible frequency dependence of ICB reflection coefficient (Tanaka and Tkalčič., 2015) is obviously beyond the scope of this paper, but we can summarise that in addition to favourable geometry with respect to the maximum in P-wave radiation pattern, successful observations of steeply reflected PKiKP and PcP waveforms can be bound to favourable $E_p/E_r$ ratio of the analysed seismic source.

3.2 Differential travel times

We find that residuals measured in the eastern hemisphere are by 0.72 s below the ones in the West. Concretely, the mean PKiKP–PcP differential travel time residuals calculated with respect to ak135 (Kennett et al., 1995) and PREM (Dziewonski et al., 1981) over 1016 Japanese records were, respectively, $-1.79$ s and $-0.41$ s with s.d. of $0.51$; same estimates for the western hemisphere made $-1.07 \pm 0.45$ s and $0.31 \pm 0.45$ s. The unequal variances t-test of the eastern and western subsets rejects the hypothesis that the two populations have equal means ($p < 2e-69$ for significance level of 0.05), which indicates the dataset subdivision into the western and eastern fragments is statistically justified.

Using the estimate from (Shen et al., 2016) we may deduce the OC under the Americas is about 3 km thicker than under Southeastern Asia. However, this estimate of OC thickness variability is rather a rough upper bound subject to allowance for ellipticity and possible influence of strongly heterogeneous lower mantle. While elliptic corrections are almost one order of magnitude smaller than the observed 0.7 s, mantle corrections can be quite large and variable depending on the model used. Here we address the up-to-date 3-D high-resolution P-wave
tomographic model (Simmons et al., 2012) of LLNL-Earth3D that takes into account Earth’s ellipticity, undulating discontinuity surfaces and heterogeneities in mantle and crust and, what’s more important, produces a physically credible result. Specifically, qualitative analysis predicts that crust and mantle heterogeneities have essentially similar influence on almost vertically propagated PKiKP and PcP (e.g. at the epicentral distance of 3.2°, where the respective Fresnel zones are larger than separation between the PcP and PKiKP pierce/reflection points), but act differently a little farther, where PKiKP and PcP paths start to diverge in lower mantle. It is this pattern that we observe in Figure 4. It plots measured and modelled residuals overlaid by the $\alpha$-shape reconstruction curve conveying dependence of the measured residuals on epicentral distance. Above the epicentral distance of 16.5°, the measured residuals didactically follow the behaviour predicted by LLNL-Earth3D model and therefore mostly contain information on heterogeneities outside the Earth’s core. Thus, to decrease data contamination with non-core effects, we examined the statistics on residuals obtained only under 16.5° (data in the remainder of this paragraph are given with respect to PREM, because it has the IC radius of 1221.5 km, equal to that of LLNL-Earth3D). In this way, the mean of residuals calculated over 330 reflections in the East and 181 in the West were $-0.45 \pm 0.55$ s and $0.27 \pm 0.44$ s, accordingly, while the relevant modelled residuals made $-0.27 \pm 0.07$ s and $0.12 \pm 0.10$ s. These averages indicate that up to a half of the systematic bias between PKiKP–PcP differential travel time residuals measured in eastern and western hemispheres can be accounted for by out-of-core structures; still the rest of the bias is induced by the Earth’s core, statistically significant and equivalent to hemispherical disparity in OC thickness of about 1–3 km. Interestingly, Tian and Wen (2017) studied ICB fine structure by PKiKP wave train modelling at epicentral distances way beyond 16.5°; in this connection we wonder whether the obtained results might have been affected by out-of-core structures.

### 3.3 Differential amplitudes

To interpret measured PKiKP/PcP amplitude ratios, we calculated their predicted values with respect to modified ak135 and PREM models. The first pool of theoretical amplitude curves was calculated for the fixed CMB density jump of about 4.4 g/cm³ (as is in ak135) and various ICB density jumps between 0.3 and 1.8 g/cm³. In the second pool of curves we fix the ICB density jump at the ak135 and PREM level of about 0.6 g/cm³ and vary the CMB density jump. The theoretical curves built for various density jump models are given in Figures 5 and 6. As seen from the figures, the curves are not far apart (especially beyond 15°), which, in presence of
large scatter of measured PKiKP/PcP amplitude ratios, makes it difficult to interpret the data by fitting the model dependencies. However, as argued above, it’s reasonable to consider only data under 16.5°, since above this limit the ratios may suffer from influence of heterogeneities outside the Earth's core. It is important to note that the observed pattern of the curves’ constant decay with epicentral distance does not change, even if we account for other factors whose aggregate contribution is about an order of magnitude as small. Also, except for insignificant bias of 0.01 – 0.02, no other difference in the shape of theoretical amplitude ratio curve built for ak135 and PREM is expected, whereas ak135 estimates is in excess of PREM (Tkalčić et al., 2009).

The observed PKiKP/PcP amplitude ratios are largely scattered, but as in the case with differential travel times, the eastern and western datapoints mostly fall apart, which can be seen even at a glance on Figure 5. The unequal variances t-tests yield extremely low p-values below 0.0001 for the standard significance level of 0.05, wherein the eastern and western samples can be formed either from 1° binned or the whole dataset. In fact, the eastern and western measurements up to epicentral distances of about 16° are consistently divided by a gap roughly equivalent to 0.6 g/cm³ counted in ICB or CMB density jump units. This bias interpretable either in terms of ICB or CMB density contrasts is illustrated by the relevant α-shape reconstruction curves plotted in Figure 6. Just for information Figure 6 also shows the conventional polygon curves built on the base of binned averages analysed in (Krasnoshchekov and Ovtchinnikov, 2018). Unlike polygon curves, k-order α-shapes provide much smaller uncertainty of about 5% (Nikkilä et al., 2014) and more information on shape variation of the restored PKiKP/PcP distance dependence which can be interpreted in terms of structural elements of the Earth’s shells.

4 Discussion

In this section we discuss whether the observed pattern of PKiKP/PcP amplitudes in eastern and western hemispheres is to be attributed to ICB or somewhere else above, or even a combination of both. We start with analysing the observed PKiKP/PcP amplitude ratio curves in the context of notorious trade-off between variation of acoustic impedance contrast at ICB and CMB, and the resulting ICB density jump estimate (Tkalčić et al., 2009; Koper and Pyle, 2004). Then an option of the OC bottom with its increased or decreased density (F-layer) is considered. Finally, we collate various ICB density jump estimates with due consideration of uncertainties caused by data selection.
4.1 Multifactorial dependence and trade-off

Here we address only steep reflections (between 3° and 16.5°) for which mantle heterogeneities affect both PcP and PKiKP. For example, it is unlikely for a hypothesized common structure in D’’ to be invisible for PKiKP while yielding abnormal PcP throughout the observation profile. The largest mantle heterogeneities are now included in up-to-date 3-D Earth models that are quite detailed and effective in identifying possible sources of the observed biases.

Previous studies aimed at fitting a set of independent PKiKP/PcP amplitude ratios measured at a three-component station or averaged over a small-aperture array. The ratios usually sampled detached spots at the IC surface and thus could be accounted for by independent models envisaging contrasting properties at ICB and/or CMB. Here we are to select a structure that enables effective modelling of the observed shape of continuous dependence of PKiKP/PcP amplitude ratio on the epicentral distance within the analysed range from 3° to 16.5°.

In terms of shape analysis, the restored curves of the eastern and western datasets are almost identical (quasi-parallel in Figure 6). Specifically, the reconstructed shapes conform to the decay gradients predicted by the first pool of theoretical curves (lower panel of Figure 6). They are calculated for the CMB density jump as in ak135, and the ICB density jumps set to 0.3 and 0.9 g/cm³ for the eastern and western subsets, respectively. Less perfect match is observed in the second pool, where the eastern amplitude ratio curve crosses three out of five modelled dependencies. We may nevertheless try to interpret the behaviour of experimental data curves in terms of CMB density jump fluctuation only. Following Figure 6, we would suggest fast and strong lateral variation in CMB density contrast below Japan (between 5 and 4.5 g/cm³ or about 10%) and almost constant value of about 4.2 - 4.3 g/cm³ under South America. However, such variations can be controversial in geodynamical context because the sampled mantle sides of CMB feature essentially similar material properties specific to regions outside the Pacific large low-shear-velocity province (Li et al., 2017). In fact, current mantle models envisage neither strong difference between the analysed eastern and western spots, nor fast variation within each. For instance, Ritsema et al. (2011) show almost equal shear velocities for the analysed spots and limit max amount of variation in either of them to about 1% (Fig. 7). Strong and fast density variations on the core side of CMB are hardly possible too (Stevenson, 1987), as well as no evidence for hemisphericity of low-velocity layer in the top of the OC has been presented yet (Garnero et al., 1993; Brodholt and Badro, 2017). Still, the detailed 3-D density variation in D’’ has yet to be mapped, and thus strongly variable CMB density jump cannot be entirely ruled out,
but rather be viewed as one of few factors or an add-on in the complex inter-shell model causing the observed hemispherical bias.

Essentially similar considerations are valid for interpretations of CMB/ICB trade-off in terms of velocity. If we appeal to CMB variation only, we should suggest strong lateral changes in velocity contrast between about 4.8 and 5.5 km/s under Southeastern Asia and almost constant velocity jump of about 5.75 km/s in South America (Fig. 8). However, such pattern is not supported by global P-wave models including *LLNL-Earth3D* that, as shown above, secures good prediction of measured PKiKP-PcP differential travel times. For both spots they suggest (Fig. 9) almost equal P-wave velocities few tenths of percent below the ones in standard models. The latter envisage the negative velocity jump from mantle to core of about 5.65 km/s in absolute value. To account for experimental PKiKP/PcP amplitude curves, it is necessary to call for much stronger variability in velocity. For instance, Tkalčić et al., (2010) considered a model with 10% variation of P velocity near CMB combined with lateral variation in either viscoelastic or scattering attenuation in the lowest 150 km of mantle. The theoretical amplitude dependence corresponding to such a model roughly coincides with the curve calculated for the CMB velocity jump of 5 km/s (Fig. 8). It can be characteristic for ultra-low velocity zones of the mantle’s bottom in the Pacific region, but not for the eastern and western spots sampled by our dataset (Fig. 9). We also doubt that introduction of a low-velocity heterogeneity in one of the hemispheres for the purposes of accounting for the East-West bias is reasonable. On one hand, such asymmetrical structure indeed leads to systematic bias between the eastern and western curves throughout the analysed distance range. On the other hand, at epicentral distances below 10°, the decay gradient of such low-velocity theoretical curve is too small and does not fit the observed shape of amplitude ratio dependence (e.g. the eastern curve). This is obviously contrary to our observations that, as mentioned above, feature parallelism between the eastern and western PKiKP/PcP amplitude dependencies in the whole range of the analysed distances.

4.2 F-layer

More flexibility in adjusting the PKiKP/PcP amplitude model curves might be given by opting for variation in the F-layer (Antonangeli et al., 2010; Waszek and Deuss, 2015) that affects only one of the two analysed waveforms (PKiKP). For example, if the OC bottom is of increased density, the net ICB density jump sampled by body waves seems smaller, whereas the real density contrast between the bulk OC (beyond its F-layer) and the IC is larger. To gain more variability in ICB density jump estimates one can also appeal to non-standard attenuation of the
F-layer suggested by Zou et al. (2008). However, suggestions as to density of the OC bottom must strongly correlate with the observed PKiKP travel time, since they directly affect seismic wave velocity above the ICB. The correlation between density and velocity in the context of compositional difference generated by freezing or melting at the ICB is as follows (Badro et al., 2007; Antonangeli et al., 2010). In case of rapid growth or freezing, light elements decrease the density in the F-layer, which is equivalent to increase in its compressional velocity and ICB density jump, but decrease in PKiKP-PcP differential travel time residuals. Conversely, if melting dominates, denser liquid enriches the OC bottom, which is equivalent to decrease in F-layer compressional velocity and ICB density jump, and increase in PKiKP-PcP differential travel time residuals.

The observed PKiKP - PcP differential travel time residuals in the eastern and western samples of our dataset do not correlate with the above described pattern. In particular, we infer the thinner OC or faster compressional velocities from differential travel times measured below Japan, while the relevant PKiKP/PcP amplitude ratios yield low ICB density jump of about 0.3 g/cm³. On the contrary, we find thicker OC (or slower P-waves) in the western hemisphere where the estimated ICB density jump turns out three times as large. This indicates that altered density of the F-layer is unlikely the reason for the observed discrepancy between the western and eastern measurements. Conversely, if we assume hemispherical ICB density jump distribution (0.3 g/cm³ in the East, and 0.9 g/cm³ in the West), and variable OC thickness inferred from differential travel times, one can recognise the Earth’s core structure predicted by IC translation model (Alboussièr et al., 2010; Monnereau et al., 2010). Specifically, the model assumes that crystallization in the denser cold western hemisphere and melting on the opposite hot eastern side jointly work to remove IC surface topography, amplify the density heterogeneity and keep its centre of mass shifted toward the heavy crystallizing side.

4.3 Collation of ICB density jump estimates

The obtained ICB density jump estimates fall within the wide range of values predicted for the liquid and solid parts of the boundary. Precise distribution of this parameter over the IC surface is unknown and no distinct pattern of its geographical dependence has been observed thus far. Instead, Waszek and Deuss (2015) find ‘some regional consistency — there are more data with large-amplitude ratios beneath Central and South America and more data with smaller amplitude ratios beneath Asia’. Authors of the last referenced paper used measurements sparsely distributed around the Pacific Ocean whose total number was an order of magnitude smaller than
what we used here for the two spots beneath South America and Asia. Our observations build up
the suggested regional consistency and enhance its statistical significance — the observed
difference between the two analysed spots in this study is essentially similar in terms of
measured amplitude ratios that can be interpreted in terms of threefold difference in ICB density
jump.

We note that low ICB density jump below Asia found here has also been suggested in
other papers (Koper and Pyle, 2004; Tkalčić et al., 2009). For example, the last referenced study
does not preclude values of about 0.2 - 0.3 g/cm³ on the base of data at 16° - 17° from
Kazakhstan. As mentioned above, previous studies didn’t consider a plethora of differential
measurements, and either PKiKP or PcP was frequently not detected above noise. In contrast, we
observe PKiKP and PcP in each non-faulty trace of our dataset; if we didn’t, a bias would arise
due to selecting only those records where both phases are presented (Souriau and Souriau, 1989).
Such biasing can be mitigated by using noise level at the predicted arrival time of PKiKP or PcP
as an upper bound on its amplitude when one of the waveforms is not detected; still the ICB
density jump estimates with omitted upper bound noise measurements may be subject to
overestimation. Thus, collation of various ICB density jump estimates would benefit from
assessing possible discrepancies due to specific features of the underlying datasets (e.g. data
selection). Our dataset includes no noise-modelled amplitudes of non-observed PKiKP or PcP
waveforms, and to gauge possible overestimation factor, we address the only known to us
publicly available detailed dataset of raw Asian PKiKP/PcP measurements explicitly given in the
paper by Tkalčić et al. (2010).

We use maximum likelihood method that considers the amplitude probability distribution
function and allows using negative information, wherein the term ‘negative information’ means
substitution of PKiKP measured amplitude for noise amplitude at the time interval around its
predicted arrival. A close analog is estimation of maximum likelihood magnitude over a set of
seismic stations (Ringdal, 1975). In general, we analyse two datasets — the first one includes
only $A_{PKiKP}/A_{PcP}$ amplitude ratios measured over the detected PKiKP and PcP waveforms, and the
second one includes ratios where PKiKP is not detected and we assume its amplitude is below
the noise level at the time of its expected arrival. Omitting the second dataset obviously leads to
bias, but a priori knowledge of statistical distribution of PKiKP/PcP amplitude ratio yields
quantified probability that $A_{PKiKP}/A_{PcP} < A_n$ where $A_n$ is the measured noise
amplitude. As log-amplitude of the signal propagating in random inhomogeneous medium has
normal distribution (Rytov et al., 1989), the expected value ($m$) and variance ($\sigma^2$) of log-normal
distribution of PKiKP/PcP amplitude ratio can be estimated on the base of maximum likelihood method (Van Trees, 2004) from maximum of the function

$$L(m, \sigma^2 | a, b) = \frac{1}{(2\pi\sigma^2)^{\frac{N}{2}}} \exp\left(\frac{\ln \beta_i - m_i}{2\sigma^2}\right) \prod_{i=1}^{N} \left( \int_{-\infty}^{\ln \beta_i} \exp\left(\frac{t - m_i}{2\sigma^2}\right) \, dt \right)$$

(1)

where $L(m, \sigma^2 | a, b)$ is conditional probability for $m$ and $\sigma^2$, if parameters $a_i = A_{PKiKP}/A_{PcP}$ ($i=1,…,N$) and $b_i = \ln A_{PKiKP}/A_{pK}$ are measured. The second product operator assumes that $b_i < a_i$, i.e. noise amplitude is larger than PKiKP amplitude at the $i$-th station, and thus PKiKP waveform is not observed but known to exist in the seismogram. For numerical calculations the conditional probability expression is used in its logarithmic form:

$$\ln(L(m, \sigma^2 | a, b)) = -\sum_{i=1}^{N} \frac{(\ln \beta_i - m_i)}{2\sigma^2} - N\ln \sigma + \sum_{i=1}^{K} \ln(1 + \Phi(\frac{\ln a_i - m_i}{2\sigma}))$$

(2)

where $\Phi(x)$ – error function integral (Dwight, 1961), $m$ and $\sigma$ – parameters of PKiKP/PcP amplitude ratio distribution that deliver maximum of the function $\max_{m,\sigma}(\ln(L(m, \sigma^2 | a, b)))$.

Raw measurements for the epicentral distance ranges of $11^\circ < \Delta < 13^\circ$ and $13^\circ < \Delta < 24^\circ$ that we imported from (Tkalčić et al. 2010) are given in Supplementary Tables S1 and S2. Using formula (2) and measurements from Tables S1 and S2, we estimate log-likelihood for various unknown parameters $m$ and $\sigma$. Its contours can be found in Supplementary Information (Figure S2), and Table 2 summarises the resulting expectation and variance for maximum likelihood and mean estimates. The predicted amount of overestimation in terms of ICB density jump can be assessed from Figure 10. As expected, the output estimates obtained from a subset are in excess of those from dataset with negative information. The results show that uncertainty $\sigma$ remains almost unchanged with epicentral distance, and overestimation magnitude is about $0.023 \pm 0.009$ units of PKiKP/PcP amplitude ratio. Hence, the ICB density jumps on the base of PKiKP/PcP amplitude ratios may tend to systematic overestimation, if available negative information is not used. We infer that uncertainties associated with selection of data might be at least partly an explanation for the long known discrepancy in the estimates obtained from amplitude ratios and normal modes. At the same time, the bias is more significant at larger epicentral distances where mere hundredths divide the PKiKP/PcP theoretical ratio curves for various ICB density jumps. In an extensive dataset of narrow-angle reflections like ours, this bias is unlikely to cause the observed sustained discrepancy between any its parts including the eastern and western samples. We also note that our ICB density contrast of about $0.3$ g/cm³ obtained for Southeastern Asia can be consistent with some other estimates for Asia, no matter whether they are additionally...
corrected for data selection uncertainty or not. Hence, low values of ICB density jump could probably be spread out all over the whole IC region below Asia, which would support a simple degree-one global ICB density jump distribution.

5. Conclusions

The analysed reflected data indicate dissimilarity of two spots of the Earth’s core sampled in its eastern and western hemispheres. Beyond concoctions connecting the observations to multifactorial contributions of out-of-core inhomogeneities, we are motivated to consider a model with variable ICB density jump. We estimate it to be about 0.3 g/cm$^3$ under Southeastern Asia, and about 0.9 g/cm$^3$ under South America. Finding out whether it is a sign of IC dichotomy or mosaic character of the IC surface is not possible by means of the presented dataset. Neither mosaic nor dichotomy is preferred, but a simple degree-one global ICB density jump distribution goes in line with previously established hemispherical differences in the bulk IC (e.g. (Tanaka and Hamaguchi, 1997)). Together with variable OC thickness inferred from differential travel times, the distribution complies with crystallization in the denser cold western hemisphere and melting on the opposite hot eastern side (Alboussièr et al., 2010; Monnereau et al., 2010), and not vice versa as argued by Aubert et al. (2008).

Acknowledgements

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References


Tkalčić, H., V. Cormier, B. Kennett, and K. He (2010), Steep reflections from the Earth’s core reveal small-scale heterogeneity in the upper mantle, *Phys. Earth Planet. Inter.*, 178, 80–91.


Table 1. Parameters of seismic sources and arrays/networks.

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<th>Date</th>
<th>Origin Time</th>
<th>Latitude, °</th>
<th>Longitude, °</th>
<th>Depth, km</th>
<th>M_b</th>
<th>Δ, °</th>
<th>Networks</th>
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<td>3.2–35.2</td>
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*DOI of networks used for observations in the Western hemisphere: ZL (10.7914/SN/ZL_2007), X6 (10.7914/SN/X6_2007), XH (10.7914/SN/XH_2008), TO (10.7909/C3RN35SP), YS (10.7914/SN/YS_2009), CX (10.14470/PK615318), XS (10.15778/RESIF.XS2010), XP (10.7914/SN/XP_2010), ZG (10.7914/SN/ZG_2010), ZD (10.7914/SN/ZD_2010), ZV (10.7914/SN/ZV_2012). No DOI has the 3A network (Maule Aftershock Deployment (UK)).
++http://jarray.eri.u-tokyo.ac.jp/
§ (Okada et al., 2004; Obara et al., 2005)

Table 2. Output expectation and variance obtained from two datasets.

<table>
<thead>
<tr>
<th>Epicentral distance</th>
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Figure 1. Record section plot of 18 frequency-filtered vertical components of raw data (top) and their DSM theoretical counterparts with respect to ak135 (bottom). Station names are on the right. Left pane: passage corresponding to arrival of PcP; right pane: to PKiKP.
Figure 2. Map with epicentres of analysed earthquakes (beach balls) and daylight surface projections of PKiKP reflection points (circles). Left panel shows datapoints sampling the IC surface in its Eastern hemisphere, right – in the western. Inset globe displays the regions of the larger maps.
Figure 3. P- and S-wave energy radiation patterns for four events from Table 1 and another event in Okhotsk Sea. Vertical plane is shown on the left, and horizontal plane on the right (except for the focal mechanism in the last row). Black solid line is for P-wave, dashed yellow for S. Ranges of theoretical incident angles of PcP and PKiKP from the ak135 model are shown on the left in red and blue lines, respectively. The corresponding horizontal cross-sections are shown on the right for PcP (red) and PKiKP (blue) along with range of azimuths to stations (dash). A detailed figure with decomposition into SV – SH see in Supplementary Information (Figure S1).
Figure 4. Differential travel time residuals for 1016 records collected in Japan. Green dots with standard deviation bars are 0.5° binned averages of measured residuals. Blue line – α-shape reconstructed distance dependence of measured residuals.
Figure 5. Measured PKiKP/PcP amplitude ratios and their theoretical estimates for ak135. Red and blue dots – measured ratios in eastern and western hemispheres, accordingly. Theoretical curves are for ICB density jumps of 0.3 g/cm$^3$ (lower dash), 0.6 g/cm$^3$ (lower solid), 0.9 g/cm$^3$ (upper dash), 1.8 g/cm$^3$ (upper solid).
Figure 6. Theoretical and observed dependencies of PKiKP/PcP amplitude ratio on distance. Theoretical curves on the base of ak135 are for varying ICB and CMB density jumps given in the legends in g/cm$^3$. Red and blue dots with standard deviation bars are $1^\circ$ binned averages of amplitude ratios measured in eastern and western hemispheres, respectively; thick red and blue lines are the $\alpha$-shape distance dependencies reconstructed from the eastern and western subsets, respectively.
Figure 7. Shear velocity distribution on the mantle side of CMB in conformity with S40RTS20. Black boxes delineate the areas sampled by reflected waves from our dataset.
Figure 8. Theoretical and observed dependencies of PKiKP/PcP amplitude ratio on distance. Theoretical curves on the base of PREM are for varying ICB and CMB velocity jumps given in the legends in km/s. Thick red and blue lines are the α-shape distance dependencies reconstructed from the eastern and western subsets, respectively.
Figure 9. P-wave velocity distribution on the mantle side of CMB in conformity with LLNL-Earth3D. Black boxes delineate the areas sampled by reflected waves from our dataset. The velocity unit of the colour scale bar is km/s.

Figure 10. Theoretical and experimental estimates of ICB density jumps in conformity with ak135 and Table 2. Black dots – mean of PKiKP/PcP amplitude ratios (Dataset #1). Empty dots – PKiKP/PcP amplitude ratio estimated by maximum likelihood method (Datasets #1 and #2). Theoretical PKiKP/PcP amplitude curves are for ICB density jumps in conformity with the legend in the upper right corner.
Supplementary information for

Dissimilarity of the Earth's inner core surface under South America and Southeastern Asia revealed by core reflected phases

by

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Contents of this file

1. Supplementary Figures S1 and S2

2. Supplementary Tables S1 and S2
Supplementary Figure S1. A detailed P- and S-wave energy radiation patterns for four events from Table 1. Vertical plane is shown on the left, and horizontal plane on the right. Black solid line is for P-wave, dashed for SV, dots for SH. Ranges of theoretical incident angles of PcP and PKiKP from the ak135 model are shown on the left in red and blue lines, respectively. The corresponding horizontal cross-sections are shown on the right for PcP (red) and PKiKP (blue) along with range of azimuths to stations (dash).
Supplementary Figure S2. Contours of logarithmic probability function plotted in coordinates $(m \sigma)$ for epicentral distances $11^\circ < \Delta < 13^\circ$ (left) and $13^\circ < \Delta < 24^\circ$ (right).
Supplementary Table S1. The first dataset of PKiKP/PcP amplitude ratios where both waveforms are detected (a.):

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<th>$A_{PKiKP}$, cts</th>
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Supplementary Table S2. The second dataset of PKiKP/PeP amplitude ratios where PKiKP waveform is not detected at some stations (b.):

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