Constraints on localized CMB structure from multichannel, broadband $SKS$-coda analysis

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Abstract. In recent years, a wide range of geophysical results have offered evidence that Earth’s lowermost mantle is characterized by strong lateral variations in material properties. Among the structures of particular interest are intermittent ultra-low velocity zones (ULVZ’s), located directly above the CMB, which have been originally inferred from the distortion of teleseismic $SpdKS$ phases. ULVZ’s have been modelled as layers with sharp boundaries and seismic velocity reductions $\geq 10\%$, and interpreted as regions of partial melt. In this study, we further constrain local ULVZ structure beneath North America by signal processing and waveform modelling of the $SKS$-coda recorded at broadband seismic arrays. Secondary phases in the $SKS$-coda are effectively isolated by eigenimage processing. Residual (i.e. $SKS$-less) data sections from various western Pacific events display clear $SpdKS$ arrivals, followed by a secondary phase whose timing and slowness are consistent with CMB origins. One-dimensional modelling of these phases by reflectivity and generalized ray synthetics favours an asymmetric model, with ULVZ present at only one of the CMB-intercepts. The preferred ULVZ is characterized by reductions in P and S velocities of 18% and 50%, respectively, and a diffuse upper boundary. These characteristics are interpreted in the context of local production and gravitational sinking of dense (i.e., iron rich) partial melt above the CMB. We postulate that a gradational ULVZ beneath North America may mark a lateral transition domain between regions of mantle upwelling, where more uniform ULVZ’s exist, and regions of downwelling, where ULVZ’s are either nonexistent or imperceptibly thin.
1. Introduction

An ever-increasing body of seismological, geodynamical and experimental evidence points to the core-mantle boundary (CMB) region as a zone which is characterized by strong lateral variations in physical and compositional properties. These variations occur at a variety of scales, ranging from degree 2-3 spherical harmonics in the lower 300km (i.e., D” layer) [e.g., Liu and Dziewonski, 1998; Masters et al., 2000] to kilometer scale, local boundary layers situated at or just beneath the CMB [Rost and Revenaugh, 2001]. That such strong gradients may exist in this region is to be expected, as the CMB itself marks a major compositional and thermal discontinuity. Specifically, it separates the solid state convective lower mantle, composed primarily of perovskite and iron-magnesium oxides, from the liquid outer core, which is warmer and composed primarily of iron. On the mantle side, the CMB may represent both the lower boundary where subducted plates end their descent [e.g., van der Hilst et al., 1998], and the source of ascending material that may or may not rise all the way into the upper mantle. On the core side, a recent study has shown that sedimentation of iron alloying elements may occur at regional scale along the CMB [Buffett et al., 2000]. Exchanges between the two domains are believed to take place through chemical reactions involving iron and high pressure silicates [Knittle and Jeanloz, 1989]. Thermally, the CMB has been inferred to mark a $\sim$1500 K superadiabatic gradient between the core and the lower mantle [Williams, 1998], contributing 10-15% of the surface heat flow.

Seismological methods represent the principal tool for imaging structure in the CMB region. Common analyses focus on teleseismic body waves that interact with the CMB and normal mode data that are sensitive to lower mantle structure. Their results provide insight into seismic velocities, attenuation, mineral fabric, and topography at the CMB [e.g., Lay et al., 1998, and references therein].

In recent years, the teleseismic body wave $SPdKS$/$SKPdS$ has been extensively employed for CMB imaging purposes. This phase is defined as an $SKS$ wave whose
ray-geometry includes a $P_{diff}$ segment that travels along the CMB [e.g., Choy, 1977; see Figure 1 and further discussion in section 2]. By virtue of its characteristic path, the phase samples seismic velocities in the lowermost strata of the mantle. The systematic analysis of $SPdKS(SKpDpS)$ waveforms for imaging CMB structure was introduced by Garnero et al. [1993; see also Garnero and Helmberger, 1995, 1996; and Helmberger et al., 1996]. This original study investigated rays which sampled the CMB beneath the central Pacific and displayed significant $SPdKS(SKpDpS)$ waveform distortions relative to signal expected for average, 1D Earth models. These anomalous waveforms were successfully modelled with the addition of a finite layer of greatly reduced velocities above the CMB. Such basal layers have acquired the appellation of ultra-low velocity zones (ULVZ’s) and have been inferred to exist intermittently along the CMB.

Using 1D approaches, ULVZ’s have been generally modelled as 2-40km thick layers with sharp boundaries and uniform seismic velocity reductions $\delta V_p>10\%$ for $P$-waves and $\delta V_s>30\%$ for $S$-waves. Note that the intrinsic nature of the rays utilized in these approaches generally yields more robust constraints on $\delta V_p$ than on $\delta V_s$ [see, e.g., Garnero and Jeanloz, 2000]. The magnitude of $\delta V_p$ and the preferred $\delta V_p: \delta V_s$ ratio of 1:3, established through the analysis of $PcP$ precursors, have led to the suggestion that ULVZ’s represent layers of partial melt at the bottom of D” [Williams and Garnero, 1996; Revenaugh and Meyer, 1997]. In addition, the global distribution of ULVZ’s has been correlated with regions of mantle upwelling [Garnero et al, 1998] and the surface expression of mantle plumes [Williams et al., 1998]. Recently, Wen and Helmberger [1998a] have developed a hybrid method (generalized ray and finite difference) for modelling two-dimensional (2D) CMB structure. They showed that certain perturbations in the $SKS-SPdKS$ wavefield may be explained by scattering from 250-400 km wavelength, ridge-shaped ULVZ’s. It is important to note that, in both 1D and 2D modelling schemes, significant trade-offs exist between the following ULVZ parameters [Garnero and Helmberger, 1998; Garnero and Jeanloz, 2000]: thickness, %
velocity and density anomaly, sharpness of bounding discontinuities, and exact location of the layer relative to the CMB (i.e., core or mantle side). Further constraints on the existence and characterization of ULVZ’s have also been obtained through the analysis of PKP precursors [e.g., Wen and Helmberger, 1998b], and ScP/PcP core-reflected phases on stacked sections of short-period records [Mori and Helmberger, 1995; Revenaugh and Meyer, 1997; Rost and Revenaugh, 2001].

To date, most SPdKS/SKPdS studies have relied on long period recordings from sparsely distributed permanent stations of the WWSSN network. In recent years, however, a marked increase in worldwide coverage of both permanent and temporary broadband stations has greatly improved our ability to record large numbers of high-quality SPdKS/SKPdS waveforms. The main objective of this paper is therefore to exploit these new, dense data sets and improve constraints on local ULVZ structure through multichannel analysis of SKS and SPdKS/SKPdS waves. Two notable improvements are demonstrated in the study. First, the increase in spectral content sharpens the signal and allows for higher resolution in the modelling of CMB structure. Second, multichannel processing tools yield robust estimates of the SKS wavelet and powerful phase-stripping capabilities that enhance the observation of secondary phases in the SKS-coda. These two improvements are illustrated in the paper through synthetic and observed data examples. We then present the analysis of teleseismic data recorded in North America by permanent stations of the Global Seismic Network (GSN) and the Canadian National Seismograph Network (CNSN), and portable stations of the Missouri to Massachusetts (MOMA) and Abitibi arrays. We proceed with 1D waveform modelling of the North American data and conclude with the interpretation of the results in terms of local ULVZ structure.
2. **SPdKS-SKdS waves**

SPdKS-SKdS paths are illustrated in Figure 1. The $P_{\text{diff}}$ segment of the ray samples velocities in the vicinity of the CMB, on both source (SPdKS) and receiver (SKdS) sides. For the remainder of this paper, we will use the general term $SPdKS$ to describe both source and receiver side phenomena, specifying the exact side if necessary.

The $P_{\text{diff}}$ phase is generated when $SKS$ intersects the CMB at a critical angle that corresponds to a null S-to-P transmission coefficient between mantle and core [e.g., Helmberger et al., 1996]. This critical angle is dependent on the velocities of the media located on either side of the CMB. Therefore, the onset of $SPdKS$ occurs at a precise source-receiver epicentral distance which is tied to the critical angle. In 1D, mantle-side ULVZ models, the phase has a ray parameter (i.e., moveout, in rad/s) that is entirely defined by seismic velocities above the CMB:

$$p = \frac{R_{\text{cmb}}}{\alpha_{\text{cmb}}},$$

where $R_{\text{cmb}}$ is the radius of the CMB, and $\alpha_{\text{cmb}}$ is the $P$-wave velocity sampled by the $P_{\text{diff}}$ wave in the lowermost mantle.

The characteristic $SKS$-$SPdKS$ wavefield is illustrated in Figure 2a, which shows radial synthetics produced with the generalized ray method [see, e.g., Helmberger, 1983; Aki and Richards, 2002] through the Preliminary Reference Earth Model [PREM, Dziewonski and Anderson, 1981]. Individual seismograms are represented as a function of station-event epicentral distance (in degrees) and time (in seconds), and all traces are aligned with respect to the $SKS$ arrival at 10 s. Note that the traces presented here have been low-pass filtered with a corner frequency at 0.125 Hz (8s), a value which reflects long period data from WWSSN stations. $SPdKS$ emerges as a distinct secondary pulse in the $SKS$-coda near 110°. However, tau-p calculations through PREM indicate that the phase actually appears near 106°, where the ray parameter of $SKS$ reaches the critical value of 4.43 s/° (corresponding to PREM velocity $\alpha_{\text{cmb}}=13.7\text{km/s}$ in
equation 1). The discrepancy between ray theoretical and modelled onsets of SPdKS is due, in large part, to the long period nature of the synthetics. Specifically, this causes SPdKS to be completely incorporated into the SKS wavefield between 106-110°.

The existence of ULVZ’s has been inferred from intermittent observations of distorted SPdKS waveforms relative to those predicted by PREM [Garnero and Helmberger, 1995]. Based on 1D modelling work by Garnero and Helmberger [1996, 1998], these distortions were interpreted as arising from (i) decoupling of source and receiver side SPdKS waves, and (ii) constructive interference from multiple reverberations/conversions within the ULVZ. A synthetic example of distorted waveform is presented in Figure 3 for a source-side, 5 km thick ULVZ. The following perturbations in P-velocity, S-velocity and density were used for this model: \( \delta V_p=10\% \), \( \delta V_s=30\% \), \( \delta \rho=0\% \). Note that the distortion includes a time shift of the apparent SPdKS arrival, which is associated with a smaller onset distance (\( \sim 104° \)) than that observed for PREM (\( \sim 110° \)). In field data, these anomalous SPdKS are observed only for rays sampling specific regions of the CMB, pointing to a lateral variability in ULVZ structure [see Garnero et al., 1998 for a review].

3. Data processing

Whereas early SPdKS analyses were limited to using records from sparsely distributed permanent stations, in recent years, broadband arrays have yielded denser spatial sampling equivalent to that in Figures 2-3. Consequently, data sections have become readily amenable to multichannel signal processing methods that can greatly facilitate the analysis of specific seismic phases. In this context, we introduce a signal processing algorithm that allows detailed analysis of the SKS-coda by effectively stripping the SKS-phase from the waveform, leaving any secondary phases (including SPdKS) nearly intact. The algorithm comprises three main steps, which are described below.

First, all the traces from a single event are normalized relative to the maximum
amplitude of the SKS pulse. Second, the traces are precisely aligned with respect to the SKS arrival using optimal delay times derived by multichannel cross-correlation [i.e., estimated from cross-correlation between each possible pair of traces; see VanDecar and Crosson, 1990]. The synthetic traces shown in Figure 2a are thus normalized and aligned. Third, the SKS-signal is effectively stripped from the complete waveform by eigenimage (i.e., singular value) decomposition of the record section [Ulrych et al., 1999]. The SKS-waveform represents the signal that is most correlated from trace to trace and is thus estimated to be contained in the first eigenimage, which corresponds to the largest eigenvalue of the section. Following Ulrych et al. [1999], a residual (i.e., SKS-less) data section can be constructed by excluding the first eigenmode of the original section:

\[ X_R = U_{2-n} U_{2-n \, T} X, \]  

where \( X \) is the original \( n \times m \) data section matrix containing \( n \) traces of \( m \) time samples (with, generally, \( n \ll m \)), and \( U_{2-n} \) is an \( n \times n \) matrix containing a column of zeros followed by the 2-to-\( n \) column eigenvectors of the covariance matrix \( C = XX^T \). Similarly, the first eigenimage is obtained through the following operation:

\[ X_1 = U_1 U_1^T X, \]  

where \( U_1 \) is an \( n \times n \) matrix whose first column is the only non-zero column and contains the first eigenvector of \( C \). Note that the eigenvectors in Eqs. 2-3 must be sorted in order of decreasing magnitude of their corresponding eigenvalues. The residual section obtained in Eq. 2 preserves all the coherent phases whose moveouts differ from that of SKS. Alternatively, the first eigenimage (Eq. 3) provides an estimate of the combined SKS and instrument time functions (hereafter referred to as “SKS-estimate”) which can be used for modelling and deconvolution purposes.
Figures 2b-c show the residual data section and SKS-estimate obtained from the synthetic records of Figure 2a. The SPdKS-wave has become a dominant phase in Figure 2b, with a pulse that is nearly void of SKS interference and an onset detected at smaller epicentral distances (107-108°) than in the original section. Furthermore, this example shows that the processing algorithm also isolates SKiKS, which is distorted by SKS-SPdKS between 117-130° in the original section. Figure 2c shows a comparison between the SKS-estimate and the synthetic source-time function used to produce the original data section. The two traces are generally well correlated (correlation coefficient=0.99), despite some noticeable discrepancies. The inability to perfectly recover the source-time function is due, mainly, to variations in SKS waveform over the sampled epicentral distance range. In particular, SKS-waves propagating through PREM are inherently phase-shifted at distances <106°, as they intersect the CMB at supercritical incidence.

4. ULVZ distribution
In general, the process of locating ULVZ’s is hindered by the fundamental ambiguity that exists between source and receiver side intercepts of SPdKS at the CMB. Specifically, the geometry of SPdKS rays (c.f., Figure 1) implies that either source or receiver side ULVZ’s produce identical waveforms. This ambiguity can however be clarified by analysing the correlations between responses from multiple source-receiver pairs and identifying CMB regions that consistently produce anomalous SPdKS [e.g., Garnero and Helmberger, 1996]. Using this approach, and including results from ScP and PcP precursor, a compilation map of global ULVZ distribution was generated by Garnero et al. [1998]. Figure 4 shows a modified version of this map, along with S-velocity anomalies in the lowermost mantle inferred from Grand’s [2002] global tomographic model. Regions outlined in Figure 4a are defined by the Fresnel zones of the rays sampling the CMB. As noted by Garnero et al. [1998], ULVZ’s are predominantly detected in
slow-velocity regions believed to represent warmer temperatures and the base of mantle upwellings (e.g., central Pacific superplume). Conversely, regions of the CMB showing no evidence for ULVZ’s tend to be associated with faster than average velocities, probably related to colder temperatures in mantle/slab downwelling areas. Outlined areas in the northwestern Pacific and central North America (Figure 4a) denote the CMB regions investigated in the following sections.

5. Analysis of North American data

In this section, we employ the eigenimage processing algorithm to investigate SKS data recorded at North American broadband stations. A total of 41 events sampling the CMB beneath North America were considered in this study; four of these were deemed representative of the entire data set and are reported here (see Table 1). Earthquakes were selected based on the following criteria: (i) sampled distance range comprised between $\sim$95-115$^\circ$, in order to observe $SPdKS$, (ii) magnitude $m_b > 6.0$ to ensure high signal-to-noise ratio (SNR) in the coda of SKS, and (iii) intermediate to large focal depths, to minimize near-source scattering effects. For each event considered, a composite broadband array was formed by including portable stations from temporary deployments and permanent stations from the GSN and CNSN. To render the composite data sections amenable to eigenimage processing, the instrument response of each record was normalized to that of a generic Guralp CMG-3T broadband sensor.

5.1. Marianas - 1995/08/23

For this first Marianas event (#1 in Table 1), we analyse waveforms that were recorded in eastern North America by 18 portable stations of the Missouri to Massachusetts (MOMA) array [see, e.g., Li et al., 2002], and by permanent GSN stations CCM and HRV. The location of the stations and the theoretical SKS-$SPdKS$ ray paths calculated for PREM are shown in Figure 5a. CMB intercepts along the rays paths are indicated
either by a circle for \textit{SKS} waves (i.e., distance <106°), or a thick line for \textit{SPdKS} waves (i.e., distance >106°).

Of the four events reported here, this is the one that generated the highest SNR in the \textit{SKS} coda. We therefore use this example to illustrate the improvement in data resolution afforded by the broadband spectrum of the signal and eigenimage processing. Figure 6 shows a set of record sections from Event #1, where all the traces are normalized and aligned relative to the \textit{SKS}-arrival, which is centered at 5 seconds. The first section (Figure 6a) shows the complete waveform low-pass filtered with cut-off frequencies at 0.015 Hz (i.e., 8 s period), which corresponds to the characteristic spectrum of long-period WWSSN data. The long-period section shows no clear evidence for \textit{SPdKS} in the epicentral distance range 103-110°. A clear improvement in resolution occurs by increasing the spectral content of the signal, as illustrated in Figure 6b (see, also, Figure 7a) for cutoff frequency at 1.5 Hz. This has the effect of sharpening the \textit{SKS} arrival and revealing \textit{SPdKS} as a shoulder to \textit{SKS} near 110°.

Ultimately, removal of the \textit{SKS}-signal by eigenimage processing yields the clearest data section (Figure 6c). The residual section provides an unobstructed view of \textit{SPdKS} from \(\sim109°\) and a set of secondary, coherent phases that are continuous over the entire epicentral distance range, arriving some 5-20 s after \textit{SKS}. The section is reproduced in Figure 7b, with positive pulses shaded in black to emphasize the coherent arrivals. The general trend of \textit{SPdKS} is indicated by a dashed black line and describes an average moveout of 4.5 s/°, which is representative of PREM-like velocities at the CMB. The secondary wavefield is dominated by a coherent phase comprised of two consecutive pulses (c.f., dashed gray lines in Figure 7b) separated by a trough, showing an average moveout of 5.0 s/°. Given that these coherent pulses are not observed on either vertical or transverse record sections (not shown here), the moveout is clearly indicative of SV particle motion. To the best of our knowledge, the existence of such a phase in the \textit{SKS}-coda has never previously been reported. In analysing records from
the other events, we shall therefore pay particular attention to \(SPdKS\) waveforms and possible secondary phases in the coda of \(SKS\). Accordingly, the dashed lines shown in Figures 7a-b will be used as references in the other sections of Figure 7 and for synthetic waveform modelling (section 6).

To verify the robustness of our visual observations, we construct a slant stack map [i.e., vespagram; Figures 7c,f,i,l] from the residual waveform section. Localized extrema on the slant stack map help identify and determine the moveout of coherent signal across the waveform section. The map is generated by realigning the traces according to incremental moveouts and stacking them. For \(N\) traces of residual waveforms \(x_i'(t)\), slant stacking is performed through the following expression:

\[
S(t, p) = \sum_{i=1}^{N} x_i'(t - \tau_i),
\]

with

\[
\tau_i = [\Delta_i - \Delta_r]p,
\]

where \(S(t, p)\) is the amplitude of the stacked traces relative to the normalized \(SKS\) wavelet, \(p\) is the moveout relative to that of \(SKS\), \(\Delta_i\) is the epicentral distance of the \(i^{th}\) trace, and \(\Delta_r\) is the reference distance corresponding to the middle trace of the section. The maximum of the section, \(S(t, p)_{\text{max}}\), is shown with a white cross. A 95% confidence interval on this value can be determined with a \(t\)-test, as the \(S(t, p)\) are similar to estimates of a mean. For each point in the map, we construct a sample with \(x_i'(t - \tau_i)_{\text{max}} - x_i'(t - \tau_i)\), \(i=1\)-to-\(N\), and preform a two-tailed \(t\)-test to verify the hypothesis that this sample’s mean is zero, at a 95% confidence level. For event #1 (Figure 7c), slant stacking produces a well defined maximum at \(t=13.7\) s and \(p=0.82s/°\), corresponding to a total ray parameter of \(5.16\) s/°, with a confidence interval comprised between \(12.6\)-\(14.8\) s and \(0.28\)-\(1.20\) s/°.
5.2. Izu Bonin - 1996/03/16

For this event (#2 in Table 1), we analysed records from the same array of broadband stations as in section 5.1 (i.e., MOMA and GSN). The theoretical ray paths for PREM, displayed in Figure 5b, show that the CMB regions sampled by events #2 and #1 are farther apart on the source side than on the receiver side (compare with Figures 5a). The corresponding waveform sections are shown in Figures 7d-e. Here, the \( SPdKS \)-wave is not observed over the epicentral distance range covered by the data. However, a secondary phase with moveout similar to that in event #1 (compare with dashed gray lines) is clearly identified between 5-14 s over the range 101-103.5°. A vespagram is constructed using the traces comprised in this range (Figure 7f) and shows a well defined maximum at \( t=9.9 \) s and \( p=1.30 \) s/°, with a confidence interval comprised between 9.2-10.6 s and 0.37-1.81 s/°. This result implies a total ray parameter of 5.95 s/°, a value that is slightly higher than that of the phase observed in event #1. Despite this difference, the two maxima fall in overlapping confidence intervals in terms of their moveout. Note that the difference in \( t_{\text{max}} \) between events #1 and 2 reflects the difference in distance sampling of the two events.

In order to further investigate the relationship between the secondary phases observed in events #1 and #2, the residual waveform from those two events are combined into a single section, presented in Figure 8. The consolidated section shows that the phase is remarkably continuous across the epicentral distance range 101-110°, thus supporting the hypothesis of a common origin.

5.3. Marianas - 1996/06/09

For this second Marianas event (#3 in Table 1), the waveform section includes records from the IRIS-PASSCAL Abitibi 1996 array [Rondenay et al., 2000], and permanent stations from the CNSN and GSN. The theoretical ray paths for PREM are displayed
in Figure 5c, and the corresponding waveform sections are shown in Figures 7g-h. Here again, the \textit{SPdKS}-wave is not observed over the epicentral distance range covered by the data. Furthermore, there is no strong evidence for a secondary phase in this data section, although a sequence of admittedly weak but coherent pulses between 104-108° display a moveout similar to the phase in Figure 7a-b (compare with dashed gray lines). \textbf{Slant stacking of all residual traces} (Figure 7i) produces a very low amplitude maximum at $t=12.0$ s and $p=1.51$ s/° which is poorly defined, as it is characterized by an elongated confidence interval spanning nearly the entire moveout range (i.e., 0.2 to $>2.6$ s/°). Note that, in this case, the CMB regions sampled by events #3 and #1 are nearly identical on the source-side but differ on the receiver side (compare Figures 5a and 5c).

5.4. Argentina - 2000/04/23

The last analysis presented in this section was performed on traces recorded by CNSN and GSN permanent station in northwestern North America, for a deep South American event (#4 in Table 1). Figure 5d shows the corresponding theoretical ray paths calculated for PREM. Note that these rays provide an overlapping CMB coverage beneath North America with data from events #1-#3, while sampling a totally different region on the source-side. The complete and residual waveform sections are presented in Figures 7j-k. In this case, \textit{SPdKS} is observed at distances $>109°$ as a positive pulse in the 5-10s time range (see dashed black line), whereas a clear secondary phase is not observed in the \textit{SKS}-coda. \textbf{A vespagram generated with all the residual traces} (Figure 5l) produces a very poorly defined maximum at $t=6.5$ s and $p=0.29$ s/°, with a confidence interval delineating a complex pattern that spans the entire moveout range and appears to be dominated by noise.
6. Waveform modelling

The seismic data shown in Figure 7 reveal two significant characteristics of the SKS-SPdKS wavefield recorded beneath North America. First, SPdKS emerges from SKS at an epicentral distance of 109° for events in the western Pacific and South America. This corresponds to the theoretical SPdKS onset predicted by PREM. Second, a coherent secondary phase is observed between ~101-110° on selected events recorded by the combined GSN-MOMA array. Note that data sections for other events in the Sea of Japan and SW Pacific recorded at the same array (not shown here) do not manifest the phase, although SPdKS phases from SW Pacific events recorded at MOMA do indicate significant ULVZ structure.

In this section, we describe the methodologies employed to model the anomalous SKS-SPdKS wavefield (including the enigmatic secondary phase) in terms of CMB structure. Synthetic seismograms are computed using the one-dimensional (1D) reflectivity and generalized ray methods. Whereas modelling techniques have recently been proposed for more complex architectures [see, e.g., Wen and Helmberger, 1998a], we chose the 1D approach as a first step to verify whether simple layered models could produce the observed waveform.

6.1. Origin of secondary phase

The assumption that the secondary phase might be generated at the CMB stems from two main observations: first, its close association (in time and epicentral distance) with SKS and SPdKS; and second, its average moveout of 5.0 s/°, which is characteristic of Pdiff waves sampling lowermost mantle velocities. The robustness of this assumption was evaluated by testing two likely alternatives for the origin of the secondary phase, namely near-surface structure interactions and independent body waves unrelated to SKS.

To test the possibility that the secondary phase may have originated at near-surface
structure, we investigated synthetic responses for \(SKS\) conversions and associated surface multiples from velocity discontinuities in the lithosphere. A single, three-dimensional scattering source was not considered given that the moveout of the secondary phase is not representative of realistic \(P\)- or \(S\)-diffractions in the upper \(\sim400\) km. The synthetic traces were therefore computed with the method of Frederiksen and Bostock [2000], which allows for the treatment of dipping and anisotropic planar discontinuities. Using this approach, the secondary phase of Figure 7b could only be reproduced by introducing a uniformly dipping layer extending beneath the entire length of the composite array (Figure 5a). In this case, the arrival that most resembles the secondary phase corresponds to the first free-surface multiple of the discontinuity, \(SKS_{fs}S_{d}S\), where subscripts \(fs\) and \(d\) indicate interaction with the free-surface and discontinuity, respectively. However, the required extent, depth range (\(\sim5\) to 14 km from western to eastern end of the line) and impedance contrast (\(\sim55\%\)) of the discontinuity are not consistent with constraints on crustal structure from \(Ps\) or active source studies [Braile et al., 1989; Li et al., 2002]. If such a discontinuity did exist, it should produce distinctive \(Ps\) scattering, and no such phases were observed at MOMA stations [Li et al., 2002]. In addition, a discontinuity would be detected on most \(SKS\) record sections for the MOMA-GSN array, which is not the case. We therefore conclude that the secondary phase does not likely originate at near-receiver structure.

The possibility that the secondary phase might in fact be a body wave unrelated to \(SKS\) was tested using two approaches. First, we generated full waveform synthetics in the 95-130\(^\circ\) distance range using the 1D reflectivity method [Fuchs and Müller, 1971; see also section 6.2] for general PREM architecture. The results did not produce any wave resembling the secondary phase. Second, we computed tau-p arrival times and ray parameters for a variety of ray paths. A strong constraint on the ray is dictated by the average moveout of the secondary phase (i.e., \(\sim5.0s/\circ\)), a value which implies body waves turning in the lower mantle or outer core for \(P\)-waves and in the inner core
for $S$-waves. Omitting waves that undergo multiple $P-S$ or $S-P$ conversions at second order discontinuities, we did not find any body wave that satisfied these constraints and displayed the same characteristics as the secondary phase. Based on these results, we conclude that the secondary phase is unlikely to represent an independent body wave.

Other, more complex (i.e., 3D) structure along the ray path has not been considered here and cannot be ruled out as a possible source for the secondary phase. However, evidence pointing to a CMB origin is strong enough to warrant further investigation in that direction.

6.2. Reflectivity synthetics

The first tool employed to model the anomalously $SKS-SPdKS$ waveform of Figures 7a-b and 8 is the reflectivity method \cite{Fuchs and Muller 1971}. The method involves the integration, in Fourier domain, of the reflectivity matrix over a range of possible slownesses. The input model is one-dimensional and the resulting waveform includes all possible reflected, transmitted and horizontally refracted rays.

As with previous reflectivity modelling aimed at CMB structure \cite{Garnero et al. 1998}, we treat ULVZ’s as discrete layers with sharp upper and lower interfaces. Such sharp discontinuities are required in the generation of conversions and multiple reverberations that have been inferred as a major source of $SPdKS$ distortion. Furthermore, the reflectivity code employed in this and earlier studies (a descendant of the original program by Fuchs and Muller [1971]) only allows for symmetric models on both source and receiver side CMB intercepts (see Figure 9a). The source-time function used to generate the synthetic waveforms consists of a displacement pulse at a double-couple representing event #1, with the following fault plane solution: strike=136°, dip=42°, and slip=-118° [Harvard CMT catalog].

Our initial investigations concentrated on single-layered ULVZ’s with variable thicknesses and velocity contrasts. Ensuing results were comparable to those obtained by
Garnero and Helmberger [1998], but did not contain the post-\textit{SKS} ringing characteristic of the secondary phase. We therefore elected to investigate more complex ULVZ architectures involving multiple low-velocity layers stacked above the CMB. The rationale behind such a model was that various sharp boundaries might generate enough reverberations to reproduce the multiple pulses and troughs of the secondary phase, as observed in the residual section of Figure 7b. Model space was investigated by varying the number of layers (2-4), layer thicknesses (2-15 km) and velocity perturbations ($\delta V_p=5-10\%$, $\delta V_s=15-30\%$). The quality of the waveform fits was assessed visually by comparing recorded and synthetic waveforms (i.e., number of pulses, moveout), and quantitatively through the average correlation coefficient between recorded and synthetic waveforms.

Using this approach, we obtained a set of best fitting reflectivity synthetics for a model consisting of two uniform ultra-low velocity layers, superimposed directly above the CMB. The model is described in Figure 9b, with corresponding residual and complete data waveforms shown in Figures 9c-d. Note that the best fit is achieved with a stronger velocity reduction in the upper layer, thus implying a negative, upward velocity gradient above the CMB. The residual section (Figure 9c) contains coherent arrivals in the \textit{SKS}-coda that resemble both \textit{SPdKS} and the secondary phase (compare with dashed gray lines from Figure 7a-b). However, even for the best-fitting reflectivity model, the complete synthetic waveform (thin black lines in Figure 9d) contains important precursors and postcursors to \textit{SKS} that are not observed in the real data (thick gray lines). Precursors are related to \textit{S}-to-\textit{P} conversions at the top of the ULVZ, whereas postcursors are generated by multiple reverberation within the ULVZ [see, e.g., Garnero and Helmberger, 1998]. Since these features are not present in the recorded data, we conclude that the model of Figure 9 is not a viable candidate to explain the secondary phase.

This example illustrates the numerous, unsuccessful attempts that were made at
modelling the secondary phase with the reflectivity method. We consistently found
that the level of complexity in CMB structure necessary to fit the residual waveform
produced large arrivals in the complete synthetic waveform that do not appear in the
data.

6.3. Generalized ray

The generalized ray technique was also employed to model the anomalous SKS-SPdKS
waveform. The method was originally developed by Cagniard [see Cagniard, 1962],
and later simplified by de Hoop [1960]. It was adapted for propagation of seismic
waves through stratified media by Helmberger [1968; see, also Aki and Richards, 2002,
for a review]. This method produces synthetic waveforms by solving the elastic wave
equation for individual, prescribed rays in a 1-D layered Earth. The approach has
been previously applied to ULVZ modelling by Helmberger et al. [1996] and Wen and
Helmberger [1998a]. Here, we employ a modified version of the program developed in the
former paper, where ULVZ’s are treated as discrete layers with either a sharp or diffuse
upper interface and a sharp lower boundary at the CMB. The algorithm allows for the
treatment of asymmetric structure between source and receiver-side CMB intercepts
(Figure 10a). Synthetic waveforms are generated by convolving the displacement
potential, which is output by the program, with appropriate source-time function and
instrument response. Here, we convolve the output with the SKS-estimate obtained for
event #1 (i.e., first eigenmode of data section in Figure 7a).

A variety of models including single and double ULVZ’s with different
thicknesses (2-15km) and velocity perturbations ($\delta V_p=5-20\%$, $\delta V_s=15-50\%$)
were tested using generalized ray synthetics. Resulting waveforms showed that
the anomalous waveforms in Figures 7a-e could not be explained with any combination
of symmetric or asymmetric ULVZ’s that contained sharp upper boundaries. Wave
conversions and multiples arising from sharp ULVZ upper-boundaries create SKS
precursors and postcursors that are not observed in the broadband data. To reduce synthetic waveform complexity, a diffuse upper boundary was simulated by eliminating contributions from all the rays that interact with the upper boundary. Our preferred model, which is presented in Figure 10b, was obtained by varying the parameters of such simple ULVZ architecture. The model consists of PREM-like CMB velocities on one side of the $SPdKS$ path and a single ULVZ on the other side, with large velocity perturbations of 18% and 50% for $P$ and $S$ waves, respectively. Note that the synthetic data section obtained after eigenimage processing (Figure 10c) contains coherent phases that closely resemble $SPdKS$ and the secondary phase observed in Figure 7b. Furthermore, the complete synthetic waveform (Figure 10d) fits the data of Figure 7a remarkably well, with an average correlation coefficient of 0.88. Close inspection of the program’s output (displacement potential - not presented here) shows that the secondary phase is related, in this case, to a decoupling between source and receiver-side $SPdKS$ waves. Specifically, the ULVZ-side of the path produces an $SPdKS$ emerging at $\sim 95^\circ$ with a moveout of 5.40 s/°, whereas the PREM-side produces one which emerges at $\sim 105^\circ$ with a moveout of 4.43 s/°. The complex ringing of the secondary phase is associated with interference patterns of the $SKS$-estimate, when it is convolved with the distinct $SKS$, $SPdKS$, and $SKPdS$ impulse responses.

To assess the robustness of our preferred model parameters, we first investigate the effects of independent variations in $\delta Vp$ and $\delta Vs$ on the residual waveform fits (see Figure 11). Changes in $\delta Vp$ modify the moveout of the secondary phase, whereas changes in both $\delta Vp$ and $\delta Vs$ control the onset of the phase. We note that $\delta Vp$ variations $\geq 2\%$ produce significant deterioration of the waveform fit, resulting in improper alignment of the secondary phases and important reductions in average correlation coefficient (compare Figures 11a,c with preferred model in b). Values of $\delta Vs$ are not as well constrained as those of $\delta Vp$, as only changes $>15$-20% significantly affect
the waveform fit (see Figures 11d-f). Note that for a $\delta V_p: \delta V_s$ ratio of 1:1 with 18% reduction (Figures 11d), the waveform fit is compromised mainly in the lower epicentral distances, between 102-106$^\circ$. Further testing with the 1:1 ratio and variable velocity reductions did not produce any acceptable waveform fit.

In contrast to velocities, ULVZ thickness and density perturbations remain only loosely constrained with generalized ray synthetics. To gain better insight about the thickness, we compare reflectivity and generalized ray synthetics for symmetric ULVZ’s with velocity perturbations as those of our preferred model. A diffuse boundary is simulated in reflectivity with a large number of very thin layers. Results from this exercise are shown in Figure 12, with generalized ray waveforms in (a) and reflectivity synthetics in (b-d) for increasing boundary thickness. Due to the complexity of the waveforms, traces are aligned with respect to the theoretical $SKS$ arrival time. Note that the reflectivity code tends to become unstable for broadband waves propagating through a stack of very thin layers (<1 km). This problem is related, in particular, to the inclusion of higher frequencies in the signal, which require artificially low attenuation (i.e., high Q) in the lower mantle. This necessary, although non-ideal treatment of Q is likely responsible for the important discrepancies in waveforms and amplitudes observed between the two types of synthetics. For this reason, we limit our comparison to the onset and moveout of $SPdKS$ (gray dashed line in Figure 12a). A sharp boundary (Figure 12b) produces precursors and postcursors that bury completely the $SPdKS$ signal. Such pre- and post-$SKS$ ringing persists for boundary thicknesses smaller than $\sim$20 km (Figure 12d). A clearer, although still multi-pulsed $SPdKS$ waveform is observed for thicknesses >20 km (Figure 12e-f), with onset and moveout of the later pulses similar to
those observed with generalized ray. The density, which determines the impedance contrast of the upper boundary, is poorly constrained since wave interactions with that discontinuity are not considered in the final model.

In summary, our preferred model consists of an single asymmetric ULVZ located on either source or receiver side CMB intercept. The layer has a thickness of at least 20-30 km, with a diffuse upper boundary and maximum $P$ and $S$ velocity perturbations of 18% and 50%, respectively.

7. Discussion

We now interpret the preferred model of section 6.3 in terms of regional processes taking place in the lowermost mantle and at the CMB. The first challenge is to clarify the fundamental ambiguity between source and receiver side ULVZ’s, as the two possible locations produce the same theoretical waveform. **Important information** pertaining to this problem is obtained from the CMB intercepts of SPdKS waves, as calculated for our preferred model with $\delta V_p=18\%$ and $\delta V_s=50\%$. Corresponding $P_{diff}$ segments beneath the Western Pacific and North America for the events of Table 4 are presented in Figure 13. For signal in the 5-10 s period range, $P_{diff}$ segments have a Fresnel zone (half-width) of $\sim$160-240 km in the direction perpendicular to the ray (transversal), and 20-35 km in the direction parallel to the ray (longitudinal). These values can provide a rough estimate of the lateral resolution afforded by rays sampling the CMB, although recent studies have shown consistent waveform variations occurring over CMB scale-lengths $<100$ km [see, e.g., Wen, 2001].

In our investigations, we noted that the secondary phase was clearly observed solely on record sections from events #1 and #2 (Figure 7). **The two sets of rays sample regions of the CMB that are significantly different on the source side, where respective coverage areas are separated by $\sim$700 km**
(i.e., a distance significantly greater the Fresnel zone), but overlap almost entirely on the receiver side (see Figure 13). In contrast, the secondary phase is not clearly observed on records from event #3, whose rays nearly coincide with those of event #1 beneath the Pacific, but not beneath North America. On the source side, the distance between respective mantle-CMB intercepts for events #1 and #3 is <20km, which is less the longitudinal Fresnel zone. On the receiver side, the CMB coverage of the two events partly overlap, although the core-CMB intercepts (i.e., the points where receiver-side SPdKS are generated) differ by more than 120-150 km, well above the longitudinal Fresnel zone. Note that the comparisons between events #1-2-3 are consistent with the results from all the other events that were investigated. Based on these observations, we infer that the diffuse ULVZ is more likely to be located beneath North America than the western Pacific. Based on this assumption, westward variations in CMB structure beneath North America, as implied by the waveforms from event #3, might be related to the change in ULVZ response previously reported in the region by Garnero et al. [1998; see Figure 4]. Records from South American events (e.g., event #4) sample regions of the CMB further to the south beneath North America and do not contain the secondary phase. These results are therefore used to determine the southern boundary of the diffuse ULVZ region.

The inferred regional extent of the diffuse ULVZ is outlined in Figure 4a, along with the global ULVZ distribution of Garnero et al. [1998]. The contour of the diffuse layer is based on the distribution of rays that generate the secondary phase and their associated Fresnel zones. As noted in section 4, previously identified ULVZ’s were correlated with low velocity regions in the lowermost mantle, whereas a PREM-like CMB architecture was assumed to prevail in faster regions. In contrast, the diffuse ULVZ inferred here appears to be associated with nearly neutral S-velocities over the
depth interval 2650-2890 km (compare with Figure 4b).

To better assess the implication of a ULVZ embedded at the base of a zone of neutral CMB velocity, we briefly review petrological and geodynamic models that have been proposed in relation to global ULVZ distribution. In general, the CMB is assumed to be isothermal, with a temperature in the range 2500-4500K on the mantle side (D”) and an adiabatic increase of ~1000-2000K from mantle to core [Williams, 1998]. The average pressure at CMB depths is ~130 GPa. High pressure experiments indicate that, at these conditions, the solidus of lower mantle minerals (perovskite and magnesiowüstite) can intersect the geotherm, thus leading to the production of partial melt [Holland and Ahrens, 1997]. Results by Knittle [1998] suggest that the iron might preferentially fractionate into the liquid phase, favouring a melt that is denser than the solid residual. It is these observations, coupled with the preferred δVp:δVs ratio of 1:3, that have led to the interpretation of ULVZ’s as layers of partial melt [Williams and Garnero, 1996; Revenaugh and Meyer, 1997; Berryman, 2000].

In this context, two end-term models have been suggested to explain the lateral variability of ULVZ observations [Garnero et al., 1998]. First, well-defined ULVZ’s are associated with regions of large scale mantle upwelling, such as that beneath the Pacific superplume. In such regions, higher temperatures in the lower mantle may lead to more abundant partial melt and possible localized convection in the ULVZ, as schematically shown in Figure 14a [based on Garnero et al., 1998; their Figure 10]. Second, CMB regions that lack evidence for ULVZ’s may be associated with mantle downwelling. These regions generally display lower mantle temperatures and many have been the target of advected material from subducted slabs over 100-200 Myr time scales. In this case, which is schematically shown in Figure 14c [also based on Garnero et al., 1998; their Figure 10], ULVZ’s may be very thin due to the following factors: (i) lower temperatures, (ii) mantle downwelling, and (iii) decrease in melt buoyancy or shifting of the solidus due to advected material. Compositional modulation of the melting
potential at the CMB has been suggested by Wen et al. [2001] to explain small-scale, lateral variations in ULVZ structure.

In light of the CMB models presented above, we interpret the ULVZ we observe beneath North America to be a transition zone laterally separating downwelling from upwelling domains. Such transition zones may be associated with regions of average temperatures/composition in the lowermost mantle, where ULVZ’s remain stable and contain increasing amounts of partial melt with proximity to the CMB (Figure 14b). Based on the calculations of Williams and Garnero [1996], the inferred velocity perturbations $\delta V_p=18\%$ and $\delta V_s=50\%$ could indicate a melt fraction ranging between $\sim 15$-45% depending on the melt geometry. The increase in melt % with depth within the ULVZ could be explained by two processes: first, a steady increase in temperature, and second, unperturbed gravitational sinking of Fe-rich melt, unhindered by localized, small-scale convection as in Figure 14a. Therefore, if temperature fluctuations are the main cause for lateral ULVZ variability, our interpretation supports the suggestion of Revenaugh and Meyer [1997] that ULVZ’s may be a ubiquitous phenomenon, only with regional characteristics that render them more or less detectable by seismic methods. CHOICE FOR LAST SENTENCE: [Note, however, that compositional anomalies above the CMB may also modulate the melt fraction.] OR [Alternatively, if compositional anomalies are the main cause for partial melting, then ULVZ’s would be laterally intermittent features of the lower mantle. Presumably, both temperature and compositional anomalies may be present at the CMB, suggesting that ...]

8. Concluding remarks

In this study, we have shown that a recent increase in spatial density of broadband seismic data can greatly improve SKS-coda analysis for CMB imaging purposes. The
richer spectral content of the signal allows for better detection of \textit{SPdKS} and other coherent phases generated by CMB structure. Furthermore, its higher spatial density renders the data amenable to multichannel signal processing approaches. Here, we have developed an eigenimage decomposition algorithm that effectively isolates the phases of interest from the \textit{SKS} waveform.

Applying this approach to North American broadband data, a coherent secondary phase was identified in the \textit{SKS}-coda on paths sampling the CMB beneath North America. Using 1D \textit{asymmetric} modelling approaches, the phase could be reproduced by introducing a ULVZ above the CMB on one side of the \textit{SPdKS} path. This model was found to be valid only if the upper boundary of the ULVZ was diffuse enough to prevent the generation of significant reflections and conversions. It is important to note, however, that although the anomalous \textit{SKS-SPdKS} waveform could be explained with a simple 1D architecture, one cannot exclude the contribution from more complex (i.e., 2D, on- and off-azimuth 3D) structure. The investigation of complex structure is the topic of ongoing research, which should greatly benefit from further improvement in broadband data coverage [e.g., USAArray, \textit{Levander et al}, 1999], and the recent development of full 3D modelling approaches [e.g., \textit{Komatitsch et al.}, 2002]. Nevertheless, our preferred model is physically plausible. It suggests that laterally variable and vertically diffuse ULVZ’s may be a characteristic of transitional CMB domains that lie between regions of mantle upwelling, where ULVZ’s are more uniformly observed, and regions of downwelling, where ULVZ’s are either nonexistent or imperceptibly thin.

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the Abitibi experiments. We also wish to acknowledge the researchers and students who made these two experiments possible: Julie Zaslow, who conducted an early SPdKS analysis on MOMA waveforms; Andrew Frederiksen, for his modelling code; and Steve Grand, for providing his tomographic model. S.R. wishes to thank Ken Creager for his hospitality at UW. The authors made use of the Generic Mapping Tool [Wessel and Smith, 1995] for some figures. This research was supported by an NSERC Postdoctoral Fellowship to S.R. and NSF grant EAR-XYZ.
References


Garnero, E. J., and D. V. Helmberger, Seismic detection of a thin laterally varying boundary


Received xx, yyyy; revised xx, yyyy; accepted xx, yyyy.
Table 1. Events recorded at North American stations.

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<td>01:12:19</td>
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<td>145.71</td>
<td>167</td>
<td>6.0</td>
</tr>
</tbody>
</table>
Figure 1. Ray geometry of teleseismic shear-waves that illuminate the CMB. The phase $SPdKS$-$SKPdS$ is defined as an $SKS$-wave which includes $Pdiff$ segments that samples velocities and structure directly above the CMB. Symbols: star = source location, triangle = receiver location.

Figure 2. Synthetic data sections (i.e., velocity seismograms) obtained with the Generalized Ray method, for PREM architecture and a source depth of 600 km. The source time function is modelled with 1.6 s rise time and 2.0 s rupture time. Traces are normalized and aligned with respect to the main $SKS$ pulse (centered at 10s).

a) Complete waveform. b) Residual waveform, where $SKS$ has been effectively stripped from the section by eigenimage processing. The resulting section offers an unobstructed view of $SPdKS$ and $SKiKS$, which remain unaffected by the processing. c) Comparison between the input source-time function (thick gray line) and the estimated $SKS$-time function (thin black line), which corresponds the first eigenmode of (a).

Figure 3. Generalized Ray synthetics computed for PREM (thick gray lines) and a source-side ULVZ (thin black lines). Traces are normalized and aligned with respect to the main $SKS$ pulse (centered at 10s). ULVZ characteristics are: thickness=5km, $\delta V_p=10\%$, $\delta V_s=30\%$, and $\delta \rho=0\%$. The presence of an ULVZ distorts the $SPdKS$ waveform, which emerges at smaller distances ($\sim 104^\circ$) and is observed later in the coda of $SKS$. Note that a PREM-like $SPdKS$ is still observed in the distorted waveform, due to decoupling between source- and receiver-side $SPdKS$. Also note the presence of a small phase in the PREM waveforms, which is nearly coincident with the distorted $SPdKS$. This phase is a small, reproducible artifact of the method which is due to the discretization of the 1D Earth model.
Figure 4. (a) Global ULVZ distribution inferred from previous teleseismic studies [modified from Garnero et al., 1998]. Outlined CMB regions in the northwestern Pacific and central North America are investigated here as possible sources for a secondary phase observed in the SKS coda. (b) 3D shear-velocity model of the lowermost mantle (2650-2890 km depth) determined from global shear-wave traveltime tomography [Grand, 2002].

Figure 5. Theoretical SKS-SPdKS ray paths for events #1-4, listed in Table 1.

Figure 6. Radial data from event #1 (Table 1), recorded at broadband stations in NE North America. Traces are normalized and aligned with respect to the main SKS pulse (centered at 5s). The three successive sections illustrate how signal in the SKS-coda can be enhanced by broadening the frequency spectrum from 0.03-0.125 Hz (a) to 0.03-1.5 Hz (b), and by removing the SKS waveform with eigenimage processing (c).

Figure 7. Radial data sections for events #1-4, listed in Table 1: complete waveforms (a,d,g,j) and residual waveforms (b,e,h,k). Traces are normalized and aligned with respect to the main SKS pulse (centered at 5s; see thin dashed lines). The dark and gray dashed lines outline the moveout of SPdKS and the secondary phase for event #1 (a-b), respectively, and serve as references for comparison in subsequent data sections (d-k, Figures 9c and 10c). Note that the secondary phase is clearly observed only in the data sections for events #1 (a-b) and #2 (d-e). These observations are supported by slant stacks (c,f,i,l) constructed from the residual waveforms, with incremental slowness increases relative to SKS. Maxima are indicated by white crosses, with highlighted areas representing the 95% confidence interval. Well-defined maxima are obtained only for events #1 and 2.

Figure 8. Radial data section combining seismic traces from events #1 (black shading) and #2 (gray shading), listed in Table 1. Traces are normalized and aligned with respect to the main SKS pulse (centered at 5s). Note the continuity of the secondary phase (double pulse between 5-20s) across the epicentral distance range 101°-110°.
Figure 9. Forward modelling of SPdKS and secondary phase using the reflectivity method. (a) ULVZ’s are modelled as discrete layers with sharp upper and lower boundaries, that are present on both source and receiver side CMB intercepts. Downgoing and upgoing rays interact with the upper boundary to create converted phases and multiples that contribute to the distortion of SPdKS. (b) Best reflectivity model consisting of two uniform ULVZ’s, with a top layer characterized by lower velocities than the bottom one. (c) Residual synthetic waveform, with moveouts of SPdKS and secondary phase from Figure 7a-b indicated by black and gray dashed lines, respectively. Note that due to the complexity of the waveforms and the strong coherence of multiples, eigenimage processing does not entirely strip the SKS phase from the section. (d) Comparison between complete synthetic waveform (thin black lines) and the complete waveform from event #1 (thick gray lines; from Figure 7a). Average correlation coefficients for the complete and residual waveforms are 0.32 and -0.15, respectively.

Figure 10. Forward modelling of SPdKS and secondary phase using the generalized ray method. (a) ULVZ’s are modelled as discrete layers with sharp or diffuse upper interface (lower interface stays sharp). The layers can be present on source and/or receiver side CMB intercepts, thus allowing for asymmetric structure. (b) Preferred model consisting of a single ULVZ, with a gradational upper boundary. (c) Residual synthetic waveform, with moveouts of SPdKS and secondary phase from Figure 7a-b indicated by black and gray dashed lines, respectively. (d) Comparison between complete synthetic waveform (thin black lines) and the complete waveform from event #1 (thick gray lines; from Figure 7a). Average correlation coefficients for the complete and residual waveforms are 0.88 and 0.41, respectively.
Figure 11. Effects on waveform fits of small changes in $\delta V_p$ and $\delta V_s$ from the preferred model in Figure 10. The sections show comparisons between the residual waveform from event #1 (thick gray lines) and generalized ray synthetics (thin black lines). Average correlation coefficients between real and synthetic waveforms are given in the insets. The preferred model is shown in (b). $\delta V_p$ variations $\geq 2\%$ (a,c) produce significant deterioration of the waveform fit, resulting in improper alignment of the secondary phases and important reductions in average correlation coefficients. Conversely, the waveforms are not as sensitive to $\delta V_s$ variations (d-f), where changes $>15\text{-}20\%$ are necessary to lower the quality of the fit.

Figure 12. Comparison between generalized ray and reflectivity synthetics for a symmetric, 10 km thick ULVZ with $\delta V_p=18\%$ and $\delta V_s=50\%$: a) generalized ray with no conversions/ reflections from the upper boundary; b) reflectivity with sharp upper boundary; other panels show reflectivity synthetics for a diffuse upper boundary with thickness of c) 10 km, d) 20 km, e) 30 km, and f) 40 km. Traces are aligned with respect to theoretical $SKS$ arrival times for PREM. Dashed gray line indicates the moveout of $SPdKS$ observed with generalized rays (section a).

Figure 13. Combined CMB intercepts of $SPdKS$ waves calculated for the preferred model with $\delta V_p=18\%$ and $\delta V_s=50\%$. (a) Map of the SW Pacific showing source-side CMB intercepts for events #1-3. (b) Map of North American showing receiver-side CMB intercepts for events #1-4.
Figure 14. Schematic representation of laterally varying CMB domains. Abbreviations: G - geotherm, S - solidus of lowermost mantle materials. The CMB region underlying central North America, where a diffuse ULVZ is modelled, is inferred to be a transition (b) between regions of mantle upwelling (a), where sharp ULVZ’s may be present, and regions of mantle downwelling (c), where ULVZ’s are either nonexistent or imperceptibly thin. See text for details.