Detection of an ultralow velocity zone at the CMB using diffracted \( PKKP_{ab} \) waves

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Abstract

Seismic phases diffracted around Earth’s core contain information about lowermost mantle wave speeds. By measuring the slowness of incident diffracted energy from array recordings, seismic velocity along the diffracted path can be estimated. Here we apply this principle to diffraction of the major-arc seismic phase \( PKKP_{ab} \) recorded at the Canadian Yellowknife array to estimate \( P \)-wave velocity variations along the core-mantle boundary. We observe \( PKKP_{ab}^{\text{diff}} \) about 7.5 degrees past the ray-theoretical cut-off distance for \( PKKP_{ab} \). We utilize 330 western Pacific rim earthquakes that allow us to probe the core-mantle boundary beneath the north Atlantic and the south Pacific Ocean using \( PKKP_{ab}^{\text{diff}} \). Slowness and backazimuth are measured by frequency-wavenumber analysis. Mapping \( PKKP_{ab}^{\text{diff}} \) slowness variations suggest 4 to 19\% \( P \)-wave velocity reductions relative to PREM, in good agreement with the magnitude of velocity reductions previously mapped in ultra-low velocity zones. The \( PKKP_{ab}^{\text{diff}} \) slowness and backazimuth variations combined with results from previous ULVZ studies using \( SP_{ab}^{\text{diff}}KS \) imply that the lowered velocities occur at the base of the mantle beneath the north Atlantic Ocean, along the receiver side of raypaths. \( PKKP_{ab}^{\text{diff}} \) array measurements thus hold important potential for mapping ultra-low velocity zone structure in so far
unprobed regions of the lower mantle, as well as for providing additional and independent information about lower mantle structure.

**Introduction**

Strong elastic heterogeneities have been mapped close to the core-mantle boundary (CMB) over the last 20 years [see *Garnero*, 2000 for a recent review]. Detected structures include a discontinuity on top of the D" layer [*Lay and Helmberger*, 1983; *Young and Lay*, 1990; *Wysession et al.*, 1998] perhaps due to a phase transition in perovskite [*Murakami et al.*, 2004; *Lay et al.*, 2005], anisotropy in D" [*Kendall and Silver*, 1996; *Lay et al.*, 1998; *Kendall*, 2000], strong reductions of seismic velocities in ultra-low velocity zones (ULVZ) [*Garnero and Helmberger*, 1996.; *Revenaugh and Meyer*, 1997; *Thorne and Garnero*, 2004; *Rost et al.*, 2005], strong scattering of seismic energy [*Vidale and Hedlin*, 1998; *Wen and Helmberger*, 1998; *Hedlin and Shearer*, 2000] and rigid layers at the top of the outer core [*Buffett et al.*, 2000; *Rost and Revenaugh*, 2001]. The large variety of heterogeneities found at or near the CMB is not unexpected for such a major thermal and chemical boundary layer in the Earth’s interior. Despite the large number of seismic studies of CMB structure, many questions of the evolution and dynamics of structural features at the CMB remain open. Additionally, large areas of the CMB have not yet been probed.

ULVZ are one of the most enigmatic features found at the CMB. Lateral scale-lengths of ULVZ range from several thousands of kilometers [*Garnero et al.*, 1998; *Thorne and Garnero*, 2004] to tens of kilometers [*Rost and Revenaugh*, 2003a; *Rost et al.*, 2005]. ULVZ thickness have been mapped between 4 to 50 km with *P*-wave and *S*-wave reductions of 5 to 40% [*Revenaugh and Meyer*, 1997; *Garnero*, 2000; *Rost and Revenaugh*, 2003a; *Thorne and Garnero*, 2004], and a notable increase of density has also been inferred [*Rost et al.*, 2005; *Garnero et al.*, 2005].
Several interesting features of ULVZ include their non-global occurrence, clear ULVZ detections often in close proximity to ULVZ non-detections [Persh et al., 2001; Thorne and Garnero, 2004; Rost and Revenaugh, 2003a; Rost et al., 2005], and their difference in P- and S-wave velocity reductions [Castle and van der Hilst, 2000]. Due to restrictions of source-receiver combinations and a limited number of seismic phases sensitive to ULVZ structure, many regions of the Earth have not been probed for ULVZ structure so far. Nonetheless, to better understand the dynamics and evolution of ULVZ and their role in mantle convection, a more complete sampling of the CMB for possible ULVZ regions and their seismic properties is essential.

Here we propose to use the diffracted path of $PKKP_{ab}$, a phase observed up to several degrees beyond its ray-theoretical distance of termination, to map the seismic velocities at the CMB. In particular, the slowness of short-period $PKKP_{ab}^{\text{diff}}$ arrivals, provide a constraint on the small-scale seismic velocity variations at the CMB. $PKKP_{ab}^{\text{diff}}$ samples lower mantle regions that are not accessible by phases like $PcP$ or $ScP$ with current earthquake–receiver geometries; also, $PKKP_{ab}^{\text{diff}}$ can be used in combination with phases like $SP_{ab}^{\text{diff}}KS$ to improve constraints on ULVZ structure. Diffracted P-wave phases have been used to map structures in the lowermost mantle before [e.g. Okal and Geller, 1979; Mula and Müller, 1980; Wysession and Okal, 1989; Young and Lay, 1990; Bataille and Lund, 1996; Wysession, 1996; Wysession et al., 1999], though these efforts primarily focused on bulk $D^\prime$ properties.

In the next section, we introduce ULVZ modeling with $PKKP_{ab}^{\text{diff}}$, as well as constraints and uncertainties of this phase. This is followed by an investigation of CMB structure in the north Atlantic using array analysis of $PKKP_{ab}^{\text{diff}}$ where we document slowness and traveltime anomalies to infer strong and variable ULVZ properties.
**PKKP**

PKKP is a P-wave that travels along the major-arc of the great-circle path (Fig. 1a). It consists of two mantle P-wave legs and two core P-wave legs with a reflection at the underside of the CMB. The ray-theoretical cut-off epicentral distance for PKKP_{ab} for a surface focus earthquake in the PREM reference model [Dziewonski and Anderson, 1981] is approximately 102.42 degrees (minor-arc distance). Diffraction of PKKP_{ab} occurs for shorter minor-arc epicentral distances, since PKKP_{ab} travels along the major-arc of the path (Fig. 1b). In the remainder of this paper we always refer to minor-arc distances. In theory, the diffraction can occur at either the source or receiver sides (or both) of the ray path (Fig 1a shows equal length diffraction segments).

PKKP has been used to study CMB structure in past studies [Doornbos, 1980; Earle and Shearer, 1997; Rost and Revenaugh, 2003b]. PKKP energy is dominant in short-period seismograms and is often the dominant phase arriving about 1000s after direct P (see Fig. 2). The travel-time branches of the PKKP triplication (PKKP_{ab}, PKKP_{bc}, PKKP_{cd} and PKKP_{df}) can often be easily identified, although PKKP_{df} and PKKP_{cd} are sometimes difficult to detect due to their low amplitude. The PKKP_{ab} and PKKP_{bc} branches are separated by a slowness difference of approximately 1.5 s/deg (which slightly varies with epicentral distance). These slowness differences can easily be resolved in short-period data from small or medium aperture arrays with apertures of a few ten’s of kms.

**Short Period Array Dataset**

We collected data from more than 330 western Pacific rim earthquakes deeper than 60 km recorded at the Yellowknife array (YKA). This Canadian array has an aperture of 20 km and consists of 18 short-period vertical-component instruments (Fig. 3). This selection represents all seismicity with a magnitude larger than 5.5 in the appropriate
distance range for $P_{\text{PKP}}^{\text{diff}}$ (89 to 117 deg) from the western Pacific from September 1989 to March 1996. Data were checked for obvious errors such as spikes and instrument outage and then band-pass filtered with a narrow filter between 0.5 Hz and 1.4 Hz optimizing the signal-to-noise ratio of $P_{\text{KK}}$.

We use phase-weighted stacking (PWS) [Schimmel and Paulssen, 1997] for better identification of $P_{\text{KK}}$ arrivals in slowness-time space and precise travel time measurements. We were able to detect $P_{\text{PKP}}^{\text{diff}}$ and/or $P_{\text{KKPbc}}$ arrivals in recordings of 131 earthquakes. We exclude earthquakes with distances larger than 104 deg where no $P_{\text{PKP}}^{\text{diff}}$ arrivals are expected (e.g., Fig. 1b). The raypaths for these 131 events are shown in Fig. 3. The CMB diffracted pathlengths are shorter than about 7.5 degrees or less than 455 km at the CMB.

Third-power PWS [Schimmel and Paulssen, 1997] processed data are shown in Fig. 4 and show that slowness differences between $P_{\text{KKPbc}}$ and $P_{\text{PKP}}^{\text{diff}}$ are easily resolvable. $P_{\text{KKP}}$ traveltimes are measured in the PWS stacked data (Fig. 5). Traveltime measurements are accurate to 0.2s.

To estimate seismic velocities along the CMB, events with a signal-to-noise ratio of $P_{\text{PKP}}^{\text{diff}}$ larger than 3 were selected. In total, 26 events meet this criterion. For these events, $P_{\text{PKP}}^{\text{diff}}$ can be identified in single seismograms (as in Fig. 2). Using frequency-wavenumber analysis [Capon, 1973], the slowness and backazimuth were measured for these events (Figs. 6 and 7). These measurements will be used in the following to determine the $P$-wave velocity along the diffracted path.

**Analysis and Results**

We measure travel times of dominant arrivals ($P$, $P_{\text{diff}}$, $PKiKP$, $P_{\text{KKPbc}}$ and $P_{\text{PKP}}^{\text{diff}}$) in the 131 earthquakes that show $P_{\text{KKP}}$ energy in the 3rd power PWS. The
event information for these events is given in the online supplemental material. Fig. 5 shows traveltimes for $PKKP_{ab}$ and $PKKP_{hc}$ (the measurements for $P$ and $PKiKP$ are omitted for clarity). The traveltimes were corrected for source depth differences using the PREM model. $PKKP_{hc}$ and $PKKP_{ab}^{\text{diff}}$ traveltimes display significant variability (Fig. 5). $PKKP_{hc}$ arrives on average about 3 s and $PKKP_{ab}$ about 4 s later than predicted by PREM, indicating three-dimensional wave-speed variations along the $PKKP$ paths. The traveltimes of $PKKP_{ab}^{\text{diff}}$ are a clear continuation of the $PKKP_{ab}$ traveltime branch beyond the ray-theoretical termination at about 102 deg defining the start of the diffracted path.

Results of the fk-analysis for $PKKP_{hc}$ and $PKKP_{ab}^{\text{diff}}$ are shown in Fig. 6. $PKKP_{ab}^{\text{diff}}$ shows in general larger slownesses than predicted by PREM with an average of $+0.53\pm0.22$ s/deg. Backazimuth varies with variations of $0.2\pm3.9$ deg. Despite the small overall backazimuth variation, there are some trends observable in the backazimuth deviations for $PKKP_{ab}^{\text{diff}}$. But these deviations are below the backazimuth resolution of the medium-aperture YKA, which has been found to be able to resolve backazimuth variations of approximately $\pm8$ deg [Rost and Weber, 2001]. We find that slowness variations for $PKKP_{ab}^{\text{diff}}$ are in the range of 0.2 to 0.8 s/deg. Slowness variations of this scale can be easily detected and resolved by YKA [Rost and Weber, 2001].

Slowness and backazimuth measurements for $PKKP_{hc}$ from the same recordings show stronger and more complicated variations, especially for backazimuths smaller than 260 deg. Backazimuth deviations are dominantly towards the east. In contrast to $PKKP_{ab}^{\text{diff}}$ the $PKKP_{hc}$ backazimuth deviations for backazimuths smaller than 260 deg can be easily resolved by YKA. Slownesses perturbations of $PKKP_{hc}$ are larger and smaller than those predicted by PREM, without any apparent geographical systematics, in contrast to $PKKP_{ab}^{\text{diff}}$ where only larger slownesses then PREM are observed. $PKKP_{hc}$ traveltimes in
the distance range from 95 to 105 deg are very similar to phases traversing \((PKiKKIKP\) or \(PKKP_{ab}\)) and reflecting off the inner core \((PKiKKiKP\) or \(PKKP_{cd}\)) (Fig. 1) with slownesses of about 1.8 s/deg and 2.0 s/deg, respectively. Interference of \(PKKP_{bc}\) with these phases could also influence its slowness, depending on the amplitudes of \(PKKP_{ab}\) and \(PKKP_{cd}\).

Measuring \(PKKP_{ab}^{\text{diff}}\) slowness and backazimuth relative to \(PKKP_{bc}\) allows to estimate the influence of structure close to source and receiver. We observe that relative slowness variations of \(PKKP_{ab}^{\text{diff}}\) are comparable to the ones shown in Fig. 6, indicating that structure close to source and receiver (which are sampled by \(PKKP_{ab}^{\text{diff}}\) and \(PKKP_{bc}\)) are not the main source for the slowness variations.

Slowness and backazimuth measurements from seismic arrays are strongly influenced by lateral variations of the seismic structure beneath the arrays [Krüger and Weber, 1992]. YKA shows very small mislocation vectors [Bondar et al., 1999] and the structure beneath the array has been found to be simple with an almost constant Moho depth of 39.4 km [Bank et al., 2000]. We can also rule out intra-array topography as source for the slowness variations, since YKA shows only station elevations from 170 m (station YKR1) to 221.6 m (station YKB0). We conclude that near source and receiver structure are unlikely to bias the slowness measurements and the slowness variations indeed originate from structures in the deep mantle.

Since the mantle paths (and core entry and exit points) of \(PKKP_{bc}\) and \(PKKP_{ab}^{\text{diff}}\) differ strongly (Fig. 1) a direct comparison of \(PKKP_{ab}^{\text{diff}}\) and \(PKKP_{bc}\) to resolve CMB or lower mantle structure is not possible. Strong variations in mantle velocities along the \(PKKP_{bc}\) path are necessary to explain the significant slowness and backazimuth scatter seen in Fig. 6. It is likely that \(PKKP_{ab}^{\text{diff}}\) shows less slowness and backazimuth variation since the receiver-side path is restricted to be along the CMB due to diffraction. Thus, the
upgoing $PKP_{ab}^{\text{diff}}$ energy should represent the slowness for diffracted energy along the CMB.

Apparent velocities $v_o$ at the CMB from the measured $PKP_{ab}^{\text{diff}}$ slownesses $u$ can be calculated using $u = \frac{R_o \cdot \sin(i)}{v_o}$ with $R_o = \frac{R_E - r}{R_E}$ and $r$ being the depth of the diffracted raypath, $R_E$ being the radius of the Earth. Fig. 7a shows the distribution of inferred velocity changes (relative to PREM) along the diffracted paths. The velocity changes are only shown at the receiver side of the path, while the source side paths are marked by red lines (Fig. 7b shows a magnification of the sampled receiver side patch). Due to the reciprocity of the seismic path, both the source and receiver CMB entry points and the CMB underside reflection points can be the region where diffraction happens. We checked waveforms for dual $PKP_{ab}^{\text{diff}}$ onsets, which would indicate different speeds of diffraction on the source and receiver sides of the $PKP_{ab}$ path. For example a combination of a PREM and non-PREM (e.g. ULVZ) CMB velocity structure at the source- and receiver side of the $PKP_{ab}^{\text{diff}}$ path would produce multiple onsets. The absence of such waveform anomalies may indicate a focusing of the energy along the CMB in a ULVZ waveguide on one side of the path yielding high (and observable) amplitudes of $PKP_{ab}^{\text{diff}}$ or similar velocity structures along both diffracted legs. All $PKP_{ab}^{\text{diff}}$ waveforms in our dataset show single arrivals with waveforms similar to $P$, and similar to a Hilbert-transformed $PKP_{hc}$, as expected [Doornbos, 1980]. An earlier study of CMB ULVZ structure [Thorne and Garnero, 2004] indicates that the region beneath the southern Pacific Ocean does not show evidence for strong ULVZ structure, while the studied area beneath the northern Atlantic Ocean likely contains ULVZ at the CMB [Thorne and Garnero, 2004]. Additionally, $PKP_{ab}^{\text{diff}}$ shows much smaller backazimuth deviations from theoretical predictions than $PKP_{hc}$. The strongest
heterogeneities in the Earth are found in the upper mantle (where the raypaths of $PKKP_{bc}$ and $PKKP_{ab}^{\text{dif}}$ are very similar) and at the CMB (where the two paths differ the most) [e.g. Lay et al., 2004]. The small backazimuth variations of $PKKP_{ab}^{\text{dif}}$ suggest the diffracted leg is not located at the receiver-side of the path, as this would result in larger variations towards the end of the $PKKP_{ab}^{\text{dif}}$ path. We therefore assume that the anomalous diffraction observed here is limited to the receiver side of $PKKP_{ab}^{\text{dif}}$ paths. Further studies using $PKKP$ and other CMB probes that result in crossing paths will give more constraints on the location of the anomalous velocity structure.

The small grey circles in Fig. 7b mark the ray-theoretical end-points of the diffracted paths for PREM slowness and backazimuth values. The backazimuth deviations are in agreement with the ones shown in Fig. 6, with stronger deviations to the west. The shortest diffracted segments in this region show the smallest decrease of apparent velocity, which is consistent with an integrative effect along the diffracted path segment. The eastern and center portions of the study area show slightly smaller reductions (0 to 10%), again the shorter paths in this regions show smaller velocity reductions.

Discussion and Conclusions

The calculated $P$-velocity reductions at the CMB are between 4 to 19 (±4)% relative to PREM. These reductions are significantly larger than those inferred for D" from longer period diffracted phases, which are in the range of 2% [e.g. Wysession et al., 1999], and more similar to reductions reported for ULVZ reductions [Mori and Helmberger, 1995; Garnero and Helmberger, 1996; Rost and Revenaugh, 2003a]. The shorter periods used in this study are sensitive to finer scale ULVZ structure due to their smaller Fresnel volume. Unfortunately, we lack independent information about the thickness of the ULVZ in this region. A minimum thickness of about 10 to 20 km can be inferred from
the ~13 km wavelength of the data with 1 s dominant period. The velocity reductions mapped in Fig. 7 show some complicated, fine-scale structure that makes it difficult to find one model to fit the observations. Both the location and the length of the diffracted paths affect the apparent velocity reductions. Nonetheless, this type of variation within general ULVZ locales is similar to that seen in previous studies [e.g. Garnero and Helmberger, 1996; Thorne and Garnero, 2004]. Fig. 7a also shows P-wave tomography [Karason and van der Hilst, 1999] with velocity variations |δVp| > 0.4 % in grey shading, indicating that we sample the edge of a very slow region of the Earth. The slow region is may be the northern extension of the South-African anomaly [Ni and Helmberger, 2003; Wang and Wen, 2004]. It has been speculated that these structures are thermo-chemical piles [Wen et al., 2001; Wen, 2001; Tackley, 2002; McNamara and Zhong, 2004, 2005] and ULVZ have been detected at the boundaries of slow regions of the Earth’s lower mantle before [Thorne et al., 2004; Rost et al., 2005]. There are indications that ULVZ primarily develop in the hot regions at the outer edges of these features [Garnero et al., 2005].

Tomographic corrections for PKKP are much smaller than the measured travelt ime variations and traveltime delays calculated from the detected ULVZ velocity reductions and are probably not the source for the slowness variations found in this study. For example, we find average traveltime corrections due to mantle P-wave structure for all source-receiver combinations with a mean of -0.18 (±0.08) s for the model by Karason and van der Hilst [2001]. Eastern events (with the westernmost receiver-side CMB diffraction paths) show the largest corrections, between -0.2 and -0.3 s. Events further to the west (with diffracted paths further east) show small corrections between -0.1 and -0.2 s. This greatly underpredicts our PKKP delays, which change between 2 and 4 s.

The area sampled by PKKP located in the northern Atlantic Ocean has been studied previously using SPKS [Garnero et al., 1993; Helmberger et al., 1998;
Helmberger et al., 2000; Thorne and Garnero, 2004] and has been found to show evidence for ULVZ. Indeed, data sampling the CMB slightly south of our study area show some very anomalous $SP_{dK}$ waveforms due to a large amplitude postcursor that is best modeled by a strong ULVZ [Michael Thorne, personal comm., 2005]. Strong variability in ULVZ structure has been reported, which makes it difficult to distinguish between a continuous ULVZ layer (in larger scale ULVZ areas) or ULVZ patches, as found in the work of Rost et al. [2005].

We find that the ULVZ velocities are able to explain the traveltime anomalies found for $PKP_{ab}$ (Fig. 3) as well as the slowness variations. A diffraction path length of 4 deg (7 deg) degrees through a ULVZ with 5 to 15% $P$-wave velocity reductions will lead to traveltime anomalies of 1 (1.6) seconds for a 5% velocity reduction and 3.1 (5.5) seconds for a 15% $V_p$ anomaly, which are of the same order as observed in our data. Therefore, our interpretation of the slowness deviations originating from ULVZ is consistent with the measured travel time delays.

Although $PKP_{ab}$ possesses the source-receiver ambiguity of distinguishing between the source or receiver diffracted paths as the source of anomalous observations, not unlike $SP_{dK}$ or $PKP$, it holds potential to fill geographic gaps in the maps of ULVZ study areas due to its unique source-receiver geometry possibilities. The combination of $PKP_{ab}$ with other ULVZ probes, such as $SP_{dK}$, to reduce the inherent source-receiver ambiguity of these probes is desirable, and will be pursued in future work.

Preliminary studies using data from different arrays (e.g. Large Aperture Seismic Array (LASA) [Frosch and Green, 1966] and Gräfenberg Array (GRF) [Buttkus, 1986]) show that the strong $PKP_{ab}$ arrivals for distances about 7.5 degrees past the ray-theoretical cut-off distance as documented in this manuscript for YKA are present elsewhere (Fig. 8). This shows that recordings of this phase from arrays with varying
apertures can be widely used to improve ULVZ detection and characterization, a necessary and important step for a better understanding of the role ULVZs play in large and small scale mantle dynamics.

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Wysession, M.E. (1996), Large-scale structure at the core-mantle boundary from core-diffracted waves, *Nature*, 382, 244-248.


**Table 1. Earthquake information for large amplitude PKKP.** Shown is earthquake location information for the selected high-amplitude $PKKP_{ab}$ events that were used to measure slowness and backazimuth of $PKKP_{ab}$. 

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Figures

Figure 1. a) Raypaths for PKKP. PKKP_{bc} and PKKP_{ab}^{diff} raypaths are shown as solid lines, raypaths for PKKP_{cd} and PKKP_{ab}^{diff} are shown as dashed lines. Raypaths are calculated for an event (star) with minor arc distance of 98 deg (major arc distance 262 deg) to the Yellowknife array (inverted triangle); event depth is 50 km. For this epicentral distance, PKKP_{ab}^{diff} includes 4.4 degrees of diffraction along the CMB. The paths of PKKP_{bc} and PKKP_{ab}^{diff} in the mantle are quite different so that PKKP_{bc} cannot be used as a reference phase. b) Total diffraction path length in degrees and kilometers of PKKP_{ab}^{diff} versus minor and major arc epicentral distances for a surface focus earthquake in the PREM model.

Figure 2. a) Raw YKA recordings for the event on April 1st 1991 UTC 05:25 (source depth h = 90 km). The time window from P to PKKP for all 18 recording stations of the array are shown. Epicentral distance to YKA is 95.63 deg, with a backazimuth of 270.35 deg. Recordings of the short-period vertical instruments with a dominant period of ~1s are shown. b) Zoom into the PKKP time window for the same event. Amplitudes are normalized to the PKKP_{bc} amplitudes. Note the apparent lower frequency content of PKKP_{ab}^{diff} due to the loss of higher frequencies from diffraction.

Figure 3. Earthquake (black circles) to receiver (YKA, black triangle) geometries for data analyzed in this study. Also shown are PKKP raypaths along the major arc of the great-circle path (grey lines), and PKKP_{bc} CMB entry, exit, and mid-reflection points (grey diamonds). Diffracted arc lengths PKKP_{ab}^{diff} for earthquakes in Table 1 are also
shown (thick black line segments). Shown are the full diffracted path lengths on both the sources and receiver side of $PKKP_{ab}^{\text{diff}}$.

**Figure 4.** A 3rd-power phase-weighted stack for the earthquake on March 09, 1994, UTC 23:28 with epicentral distance of 94.3 degrees. Travel times for the PREM model and major phases ($P$, $pP$, $PP$ and $PKKP$) are marked. $PKKP_{bc}$ and $PKKP_{ab}^{\text{diff}}$ are dominant phases in the short-period recordings and can be easily identified in the time-slowness plots. The insert shows the $PKKP$ time and slowness window. The two major arrivals of $PKKP_{bc}$ and $PKKP_{ab}^{\text{diff}}$ with slownesses of approximately 2.6 and 4.4 s/deg, respectively, can be identified. **B** Zoom into the $PKKP$ time and slowness window. Arrivals for $PKKP_{bc}$ and $PKKP_{ab}^{\text{diff}}$ are marked. The zoom window location is marked by a horizontal line in A.

**Figure 5:** Traveltime measurements for the dataset in Fig. 3 for $PKKP_{bc}$, $PKKP_{ab}$ and $PKKP_{ab}^{\text{diff}}$. Lines denote theoretical PREM predictions for the individual $PKKP$ traveltime branches. The dashed line denotes the theoretical traveltime of $PKKP_{ab}^{\text{diff}}$. Traveltime deviations in excess of 3 s relative to PREM are observed with slightly larger delays observed for $PKKP_{ab}^{\text{diff}}$. The $bc$ traveltimes show stronger scatter in the traveltimes than $PKKP_{ab}^{\text{diff}}$ ($PKKP_{ab}$).

**Figure 6.** Slowness-backazimuth measurements in polar-coordinates for events with good $PKKP_{ab}^{\text{diff}}$ SNR, as measured with fk-analysis. Theoretical (PREM) values for $PKKP_{bc}$ and $PKKP_{ab}^{\text{diff}}$ are indicated by squares. $PKKP_{bc}$ measurements are marked as grey circles and $PKKP_{ab}^{\text{diff}}$ as black circles. $PKKP_{bc}$ shows overall stronger variability in
the measurements. $PKKP_{ab}^{\text{diff}}$ shows larger-than-PREM slowness, indicating lower $P$-wave velocities along the diffracted path at the CMB.

**Figure 7.** a) $P$-wave velocity reductions along diffracted portions of $PKKP_{ab}^{\text{diff}}$ paths. Sources (blue stars) and the YKA receiver array (red triangle) are marked. $P$-wave velocity reductions are color-coded along the receiver side diffracted path. For simplicity, the source-side diffracted paths are shown as red lines. The background $P$-wave velocity variations are for the $D'$ layer from Karason and van der Hilst [2001]. Only regions with $|\delta V_p| > 0.4$ are shown with velocity reductions shown as light gray and increases shown in dark grey. b) Magnification (region shown as box in a) of the receiver side $PKKP_{ab}^{\text{diff}}$ paths with color-coded $P$-wave velocity reductions along the diffracted portions of $PKKP_{ab}^{\text{diff}}$. Black circles show the ray-theoretical termination point of $PKKP_{ab}^{\text{diff}}$ for theoretical backazimuth and PREM diffracted slowness. Western $P_{\text{diff}}$ show stronger departures from the ray-theoretical exit points than those further to the east.

**Figure 8.** a) $PKKP$ time window of a Gräfenberg array (GRF) recording of an earthquake on May 4$^{th}$ 1988 UT 23:47. The minor arc distance is a $\sim 101.3$ deg. The distance profile clearly shows $PKKP_{bc}$ and $PKKP_{ab}^{\text{diff}}$ arrivals. The panel on the right shows the source-receiver geometry for this event. b) Recordings of $PKKP_{bc}$ and $PKKP_{ab}^{\text{diff}}$ from the Large Aperture Seismic Array (LASA) in an earthquake on September 4$^{th}$ 1972, UT 13:42. Only the records from the three innermost rings of LASA are shown. Due to the large number of stations we sum the LASA recordings in 0.05 deg distance steps. The distance range to LASA is approximately 98.1 deg. The panel to the right presents source-receiver combination for this event.
Figure 1. Rost and Garnero [2006]
Figure 2. Rost and Garnero [2006]
bw, span 1 column
Figure 3. Rost and Garnero [2006]
bw, span 1 column
Figure 4. Rost and Garnero [2006]
bw, span one column
Figure 5. Rost and Garnero [2006]
bw, span one column
Figure 6. Rost and Garnero [2006]
bw, span 1 column
Figure 7. Rost and Garnero [2006]
Figure 8. Rost and Garnero [2006]

bw, span two columns