Heterogeneities of the Earth's Inner Core Boundary from Differential Measurements of PKiKP and PcP Seismic Phases

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Abstract The Earth's crystalline inner core (IC) solidifies from the liquid Fe alloy of the outer core (OC), which releases latent heat and light elements sustaining the geodynamo. Variability in solidification regime at the inner core boundary (ICB) may result in compositional and thermal multi-scale mosaic of the IC surface and dissimilarity of its hemispheres. Both the mosaic and hemisphericity are poorly constrained, not least due to a lack of available sampling by short-period reflected waves. Measured amplitude ratio of seismic phases of PKiKP and PcP reflected, respectively, off the inner and outer boundary of the liquid core, yields direct estimate of the ICB density jump. This parameter is capable of constraining the inner–outer core compositional difference and latent energy release, but is not well known (0.2–1.2 g/cub. cm), and its distribution is obscure. Travel time measurements of PKiKP and PcP waveforms can be useful in terms of getting an insight into fine structure of ICB and its topography. We analyse a new representative sample of pre-critical PKiKP/PcP differential travel times and amplitude ratios that probe the core's spots under Southeastern Asia and South America. We observe a statistically significant systematic bias between the Asian and American measurements, and carefully examine its origin. Separating the effects of core-mantle boundary and ICB on the measured differentials is particularly challenging and we note that a whole class of physically valid models involving D″ heterogeneities and lateral variation in lower mantle attenuation can be employed to account for the observed bias. However, we find that variance in PKiKP-PcP differential travel times measured above the epicentral distance of 16° is essentially due to mantle heterogeneities. Analysis of data below this distance indicates the ICB density jump under Southeastern Asia can be about 0.3 g/cub. cm, which is three times as small as under South America where also the thickness of the above liquid core can be by 1–3 km in excess of the one in the East. The findings preclude neither IC hemispherical asymmetry (whereby crystallization dominates in the West and melting in the East) nor patchy IC surface, but provide an improved and robust estimate of the ICB density jump in two probed locations.

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T. B. Yanovskaya et al. (eds.), *Problems of Geocosmos—2018*, Springer Proceedings in Earth and Environmental Sciences, https://doi.org/10.1007/978-3-030-21788-4_20

Keywords Inner core boundary · Reflected waves · Density jump

1 Motivation

The key region to understanding the Earth's crystalline iron inner core (IC) is the transition from liquid to solid core—the region where it grows by freezing [12]. Many details of this crystallisation are currently unknown, but there have been developed a number of scenarios that result in formation of inhomogeneous structures such as slurry, dendritic and non-dendritic morphologies, etc. (e.g., [9, 18, 27]. These heterogeneities are essentially due to the fact that solidification regime and the cooling rate during phase transition are not uniform throughout the inner core boundary (ICB) (e.g., [2, 11]. In seismic data such multi-scale heterogeneities may look like compositional and thermal mosaic of the IC exterior [15] and even dissimilar hemispheres [1, 2, 19].

A lot of seismological constraints on ICB structure and parameters have been obtained using the body waves reflected from it—the seismic phase of PKiKP. Studies of ICB and its vicinity by short-period pre-critical 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. For steeply reflected PKiKP waveforms, the seismic phase of PcP reflected off the core-mantle boundary (CMB) is the best reference, since this pair obviously yields adequate resolution, and close proximity of their crust and mantle paths cancels the influence of heterogeneities localized outside the Earth's core. It is these waveforms that produce the main evidence that the IC surface is mosaic [15] or rough [5], and enable localized estimates of the ICB density jump [3]. On the other hand, part of the results of joint analysis of PKiKP and PcP cannot be easily reconciled with other studies. For instance, the relevant ICB density jump estimates are usually larger (up to 1.8 g/cm^3) than normal mode outputs (0.9 g/cm^3 and below). Another controversy may arise from evidence for hemispherical pattern in ICB properties—it can be seen in teleseismic PKiKP data [19], but is not confirmed [31] by pre-critical reflections.

Lack of differential measurements of steeply reflected PKiKP and PcP is one of the reasons for controversies. 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. For instance, 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 [4] and uncertainties [28] 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 [29] and ICB [15]. 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. In this paper we revisit heterogeneities of ICB using the newly presented in [16] 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 Measurements

Pre-critical PKiKP and PcP waveforms were successfully detected on broadband and short-period records of four deep earthquakes (Table 1). The reflection points of the analysed dataset provide good sampling of two IC spots of about 125 × 240 km^2 under Bolivia and to the southeast of Sakhalin Island (Fig. 1). Each spot is scanned by hundreds of ray traces with incident angles from 2° to 20°. The number of rays and density of scanning are unprecedented and enable statistically significant and robust estimates of possible heterogeneities localized within the probed spots.

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. According to the source solution of global CMT catalogue [7, 8], 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, the

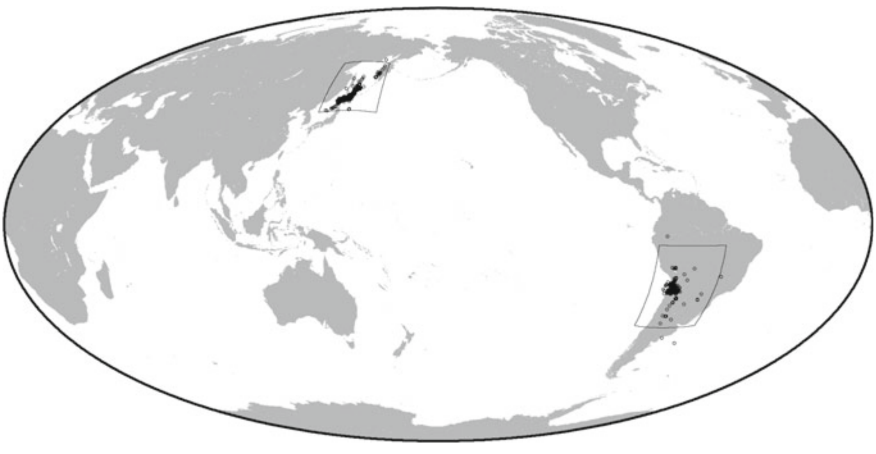

Fig. 1 Map with daylight surface projections of PKiKP reflection points below South America and Southeastern Asia. Surface rectangles roughly depict the ICB scanned spots

Table 1 Parameters of seismic sources and arrays/networks

Date (dd.mm.yyyy)	Origin time (hh:mm:ss.00)	Latitude (°)	Longitude (°)	Depth (km)	M_b	Δ (°)	Networks
Events under Southeastern America[a]							
12.07.2009	01:19:21.31	−15.0411	−70.5354	198.7	5.9	7.7–18.2	CX, TO, X6, XH, YS, ZL
24.05.2010	16:18:28.81	−8.1152	−71.6412	582.1	6.0	14.7–32.5	3A, XH, XP, XS
05.03.2012	07:46:09.23	−28.2579	−63.2916	551.9	6.0	5.4–34.2	ZD, ZG, ZV, XP
Event in Southeastern Asia (Okhotsk Sea)							
24.05.2013	14:56:31.60	52.1357	151.5688	632.0	6.8	3.2–35.2	SAGSR+, KAGSR+, J-array++,Hi-net§

[a]DOI of networks contributed into the American dataset: ZL (https://doi.org/10.7914/sn/zl_2007), X6 (https://doi.org/10.7914/sn/x6_2007), XH (https://doi.org/10.7914/sn/xh_2008), TO (https://doi.org/10.7909/c3rn35sp), YS (https://doi.org/10.7914/sn/ys_2009), CX (https://doi.org/10.14470/pk615318), XS (https://doi.org/10.15778/resif.xs2010), XP (https://doi.org/10.7914/sn/xp_2010), ZG (https://doi.org/10.7914/sn/zg_2010), ZD (https://doi.org/10.7914/sn/zd_2010), ZV (https://doi.org/10.7914/sn/zv_2012). No DOI has the 3A network (Maule Aftershock Deployment (UK))

+Regional Network of the Russian Geophysical Survey http://www.ceme.gsras.ru/new/struct/

++Earthquake Research Institute, the University of Tokyo, Japan, http://www.eri.u-tokyo.ac.jp

§ [20, 21]

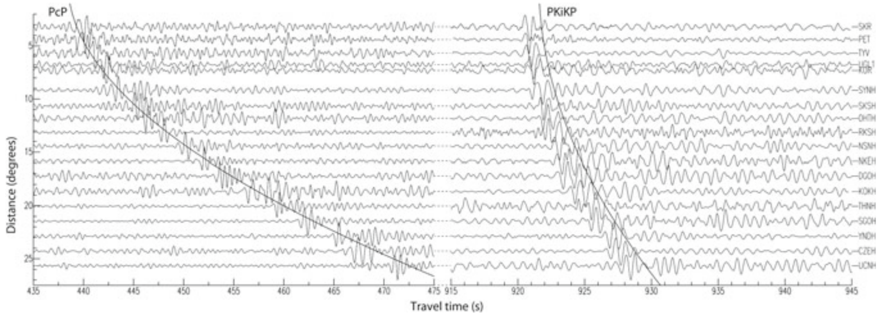

Fig. 2 Record section plot of 18 frequency-filtered vertical components (station names are on the right). Left pane: passage corresponding to arrival of PcP; right pane: to PKiKP. Standard travel time curves of PcP and PKiKP are computed for *ak135*

profound influence of seismic source can be questioned, because no PKiKP or PcP waveforms were observed in the records of the same stations after a nearby preceding event. It occurred 9 h before the analysed event in Okhotsk Sea, 300 km away to the North, and had the M_b magnitude of 7.3, similar focal depth and mechanism. Same considerations hold true and raise objections to the influence of focusing [31]. As a matter of fact, PKiKP and PcP from these two nearby events propagate in essentially the same geological settings, but are distinct after the analysed one, and not observable in the records of the preceding event in the whole distance range of 3°–35°.

To uniform the analysed dataset and increase signal-to-noise ratio of PKiKP and PcP waveforms, raw digital traces were frequency-filtered between 1.1 and 7 Hz. The filtering removed 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 build hyperbolic travel time curves, characteristic for the reflected phases (Fig. 2). We also note that each core-reflected arrival is followed by its own coda. It comes as continuous wavetrains with increased amplitudes observable not only on Hilbert transformed beams [30], but already on raw vertical and horizontal record section plots too. After filtering, both PKiKP and PcP waveforms dominate on the time interval tens of seconds long around the predicted arrival time and exhibit signal-to-noise ratios well above 2.5. 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. Picking was performed automatically in Seismic Analysis Code [10] by cross-correlation of PKiKP and PcP waveforms.

3 Results and Discussion

PKiKP–PcP differential travel time residual with respect to a standard Earth model $(t_{PKiKP}–t_{PcP})_{measured}–(t_{PKiKP}–t_{PcP})_{model}$ is an instrument providing direct constraints on OC thickness. Unless being interpreted in terms of complex velocity variations, it yields high precision estimates of OC thickness undulation that can be caused by spatial irregularities of OC boundaries, local topography of ICB, IC displacement from its geopotential centre, etc. We find that the residuals measured in Southeastern Asia are by 0.72 s below the American ones. According to the estimate given in [23], this indicates the OC under the Americas can be about 3 km thicker than under Southeastern Asia. Concretely, the mean PKiKP–PcP differential travel time residuals calculated with respect to *ak135* [13] and *PREM* [6] over 1016 Japanese records were, respectively, −1.79 and −0.41 s with s.d. of 0.51; same estimates for the American data made −1.07 ± 0.45 s and 0.31 ± 0.45 s. This estimate of OC thickness variability is rather an upper bound subject to allowance for ellipticity and possible influence of strongly heterogeneous lower mantle. We expect the elliptic corrections are almost one order of magnitude smaller than the observed 0.7 s, but mantle corrections can be quite large and variable depending on the model used. To get more accurate estimate, we invoke the up-to-date 3-D high-resolution tomographic model [24] of LLNL-Earth3D that takes into account Earth's ellipticity, undulating discontinuity surfaces and heterogeneities in mantle and crust. Also, it yields a credible result reconcilable with basic physical notions. 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). Farther away (at larger epicentre distances), where PKiKP and PcP paths start to diverge in lower mantle, mantle heterogeneities may act differently. This pattern can be observed in Fig. 3. It plots modelled and measured residuals overlaid by 0.5° binned averages for 1016 records of the Okhotsk Sea event (Table 1) by Japanese stations. Above the epicentral distance of 16.5°, the measured residuals completely coincide with predictions 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 Asian reflections and 181 American ones were −0.45 ± 0.55 s and 0.27 ± 0.44 s, accordingly, while the relevant modelled residuals made −0.27 ± 0.07 s and 0.12 ± 0.10 s. These averages indicate that up to a half of the systematic bias between PKiKP–PcP differential travel time residuals measured in Asia and America 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.

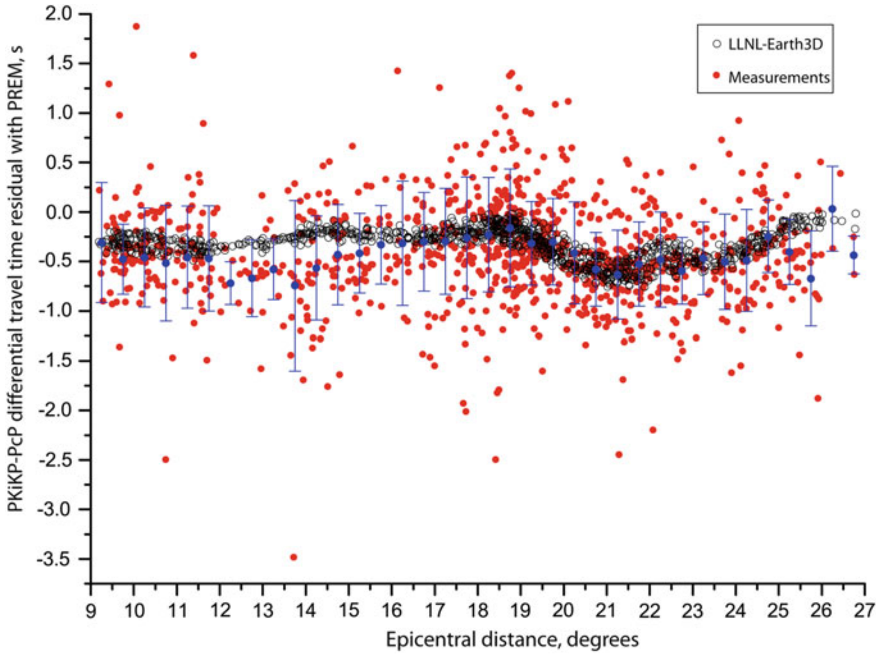

Fig. 3 Differential travel time residuals for 1016 records collected in Japan. Blue dots with standard deviation bars are 0.5° binned averages of measured residuals. Datapoint legend is in the upper right corner

Comparison of measured and model-predicted PKiKP/PcP amplitude ratios yields [3] direct estimates of the ICB density jump provided the CMB density and velocity contrasts are known and shear wave velocity in the top of the IC is fixed. Theoretical curves of various ICB density jump models are not far apart (especially above 10°), whereas the scatter of measurements is large—it can be seen in Fig. 4 that plots the whole dataset of measured PKiKP/PcP amplitude ratios. In addition, as argued above, it's reasonable to include only data under 16.5° (since above this limit the ratios may suffer from influence of heterogeneities outside the Earth's core). Figure 5 shows that Asian and American measurements up to epicentral distances of about 16° are consistently divided by a gap equivalent to the ICB density jump of about 0.6 g cm^{-3}. It is confirmed by binned averages. Given the notorious [14, 28] trade-off between variation of acoustic impedance contrast at ICB and CMB, and the resulting ICB density jump estimate, an alternative interpretation in terms of CMB density jump has to be examined too. The interpretation would assume 10–15% density variation between the probed American and Asian spots of the mantle bottom (Fig. 5). However, such variation can be controversial in geodynamical context because the sampled mantle sides of CMB feature essentially similar shear velocities [22] and material properties specific to regions outside the Pacific large low-shear-velocity province [17]. Strong density variations on the core side of CMB are hardly possible

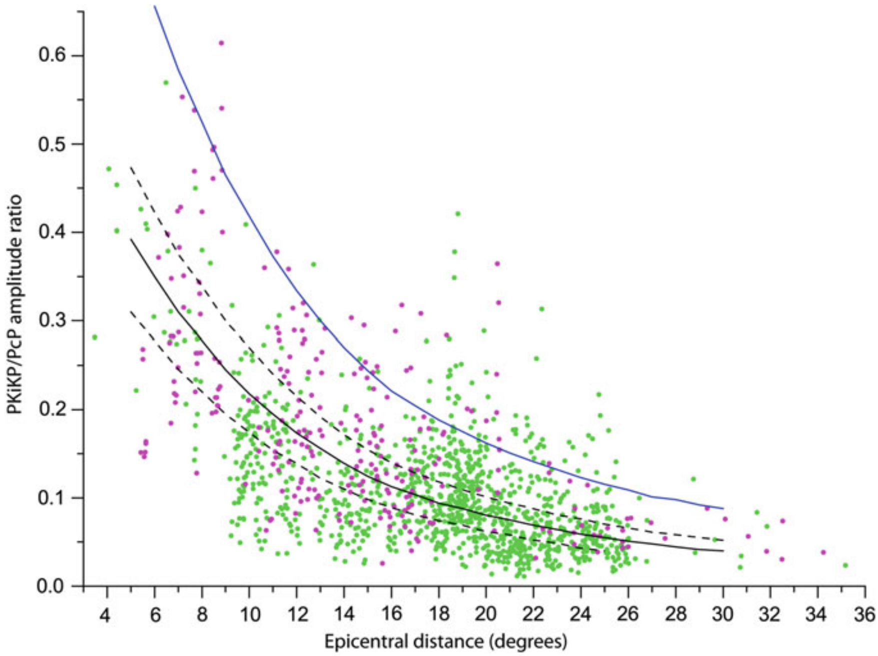

Fig. 4 Measured PKiKP/PcP amplitude ratios and their theoretical estimates for *ak135*. Green and violet dots—measured ratios from Asia and America, respectively. Theoretical curves are for ICB density jumps of 0.3 g/cm^3 (lower dash), 0.6 g/cm^3 (black solid), 0.9 g/cm^3 (upper dash), 1.8 g/cm^3 (blue solid)

too [25]. Still, the 3-D density variation in D$''$ has yet to be mapped, and thus the model with variable CMB density jump cannot be entirely ruled out, as well as, for example, a complex model with lateral variation of P velocity near CMB combined with lateral variation in either viscoelastic or scattering attenuation in the lowest 150 km of mantle. The latter model enables strong variation in PKiKP/PcP amplitude ratios [29], but can be a bit farfetched, especially if compared to a simple hemispheric scenario where ICB density jump in the eastern hemisphere is about 0.3 g cm^{-3}, and in the western—about 0.9 g cm^{-3}.

4 Conclusions

The analysed reflected data indicate that the sampled spots of the Earth's core below Southeastern Asia and South America feature dissimilar properties. The observations can be accounted for by a class of models assuming multifactorial contributions of out-of-core inhomogeneities, yet the most credible is a model with variable ICB density jump. We estimate it to be about 0.3 g/cm^3 under Southeastern Asia, and

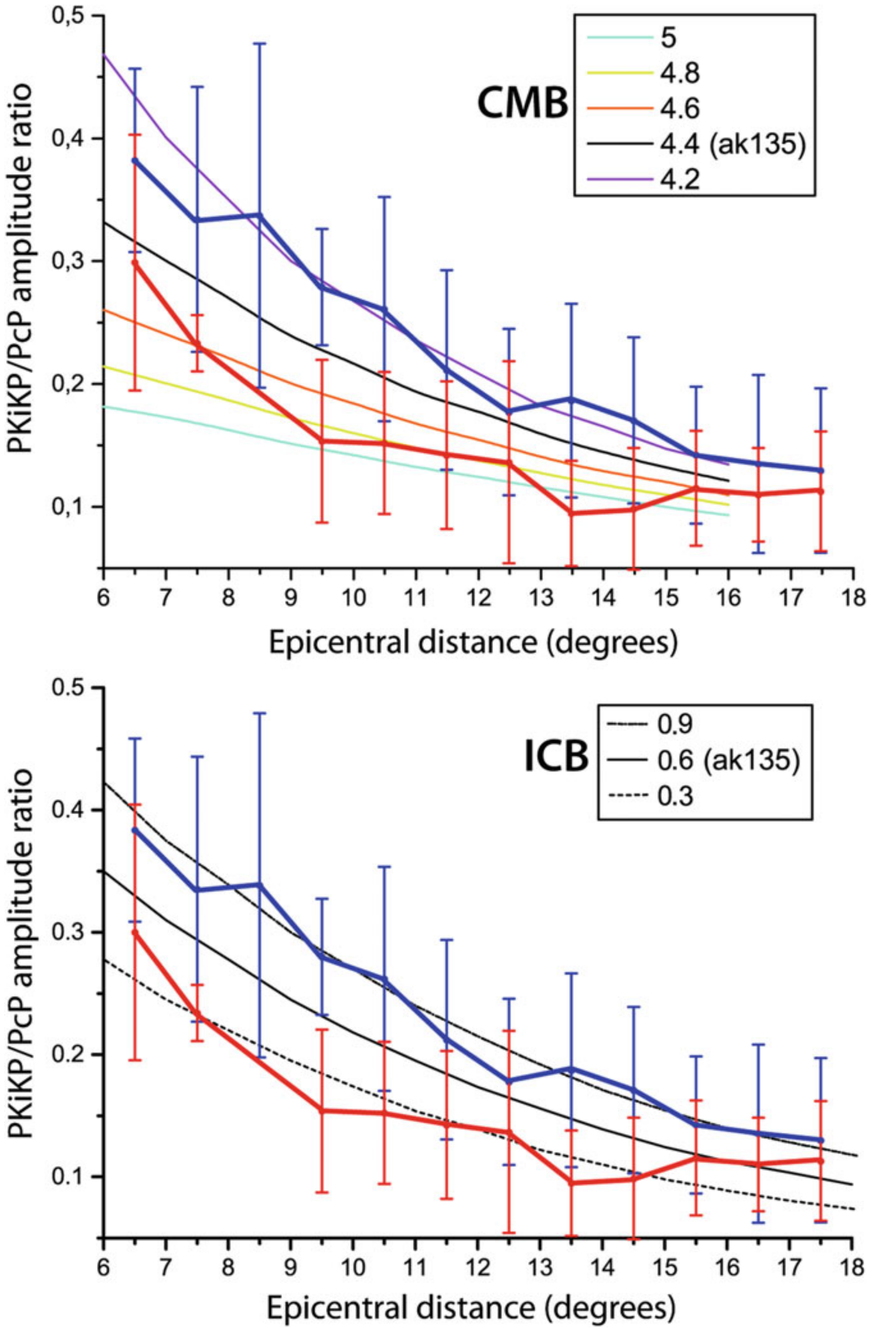

Fig. 5 Theoretical and observed dependencies of PKiKP/PcP amplitude ratio on distance. Theoretical curves on the base of *ak135* are for varying ICB and CMB density jumps given in the legends in g/cm^3. Thick blue and red lines are the polygon curves formed out of 1° binned amplitude ratios of the American and Asian subsets, respectively

about 0.9 g/cm^3 under South America, but cannot find out whether it is a sign of IC dichotomy or mosaic character of the IC surface. Either of the model is acceptable, but a simple degree-one global ICB density jump distribution is easily reconcilable with previously established hemispherical differences in the bulk IC (e.g. [26]. Furthermore, if the observed variable OC thickness is due to IC displacement from its centre of figure, the distribution would comply with crystallisation in the denser cold western hemisphere and melting on the opposite hot eastern side [1, 19], and not vice versa as argued by Aubert et al. [2].

Acknowledgements This work is supported by the Russian Foundation for Basic Research grant #18-05-00619. The facilities of IRIS Data Services, and specifically the IRIS Data Management Center, were used for access to waveforms used in this study. IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) Proposal of the National Science Foundation under Cooperative Agreement EAR-1261681. Seismic data were also obtained from Geophysical Survey of Russia (Federal research center of Russian Academy of Sciences), Data Management Center of the National Research Institute for Earth Science and Disaster Resilience (Japan) and Earthquake Research Institute, the University of Tokyo (Japan). Figure 1 was generated with Generic Mapping Tools [32].

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