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FULL PAPER

Ultra-low velocity zone heterogeneities at the core–mantle boundary from diffracted PKKP$_{ab}$ waves

Xiaolong Ma and Xinlei Sun[*]

Abstract

Diffracted waves around Earth's core could provide important information of the lowermost mantle that other seismic waves may not. We examined PKKP$_{ab}$ diffraction waves from 52 earthquakes occurring at the western Pacific region and recorded by USArray to probe the velocity structure along the core–mantle boundary (CMB). These diffracted waves emerge at distances up to 10° past the theoretical cutoff epicentral distance and show comparable amplitudes. We measured the ray parameters of PKKP$_{ab}$ diffraction waves by Radon transform analysis that is suitable for large-aperture arrays. These ray parameters show a wide range of values from 4.250 to 4.840 s/deg, suggesting strong lateral heterogeneities in sampling regions at the base of the mantle. We further estimated the P-wave velocity variations by converting these ray parameters and found the CMB regions beneath the northwestern edge of African Anomaly (Ritsma et al. in Science 286:1925–1928, 1999) and southern Sumatra Islands exhibit velocity reductions up to 8.5% relative to PREM. We suggest that these low velocity regions are Ultra-low velocity zones, which may be related to partial melt or iron-enriched solids.

Keywords: Diffracted PKKP$_{ab}$ waves, Core–mantle boundary, Lateral heterogeneity, Low velocity zones

Introduction

It is well known that there exist significantly complex structures at the core–mantle boundary (CMB). These complex structures range from large low shear velocity provinces (LLSVPs) of thousands of kilometers (e.g., Ni and Helmberger 2003; Garnero and McNamara 2008; Garnero et al. 2016) to small-scale scatterers of a few to tens of kilometers (e.g., Vidale and Hedlin 1998; Mancinelli and Shearer 2013; Waszek et al. 2015). Other complex features include ultra-low velocity zones (ULVZs) (Helmberger et al. 2000; Rost and Revenaugh 2003a; Rost et al. 2010), D″ discontinuity (e.g., Nataf and Houard 1993; Rost and Revenaugh 2003b; Hernlund et al. 2005) and seismic anisotropy in D″ (e.g., Kendall and Silver 1996; Garnero et al. 2004; Long 2009; Lynner and Long 2014). All these complex structures are not surprising since the CMB is the most dramatic thermal

and compositional boundary within the Earth (Garnero 2000). Although these structures are important for us to understand the dynamic process and evolution inside the Earth (Garnero 2004; McNamara and Zhong 2005; Tackley 2012), due to uneven distribution of earthquakes and seismic stations, there are still areas near the CMB that have not been well probed. Moreover, conventional tomographic methods often poorly resolve small-scale structures at the CMB owing to ray coverage and frequency content (Rawlinson et al. 2010; Liu and Gu 2012). In contrast, unconventional methods, such as diffracted waves traveling a long distance along the CMB, may provide additional information.

Core-diffracted waves, such as P_{diff} and SPdKS/SKPdS waves, have been widely used to probe the lowermost mantle structure (e.g., Wysession 1996; Earle and Shearer 2001; Thorne and Garnero 2004; Xu and Koper 2009; Thorne et al. 2013; Hosseini and Sigloch 2015). Although their results have revealed strong lateral velocity variations near the CMB, there are limitations in their mapping areas due to small detectable amplitudes or specific

*Correspondence: xsun@gig.ac.cn
State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Wushan, Tianhe, Guangzhou 510640, China

raypath geometry of phases used. As a complementary approach, diffracted $PKKP_{ab}$ waves can sample regions that other phases cannot, thus improving the mapping coverage of small-scale structures at the CMB.

PKKP is a P-wave traveling through the core and reflecting once at the underside of the CMB. Like PKP, there are four branches of PKKP phase ($PKKP_{ab}$, $PKKP_{bc}$, $PKKP_{cd}$ and $PKKP_{df}$) (Fig. 1). In general, $PKKP_{cd}$ and $PKKP_{df}$ are difficult to see due to very small amplitudes, while $PKKP_{ab}$ and $PKKP_{bc}$ are more easily identified in short-period seismograms (Earle 2002; Rost and Garnero 2006; Ivan and Cormier 2011; Niu et al. 2012).

The theoretical cutoff distance of $PKKP_{ab}$ for a 500-km-depth earthquake in the PREM (Dziewonski and Anderson 1981) is about 104° (minor arc distance). However, because $PKKP_{ab}$ waves can diffract around the CMB (Fig. 1), the diffracted waves can always be detected at distances beyond this cutoff distance in short-period seismograms. Although the diffraction could occur on either (or both) side(s) of the $PKKP_{ab}$ raypath along the CMB, in this paper, we name the diffracted waves as $PKKP_{ab}$ diffraction waves.

$PKKP_{ab}$ diffraction waves can be clearly detected at distances beyond this cutoff distance in short-period
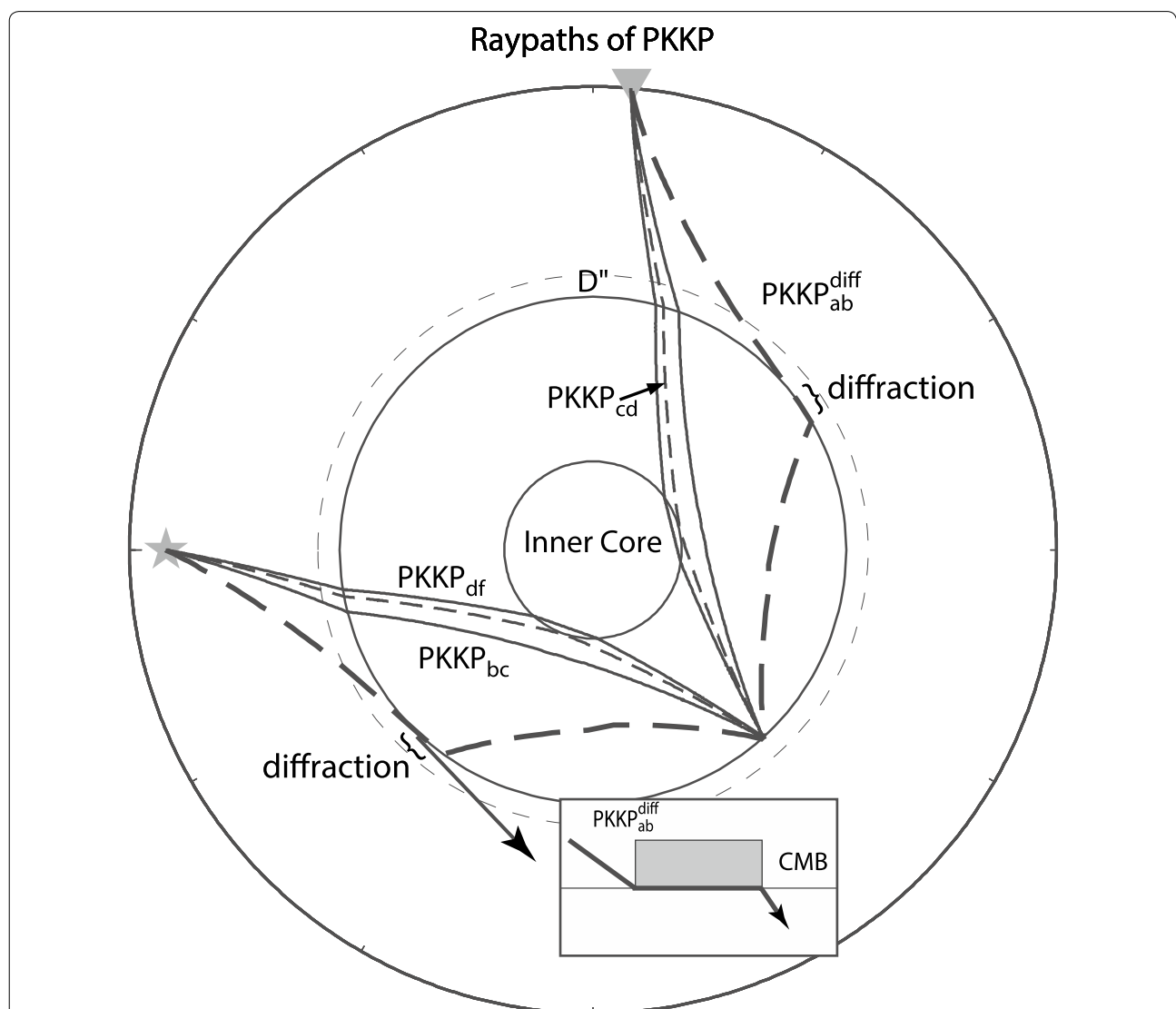

Fig. 1 Raypaths for different PKKP branches. $PKKP_{df}$ and $PKKP_{bc}$ raypaths are denoted as solid lines, and $PKKP_{cd}$ as well as $PKKP_{ab}$ diffraction paths are denoted as thinner and thicker dashed lines, respectively. The ray paths are generated for an event (*gray star*) with a focal depth of 500 km, and the minor epicenter distance to the station (*gray inverted triangle*) is 95°. The diffracted portions along the core–mantle boundary on the two sides are about 9.0° in total. The inserted *box* shows one-sided diffraction of $PKKP_{ab}$ waves along the CMB

seismograms, thus providing unique solutions to small-scale velocity structures at the CMB. In spite of these merits, there are only a few studies utilizing PKKP$_{ab}$ diffraction waves (Rost and Garnero 2006; Ivan and Cormier 2011), which is mainly because of lack of high-quality data. With the increase in temporary/permanent stations all around the world, PKKP$_{ab}$ diffraction phase now may provide more opportunities to resolve the CMB structures in regions that have not been studied previously.

In this study, we collect PKKP$_{ab}$ diffraction waves recorded by the USArray from earthquakes located along the western boundary of Pacific Ocean and try to resolve CMB velocity structures by measuring the ray parameters of these diffracted waves. The wide distribution of USArray ensures broader mapping areas sampled by PKKP$_{ab}$ diffraction waves. This study exhibits a wide range of velocity perturbations from about −8.5 to +4.2% relative to PREM. The results also show two Ultra-low velocity zones beneath the northwestern edge of African and southern Sumatra Islands, which could be explained by thermal/chemical variations, such as partial melting and iron-enriched material in the lowermost mantle.

Data and methods

In order to obtain clear PKKP$_{ab}$ diffraction phases, and to avoid possible contaminations from depth phases or strong scattering in the lithosphere, we only selected earthquakes with depths greater than 100 km and magnitudes larger than 5.4 (Table 1). We also excluded data with epicentral distances larger than 104° where PKKP$_{ab}$ waves begin to appear. Therefore, our earthquakes are generally distributed along the western boundary of Pacific Ocean (Fig. 2). All the stations we selected are from USArray, which spans a large area with a relatively dense distribution. After removing the instrument response and band-pass filtering with a frequency band of 0.9–2.1 Hz, we visually checked the seismic recordings and selected the ones with clear PKKP$_{ab}$ diffraction phases and good signal-to-noise ratios. During this process, the recordings with very complex waveforms are also discarded, to avoid possible biases from complicate rupture process in the source. Finally, a total of 2540 seismic recordings from 52 earthquakes are selected. Two examples of such PKKP waves are shown in Fig. 3.

To estimate seismic velocities of the lowermost mantle, we first determined the ray parameters of the PKKP$_{ab}$ diffraction waves. Then, we converted the obtained ray parameters into apparent velocities according to:

$$V_{\mathrm{cmb}} = R_{\mathrm{cmb}}/p \tag{1}$$

Table 1 Earthquakes used in this study

No.	Date	Latitude	Longitude	Depth	Mag (Mw)
1	2006.12.27.20.42	−11.4345	166.4710	137.5	6.0
2	2007.11.19.01.18	−13.5186	166.9850	124.7	6.3
3	2008.09.08.18.52	−13.6631	167.0310	118.4	6.9
4	2009.03.26.19.19	−18.0120	−178.4360	577.4	5.9
5	2009.09.03.13.26	19.3514	144.7600	446.9	6.2
6	2009.10.25.07.53	−20.4310	−176.2160	231.3	6.0
7	2009.10.31.19.09	−20.8720	−178.5080	536.9	5.9
8	2010.03.04.14.02	−21.2118	−178.6730	558.9	6.5
9	2010.03.08.09.47	−23.0250	−177.1090	171.4	6.1
10	2010.03.20.14.00	−23.0354	−179.1010	413.0	6.6
11	2010.06.17.13.06	−23.1320	−177.2220	155.5	6.0
12	2010.06.30.04.31	−23.2850	179.1800	572.8	6.4
13	2010.08.04.07.15	−23.5142	−179.7430	562.3	6.5
14	2010.08.15.15.09	−26.0435	178.4770	551.8	6.3
15	2010.12.13.01.14	26.9670	140.0160	524.5	6.2
16	2011.01.12.21.32	27.2502	125.7230	228.2	6.5
17	2011.01.23.19.15	27.4033	126.8230	152.0	5.8
18	2011.02.21.10.57	29.0570	139.2510	436.0	6.5
19	2011.08.25.10.39	29.9330	138.8870	421.9	5.9
20	2011.11.08.02.59	31.1797	130.1830	167.2	6.9
21	2012.02.10.01.47	−33.1905	179.7820	211.2	6.0
22	2012.07.18.08.09	−3.3752	152.2790	418.9	5.9
23	2012.10.23.08.53	−33.8530	179.4020	195.0	5.9
24	2013.04.05.13.00	42.7130	131.1050	561.9	6.3
25	2013.04.21.03.22	−5.5179	146.8590	219.7	6.1
26	2013.05.23.17.19	−5.7808	154.4580	353.5	7.4
27	2013.06.15.11.20	−5.7825	148.3750	180.8	6.0
28	2013.07.24.03.32	−23.132	−177.2220	155.5	6.0
29	2014.03.02.20.11	27.4312	127.3670	119.0	6.5
30	2014.03.05.09.56	−14.7378	169.8230	638.0	6.3
31	2014.05.04.09.15	−24.6108	179.0860	527.0	6.6
32	2014.05.09.10.32	−18.9616	−175.5360	192.3	5.9
33	2014.06.30.19.55	28.3404	138.8440	511.0	6.2
34	2014.07.21.14.54	−19.8015	−178.4000	615.4	6.9
35	2014.11.01.18.57	−19.6903	−177.7590	434.0	7.1
36	2014.12.30.21.17	−20.3263	−178.5640	599.3	6.0
37	2015.03.16.03.00	−4.0737	152.0290	196.0	5.9
38	2015.04.28.16.39	−20.8865	−178.6330	581.0	6.1
39	2015.05.20.00.30	−19.3021	−175.5250	203.0	6.0
40	2015.06.16.06.17	−20.3944	−179.0020	656.0	5.9
41	2015.06.21.21.28	−20.4307	−178.3280	562.6	6.0
42	2015.06.23.08.59	−19.5686	−175.0400	138.0	5.5
43	2015.06.23.12.18	27.7375	139.7250	460.0	6.5
44	2015.07.07.20.03	−22.9379	−177.1330	169.6	5.8
45	2015.07.17.18.49	−18.1214	−178.1890	536.1	5.8
46	2015.11.02.03.04	−18.1736	−177.8380	608.4	5.6
47	2016.02.14.18.09	30.3018	138.8500	412.8	5.7
48	2016.05.27.04.08	−20.8101	−178.6480	567.5	6.4
49	2016.05.28.05.38	−21.9724	−178.2040	405.7	6.9

Table 1 continued

No.	Date	Latitude	Longitude	Depth	Mag (Mw)
50	2016.08.22.09.33	29.8965	139.1310	404.4	5.6
51	2016.08.25.17.04	30.6151	137.8460	456.0	5.9
52	2016.09.24.21.28	−19.7819	−178.2440	596.4	6.9

where V_{cmb} is the apparent velocity of the CMB, p is the ray parameter of PKKP$_{ab}$ diffraction wave and R_{cmb} is the radius of the core in the Earth.
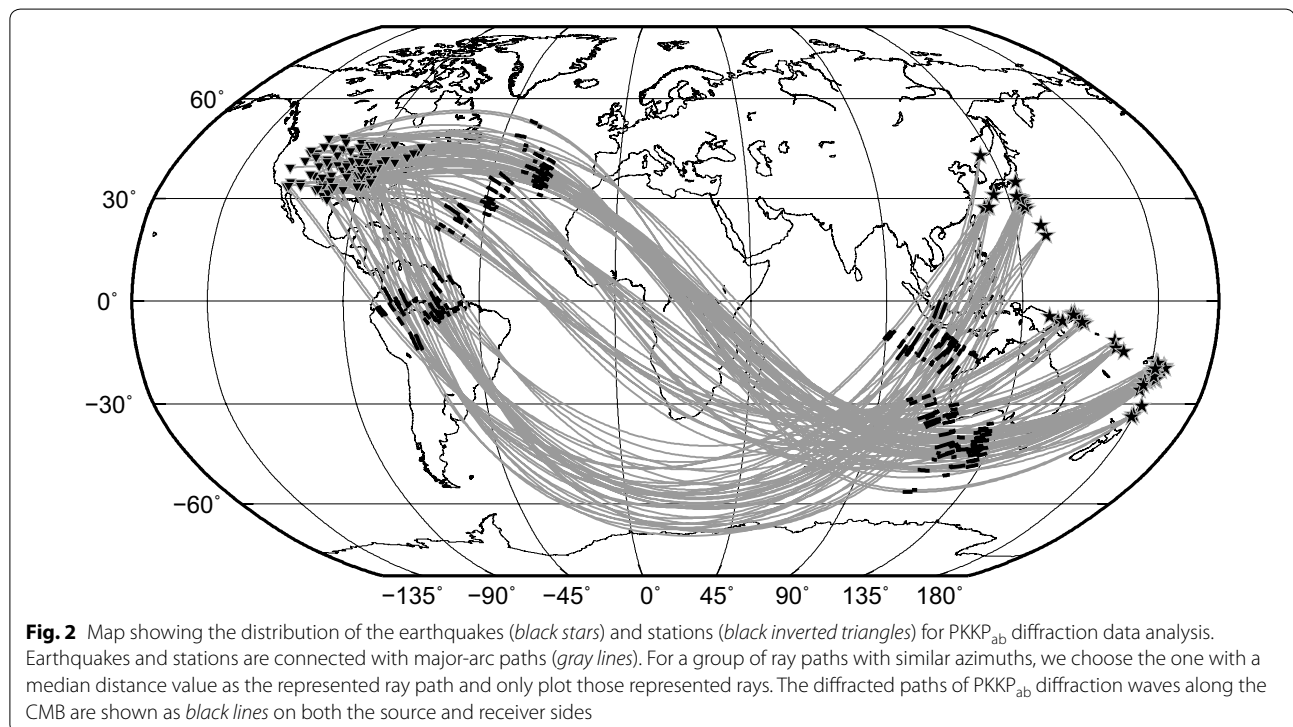
Considering the complex waveforms and the large apertures of the USArray, instead of using traditional methods such as beam forming or slant stacking (Rost and Thomas 2002), we adopted an alternative approach, the Radon transform method (we termed it as RTM hereafter) (Gu and Sacchi 2009; Schultz and Gu 2013), to calculate the ray parameters of PKKP$_{ab}$ diffraction waves. Radon transform is defined as:
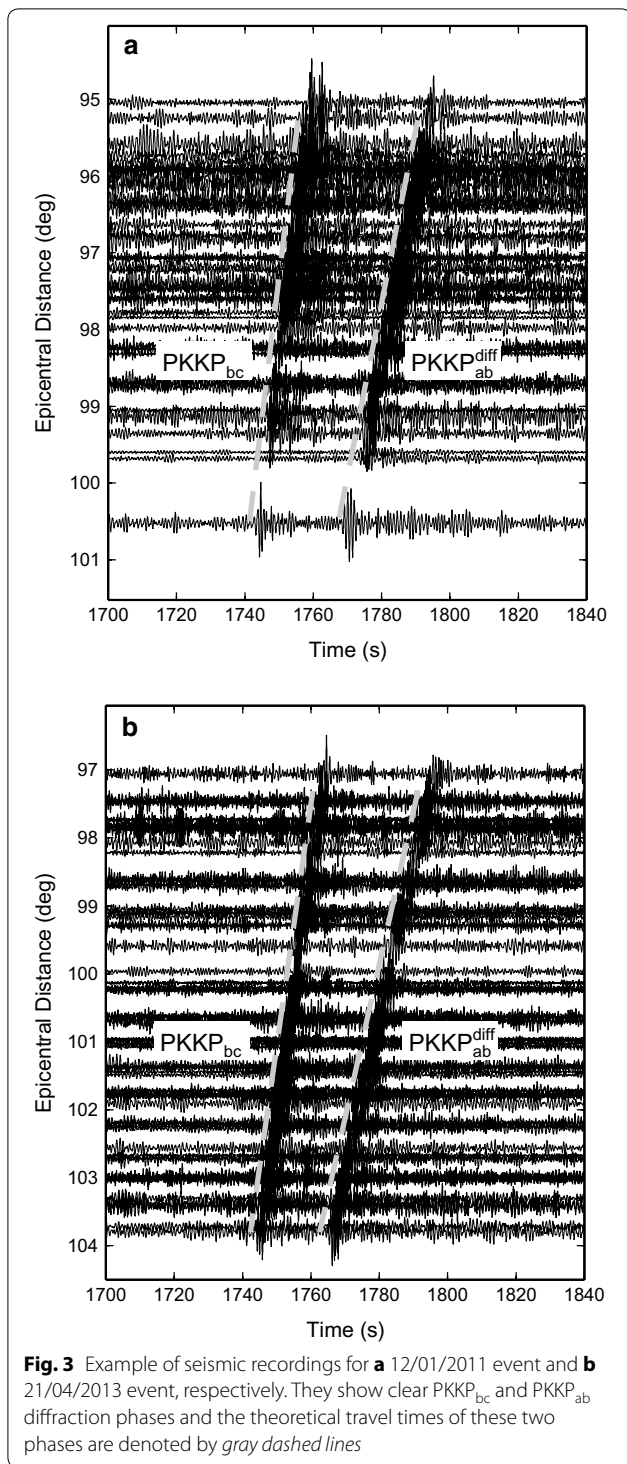
$$m(\tau, p) = \sum_{i=1}^{N} d(t = \varphi(\tau, \Delta, p), \Delta_i)$$

where φ is a time function that depends on reduced time τ, epicenter Δ and ray parameter p. In this study, we assumed a linear relationship with $\varphi(\tau, \Delta, p) = \tau + p\Delta$ for the analysis of PKKP$_{ab}$ diffraction wave owing to its geometric propagation path inside the Earth. RTM first transforms the data from $t - \Delta$ domain into $\tau - p$

domain and filters the transformed data in order to discriminate different ray parameters by inversion [details can be found in Gu and Sacchi (2009)]. The strongest energy focus in Radon (τ, p) domain corresponds to the expected ray parameter along which the data are stacked. The obvious advantage of RTM is that it could isolate the ray parameter based on inversion in $\tau - p$ domain, which is suggested to be more robust and reliable (Beylkin 1987; Sacchi and Ulrych 1995). Besides, this method could apply to a wider range of epicenter distances and is more efficient to phases whose ray parameters are very close than conventional stacking methods (Schultz and Gu 2013).

Before we use RTM, several procedures are carried out to ensure data quality and to reduce contaminations from heterogeneous structures in the mantle. Firstly, we calculated the amplitude envelope of all the seismograms. This procedure simplifies the complicated short-period waveforms without loss of general information (Eaton and Kendall 2006; Gu and Sacchi 2009), thus making it easier to handle. Then, we corrected ellipticity (Dziewonski and Gilbert 1976; Kennett and Gudmundsson 1996) and mantle heterogeneity through GyPSuM tomographic model (Simmons et al. 2010). Finally, we classified all the recorded data into different groups for every 5° according to their azimuths. Considering that the sampling regions of our data span about 30° in longitude and 75° in latitude at the CMB, this classification ensures that for each event, seismograms in the same group are aligned in almost the

Fig. 2 Map showing the distribution of the earthquakes (*black stars*) and stations (*black inverted triangles*) for PKKP$_{ab}$ diffraction data analysis. Earthquakes and stations are connected with major-arc paths (*gray lines*). For a group of ray paths with similar azimuths, we choose the one with a median distance value as the represented ray path and only plot those represented rays. The diffracted paths of PKKP$_{ab}$ diffraction waves along the CMB are shown as *black lines* on both the source and receiver sides

Fig. 3 Example of seismic recordings for **a** 12/01/2011 event and **b** 21/04/2013 event, respectively. They show clear PKKP$_{bc}$ and PKKP$_{ab}$ diffraction phases and the theoretical travel times of these two phases are denoted by *gray dashed lines*

unevenly distributed data in distance, in order to avoid possible bias from individual anomalous PKKP$_{ab}$ diffraction waves. After this selection, in total, we obtained 106 event–station subgroups (gray lines in Fig. 2). In the next step, RTM is applied to each subgroup separately to obtain ray parameters. Then, we converted all the ray parameters into P-wave velocities based on Eq. (1).

The obtained apparent velocity from ray parameter depends on the frequency of the waves and the velocity structures at the base of the mantle (Chapman and Phinney 1972; Mula and Müller 1980). Therefore, the apparent velocity in Eq. (1) is different from the actual velocity at the CMB (Mula and Müller 1980). However, in our study, the estimated sampling thickness for short-period PKKP waveforms is about one or two wavelength, which is on the order of tens of km above the CMB (Sylvander et al. 1997). Thus, the inferred apparent velocity is a good approximation of the actual velocity near the CMB.

Results

First, synthetic tests are carried out to validate the RTM we adopted. Considering our data are not sensitive to discontinuities (no top reflections at a discontinuity are observed) and the results are averaged velocities above the CMB, we tested two models modified from PREM, in which it has either a gradual P-wave velocity decrease from 0 to 8% (low velocity model) or increase from 0 to 6% (high-velocity model) in a 60-km layer atop the CMB (Fig. 4a). The choice of 60 km is because of its consistency with the thickness of general ULVZs and the resolution of our PKKP diffractions. Synthetic seismograms for a 500-km-deep earthquake are calculated using DSM (direct solution method) (Geller and Takeuchi 1995; Kawai et al. 2006) (Fig. 4b). The retrieved slownesses for the low velocity and high velocity models generally represent their characteristics of velocity change. Here we only show results from the low velocity model (Fig. 4b). It is obvious that the PKKP$_{ab}$ diffraction phases appear in the epicentral distances much shorter than its theoretical cutoff distance. The restored ray parameter for these synthetic seismograms from RTM is 4.520 s/deg, which is larger than that of PREM (4.428 s/deg) (Fig. 4c). The converted velocity according to Eq. (1) is ~2% slower than that of PREM. The recovered velocity from the high-velocity model is about +2.6%. Although the synthetic tests do not fully recover the averaged velocity changes in the input model (-4 and 3%), it is not surprising, considering the non-ray theoretical nature and finite-frequency effects of diffracted waves (Hosseini and Sigloch 2015). We then applied RTM to calculate the PKKP ray parameters for each subgroup of seismograms in our data. As an example, Fig. 5 exhibits the results of data in Fig. 3.
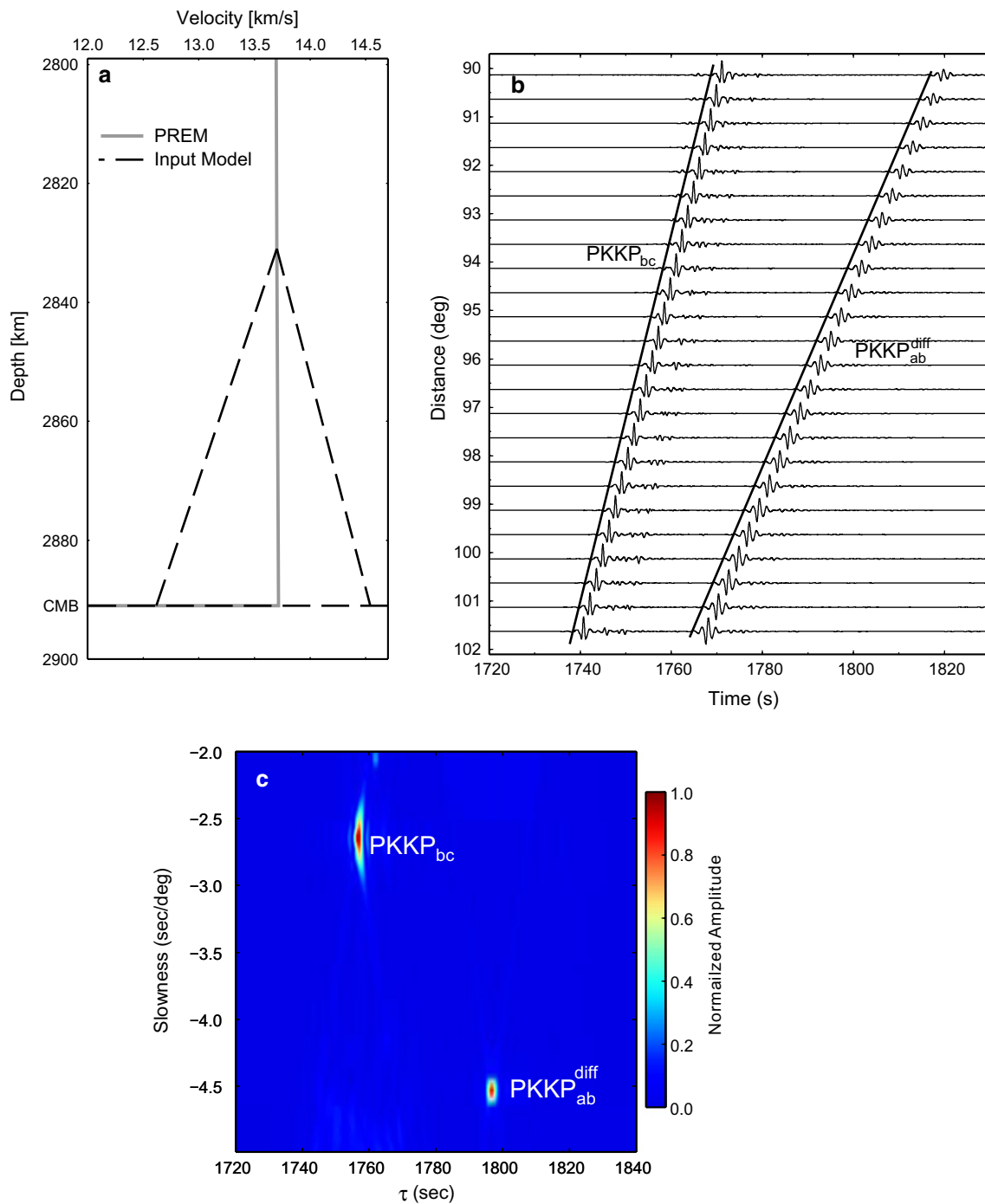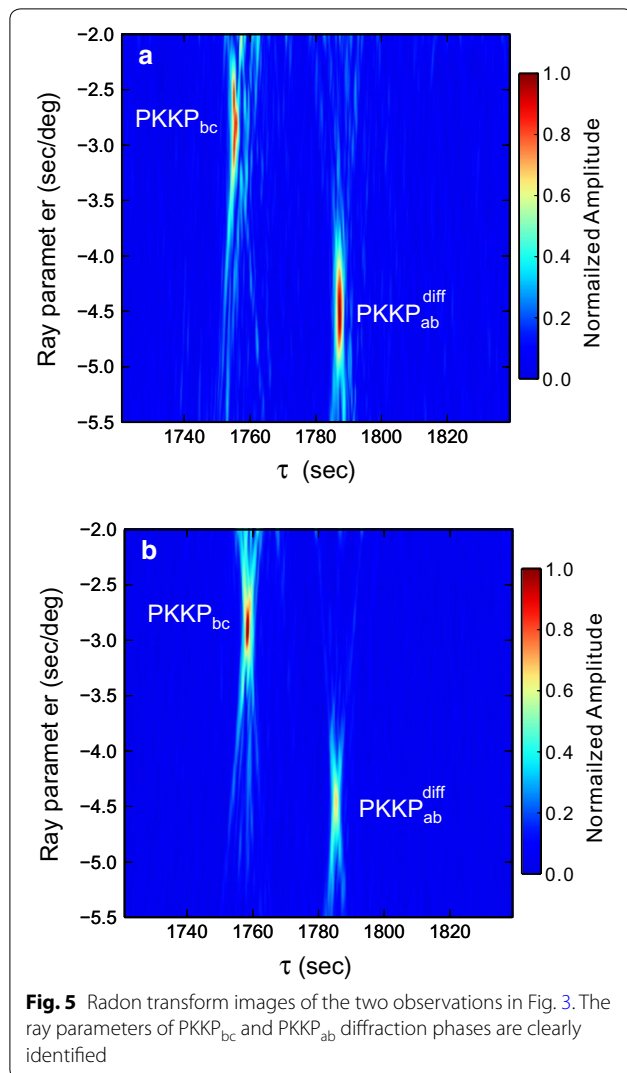
same great circle, thus avoiding azimuthal heterogeneity in the source and receiver regions. After grouping by azimuth, we further checked the number and distribution of the data in each subgroup and excluded the subgroups that have less than 10 seismic recordings and

Fig. 4 **a** Models used in synthetic tests of RMT. Compared to PREM (*gray line*), the test model (*black line*) has either a P-wave velocity decrease from 0 to 8% (low velocity model) or an increase from 0 to 6% (high-velocity model) in a 60-km layer atop the CMB. **b** Synthetic seismograms calculated using DSM for a 500-km-depth event based on the low velocity model in **a**. The seismograms are band-pass filtered with the same frequency band as the observed data. The *black lines* denote the travel times of PKKP$_{bc}$ and PKKP$_{ab}$ diffraction waves, respectively. **c** Radon transform image of synthetic seismograms in **b**. The normalized amplitudes (shown in *different color*) are energy of seismogram summations along their corresponding ray parameters

Fig. 5 Radon transform images of the two observations in Fig. 3. The ray parameters of PKKP$_{bc}$ and PKKP$_{ab}$ diffraction phases are clearly identified

The ray parameters of both PKKP phases can be identified very clearly.

Most of the PKKP$_{ab}$ diffractions can only be seen clearly in frequency bands between 0.5 and 2.1 Hz. To check the frequency effect on the velocity of PKKP$_{ab}$ diffraction, we choose several frequency bands and calculated their ray parameters separately. Figure 6 shows the histograms of ray parameters of PKKP$_{ab}$ diffraction waves in three different frequency bands (0.9–2.1, 0.5–1.5 and 0.5–2.1 Hz). The mean values of the ray parameter are 4.506, 4.517 and 4.503 s/deg, with standard deviations of 0.113, 0.093 and 0.114 s/deg, respectively. Similar results in different frequency bands suggest that velocity structures at the top of several tens of km above the CMB in this area are quite uniform.

The variations of the ray parameter are not from structures near the source/receiver, since the aperture of the stations and the earthquakes would average the difference effectively. The tomographic corrections for PKKP$_{ab}$ diffraction waves in the mantle are also rather small, indicating that the heterogeneity in the mantle may not be the cause either. It is also suggested that noise in the data or CMB topography could not account for such various and coherent ray parameter variations of PKKP$_{ab}$ diffraction waves (Sylvander et al. 1997; Doornbos 1980). Based on these evidences, we suggest that the variations in ray parameter should be from the complex structures along the CMB.

The converted velocity variations from ray parameters are plotted on the middle points of the diffracted paths along the CMB on both sides, with a P-wave tomographic model of mantle from GyPSuM (Simmons et al. 2010) as background (Fig. 7). The areas sampled by PKKP$_{ab}$ diffraction waves in this study are generally located along two "strips" at the CMB. On the source side, the sampled region starts from the southwest of Indonesia, extends across the southwest of Australia and ends up at southern Indian Ocean. On the receiver side, the region starts from the northeast side of South America, extends across the Atlantic Ocean and then ends at the northern part of Atlantic Ocean. Most of the sampled regions exhibit low velocity anomalies in the tomographic image, except for only a few high-velocity areas.

Discussion
ULVZs at the CMB

The inferred P-wave velocity perturbations along the CMB from PKKP$_{ab}$ diffraction waves exhibit a wide range, and show velocity reductions up to about 8.5%. We approximately divided the diffracted regions at the CMB into four regions, with two on the receiver side and their corresponding regions on the source side (as labeled in Fig. 7). In comparison with tomographic model of GyP-SuM, we found that the north region on the receiver side is located at the northwestern edge of African Anomaly (Ni and Helmberger 2003; Wang and Wen 2004, 2007; Sun and Miller 2013). Its corresponding region on the source side is in the southwest of Australia. The low velocity variations in these regions could be between −6.0 and −8.5%, which is quite similar to that of ULVZs. Since the southwest of Australia is a region with no low velocity signature or a low possibility of ULVZs (Thorne and Garnero 2004; Lay 2015), we suggest that the resulted P velocity heterogeneities are from the receiver side, the northwestern edge of African Anomaly.

Our results show an overall change of the velocity reduction from east to west in this region (Fig. 8), with the strongest velocity reduction (∼8.5%) in the eastern part (near the northwestern edge of African Anomaly). We binned the P-wave velocity reductions using a 10-degree moving window with a 5-degree overlap.
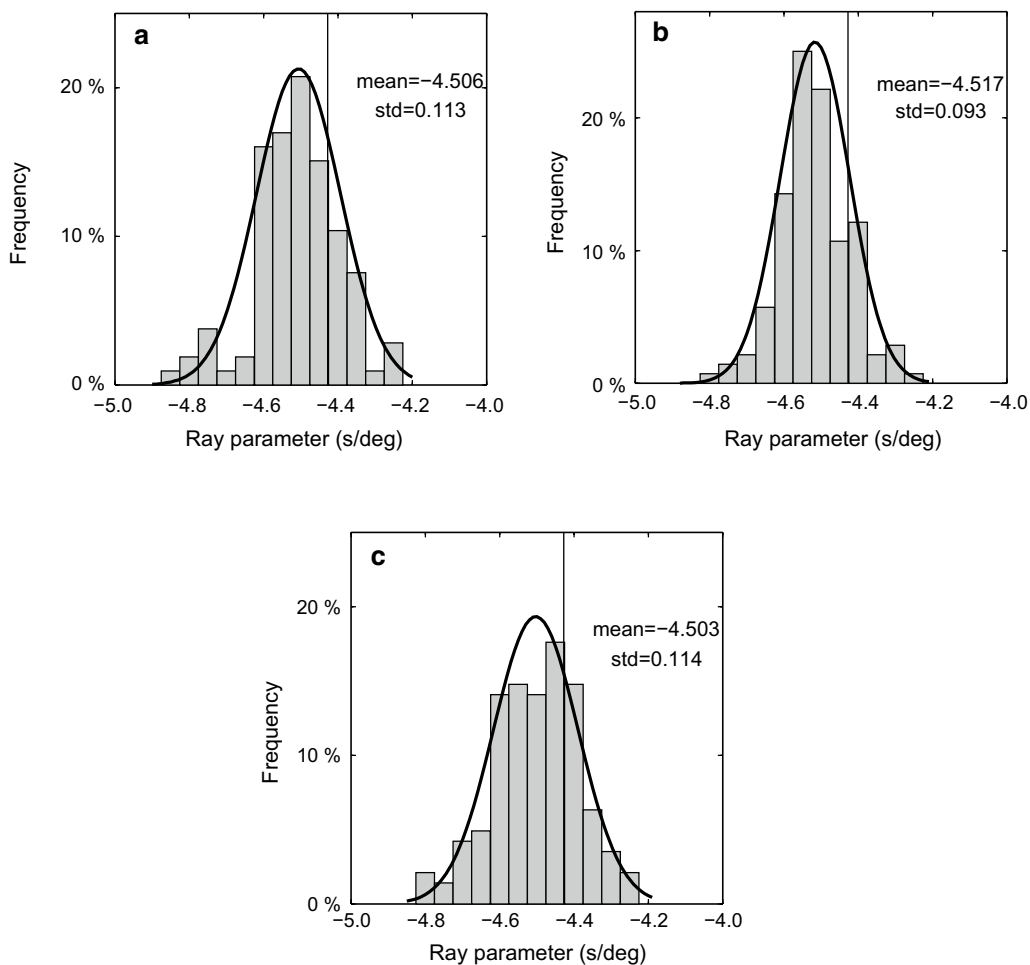
Fig. 6 a *Histogram* of PKKP$_{ab}$ diffraction ray parameters after ellipticity and mantle heterogeneity corrections. The seismograms are band-pass filtered between 0.9 and 2.1 Hz. The mean value of the ray parameters is 4.506 s/deg, and the standard deviation is 0.113 s/deg. The *vertical black line* denotes the theoretical ray parameter of PKKP$_{ab}$ diffraction calculated for PREM. **b**, **c** same as **a**, but for the ray parameter distribution of PKKP$_{ab}$ diffractions from 0.5–1.5 Hz and 0.5–2.1 Hz bands, respectively

There is an overall trend that the slow anomalies decrease gradually with the increase in longitude, although it is not very strong. This may indicate that ULVZs are closely related to the boundary of LLSVP (Thorne et al. 2004; McNamara et al. 2010; Hier-Majumber and Drombosky 2016), and the velocity reduction in ULVZ may also be associated with its distance to LLSVP. Further investigations with more data may be needed.

Thorne and Garnero (2004) have systematically studied the global SPdKS waves and proposed a ULVZ likelihood map. Our region in the northwestern side of African Anomaly in general agrees with the region of high ULVZ likelihood in their map, but extends further west. Using PKKP data recorded by Yellowknife array, Rost and Garnero (2006) also mapped ULVZs in a region located further north of our study region, with a similar lateral extension. Their results did not show systematic velocity

changes, but they did notice that PKKP$_{ab}$ diffraction waves sampling the west of the region show larger departures from theoretical ray paths than those to the east.

Some low velocity zones with velocity reductions of 3–5% are also detected on the source side beneath southern Sumatra Islands. Their corresponding regions on the receiver side are in the northeast of South America. South America is a region that generally shows high-velocity anomalies in various tomographic models (Zhao 2004; Li et al. 2008; Simmons et al. 2010) and shows low likelihood in SPdKS study (Thorne and Garnero 2004). Therefore, this region is unlikely to cause the low velocities we observed. In other words, the velocity reductions in region 2 more likely result from the CMB beneath southern Sumatra Islands.

The high-velocity anomalies (up to 4%) in region 2 are more likely to be related to subducted slabs, thus making

Fig. 7 P-wave velocity variations plotted at the middle points of diffracted paths of $PKKP_{ab}$ in two regions (marked by *box 1* and *2*) at the CMB. Slow and fast are shown using *black crosses* and *gray circles*, respectively. The background is the *P*-wave tomographic model at the CMB from GyPSuM (Simmons et al. 2010). The *gray stars* denote the earthquakes, and the *gray inverted triangles* denote the stations

Fig. 8 P-wave velocity anomalies at the CMB near African Anomaly plotted as a function of sampling longitude. Slow and fast anomalies are shown in *gray crosses* and *black circles*, respectively. The binned data (*gray solid circles* with one standard deviation) are calculated with a 10-degree moving window and a 5-degree overlap. Although there are several fast anomalies, the slow anomalies show a trend that the values decrease gradually with the increase of longitude, meaning the closer they are to the African Anomaly, the larger P-wave velocity reductions they exhibit

the north of South America a good place for these heterogeneities. However, in the corresponding source side beneath southern Sumatra Islands, the high velocities are located on both sides of the slow anomaly, which

we cannot definitely rule out the contribution from this region either. In this case, we could not clearly solve the origin ambiguity of $PKKP_{ab}$ diffraction anomalies, although South America could provide a more proper explanation. It is noted that the high-velocity anomalies could not merely result from the temperature change, because such change would be too much under the CMB conditions (Wentzcovitch et al. 2006). We suggest that chemical changes in the subducted oceanic crust may also play an important role in this case.

In general, our results show strong lateral velocity variations that can change between −8.5% and up to +4.2%, which is consistent with the magnitude of velocity perturbations from both global (e.g., Sylvander et al. 1997) and regional studies (e.g., Xu and Koper 2009). These strong lateral heterogeneities are much larger than those calculated from global tomographic models and imply significantly complex structures at the CMB that have long been known to exist [see Garnero (2000); Lay and Garnero (2011) for a review], even on the small-scale level (Ma et al. 2016; Sun et al. 2016). The explanations for these heterogeneities, however, are still inconclusive. Wysession et al. (1992) correlated the strong lateral heterogeneity at the CMB with core flow models from geomagnetics (Voorhies 1986). They demonstrated that the

adjacent fast and slow regions possibly correspond to areas of core upwelling and down welling, respectively. Other explanations probably include chemical variations and/or thermal variations [see Tackley (2012) for a review]. For the origin of ULVZ-like structures, partial melt (Williams and Garnero 1996; Berryman 2000; Lay et al. 2004; Hernlund and Tackley 2007) or iron-enriched lower mantle materials introduced by subducted paleo-slabs (Dobson and Brodholt 2005) or core interactions from below (Sakai et al. 2006) may provide reasonable explanations (Wicks et al. 2010; Bower et al. 2011).

Comparison with previous studies

Unlike previous studies (Rost and Garnero 2006), in this study, we did not carry out the analysis of absolute travel times of $PKKP_{ab}$ diffraction or relative travel times with respect to $PKKP_{bc}$. Travel time analysis, though, could verify our results inferred from ray parameters. However, in the short-period (0.5–2.0 s) recordings, both $PKKP_{ab}$ diffraction waves and $PKKP_{bc}$ waves are strongly affected by the high-frequency coda waves from scattering in the lithosphere, making it difficult to pick their onsets. In contrast, ray parameter analysis is less biased by small-scale inhomogeneities near the source and along the descending legs of the ray as long as the receivers are aligned closely in great circle paths (Ivan et al. 2015).

Global/regional studies of P_{diff} (e.g., Wysession and Okal 1989; Wysession et al. 1992; Sylvander et al. 1997; Ivan et al. 2015) generally determine ray parameters based on equation $p = dT/d\Delta$, where T is the travel time of a target phase and Δ is the epicentral distance. For dense seismic arrays, beam forming or slant stacking (Rost and Thomas 2002) is often used, assuming incoming waves are plane waves. However, in our study, the onsets of $PKKP_{ab}$ diffraction waves are hard to recognize in high-frequency waveforms; thus, the first method is not suitable. On the other hand, the distance of our data spans about 10°, so beam forming or slant stacking method is not proper either (Thomas et al. 1999). The RTM we adopted in this study could isolate different ray parameters by inversion in $\tau - p$ domain, which not only fits the data globally, but also can effectively isolate similar ray parameters with less uncertainty. Although the RTM has been used previously in mid-mantle studies (e.g., An et al. 2007; Gu et al. 2009), this is the first time we successfully apply it to PKKP signals of a large distance range.

In general, $PKKP_{ab}$ diffractions have no power to resolve the ambiguity of CMB heterogeneity locations. To resolve this problem, one way is to compare with other phases that sample similar regions, at least in one side, such as PcP, ScP, SPdKS and PKP (e.g., Idehara 2011; Jensen et al. 2013; Ma et al. 2016). In most cases, this may

be difficult to do because of limited earthquake and station distributions. Then, the much easier way is to compare with mantle tomographic models, since small-scale structures are usually related to large-scale heterogeneities as indicated in tomography models (Zhao 2004; Montelli et al. 2006; French and Romanowicz 2015). Nevertheless, more characteristics of PKKP waves may be needed to identify anomaly locations.

Conclusions

We have examined diffracted $PKKP_{ab}$ waves from 52 earthquakes occurring along the boundary of Western Pacific and recorded by USArray. Ray parameters of $PKKP_{ab}$ diffraction waves are determined using the Radon transform method and then converted to velocity variations in the sampling regions at the base of the mantle. Our results show that beneath the northwestern edge of African Anomaly and southern Sumatra Island, the velocity reductions are as large as about -8.5%, which suggests the existence of ULVZs. The velocity change in northern Atlantic Ocean may indicate different effects that LLSVP plays on ULVZs according to the distance away from it. It should be also noted that although $PKKP_{ab}$ diffractions enable us to resolve small-scale structures at the CMB and improve the sampling coverage, intrinsic ambiguity exists in identifying the exact areas of velocity anomaly. More evidences from tomographic models and additional phases such as SPdKS and ScP are needed to solve this problem in the future.

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