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Probing an Ultra-low velocity zone at the Core Mantle Boundary with P and S Waves

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Abstract. Recent studies of the core-mantle boundary (CMB) have revealed some very anomalous structures interpreted in terms of ultra low velocity zones (ULVZ). However, there remains considerable uncertainties about their physical descriptions or even if they occur above or below the CMB. They have only been detected in isolated situations using rather special techniques; these includes: distortions in SKS with the development of SKPdS and SPdKS, broadband PKP precursors, distinct ScS and S beyond 100 degree, and rapid changes in differential travel times of neighboring phases. Here we report on a situation where ray paths associated with PKP precursors and SKPdS sample the same ULVZ structure. The structure lies beneath central Africa and has been detected from WWSSN analog data (SKPdS) discussed previously. This data set has been enhanced with a collection of digital records sampling an elongated North-South zone roughly 800 km long. The entire SKPdS data set can be modeled with a ridge-shaped cross section with widths of 250 to 400 km and drops in P and S velocity of 10 and 30 percent. Fortunately, a new IRIS station (MSKU) located in Western Africa provided excellent PKP data from the New Britain Region events sampling the above structure. The PKP and strong precursors can be modeled by 2D synthetics generated from the same structure (used in modeling SKP$_d$S) which provides a strong constraint on the definition characteristics of this particular ULVZ.

Introduction

Ultra-low velocity zones (ULVZ) at the core-mantle-boundary (CMB) are probably the most anomalous structure in the mantle with S velocity reduced up to 30% and P wave velocity up to 10% [*Garnero and Helmberger*, 1996] . The initial studies on the mid-Pacific structure involved the detection of precursors to PcP [*Mori and Helmberger*, 1995], followed by studies on the interference of the two diffracted P-phases (SP$_d$KS, source-side) and (SKP$_d$S, receiver-side) with the parent phase SKS near 110° as displayed in Fig. 1 [*Garnero and Helmberger*, 1996]. The relative strength and arrival time separation between SKS and SKP$_d$S are sensitive to the velocity structure near the CMB, and modeled with a slow thin layer. Subsequent efforts has allowed us to differentiate between SP$_d$KS and SKP$_d$S as the principal cause of the interference and 2D synthetics generated accordingly [*Wen and Helmberger*, 1998a]. In particular, ULVZ's beneath Iceland and Africa have been modeled with ridge-like structures with a cross section dimension of about 200 km and with heights from 40 to 60 km [*Helmberger et al.*, 2000].Wen and Helmberger(1998b), Thomas et al (1999) noted that some PKP precursors (Fig. 1) contain long-period energy which could be modeled by placing ULVZ at appropriate locations at the CMB. Again, 2D domes of comparable dimensions to the above proved effective. As for short period PKP precursors, Vidale and Hedlin(1998) interpreted the strong precursors recorded at NORSAR array from earthquakes around Fiji as scattering from localized partial melts above CMB, and the P velocity variation is about 13% which they interpreted as an ULVZ. small scale modeling techniques include SKS and S differential times [*Breger and Romanowicz*, 1998], and SV-SH polarization [*Lay and Garnero*, 1997]. Recently, Ni and Helmberger(2001) modeled the large separation (more than 5 seconds) between S and ScS for epicentral distances beyond 100 degree; their model contains an ULVZ beneath the Southern Atlantic Ocean.

A global map containing a combination of ULVZ and LVZ regions has been attempted by Garnero et al (1998). However, each of these regions is modeled with only one technique; thus, considerable ambiguity exists between velocity reduction versus thickness. The introduction of horizonal dimensions (2D structures) produces still more ambiguity [*Helmberger et al.*, 2000]. Unfortunately, these very localized features require the seismic stations and earthquakes to have precise geometries for sampling as displayed in Fig. 1. Fortunately, with increasing number of broadband stations, modeling of ULVZ with combined techniques is becoming possible. Here, we extend the earlier study of the ULVZ structure situated beneath central Africa [*Helmberger et al.*, 2000], referred to as Part 1 by adding more broadband SKP$_d$ S and PKP observations sampling the same region.

Waveform Data and Analysis

The IRIS stations and events used are displayed in Fig. 2a. The South American events produced the SKP$_d$S phases and the three PKP precursors were generated by the New Britain events. The ray path surface projections are indicated along with the CMB sampling segments, see Table 1 for source details. SKP$_d$S waveforms are presented in Fig. 2b with peaks aligned on SKS. The predicted SKP$_d$S (arrival time) by PREM [*Dziewonski and Anderson*, 1981] relative to SKS is indicated by the dotted line and that is expected from an ULVZ by the dashed line. Note that we have color coded the observations associated with the particular station paths to emphasize the contrast in waveform differences. Essentially, the reduced P-wave velocity shifts the critical angle of the reflected S-to-P phase to shorter distances which moves the SKP$_d$S onset from 108° (PREM) to about 105° (ULVZ) as displayed[*Helmberger et al.*, 1996a] . The strength of the SKP$_d$S phase is strongly controlled by the shape and the

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precise ULVZ position [*Wen and Helmberger*, 1998a]. The black traces observed at KMBO are the simplest and align roughly along the PREM predictions, although the SKP_dS strength at 114.8° is anomalously strong. The observations at FURI (red) show a strong SKP_dS starting at 109° and remain prominent over all distances. The arrival time is about 2 secs late and agrees with the ULVZ timing prediction observed from Part 1. Note that we have included an analog AAE record (dotted red) at 112.3° from that study as a reference. The FURI waveforms show complexity about three degrees earlier than ATD waveforms (Green). The differential behavior of these waveforms at FURI relative to ATD requires very localized velocity structure. Since the western boundary of the ULVZ appears to be further away from ATD perhaps the difference is caused by geometry. A schematic picture to explain the different waveform complexity at AAE and ATD is displayed in Fig. 2c. For FURI, the SKP_dS segments sample the ULVZ for distances from 109 ° to 115 °, while for ATD, which is about 5 degree to the east of FURI, the SKP_dS path does not sample the ULVZ for epicentral distances less than about 109°. However, with increasing distances, the longer SKP_dS segments begin to sample the ULVZ and complicate the waveforms as displayed. From Part 1, this ULVZ is about 240 km across and 60 km high, with S velocity reductions of about 30% and P velocity drops of 10%. We have included the SKP_dS segments from Part 1 as dotted lines in Fig. 2d. Most of the analog data ob-

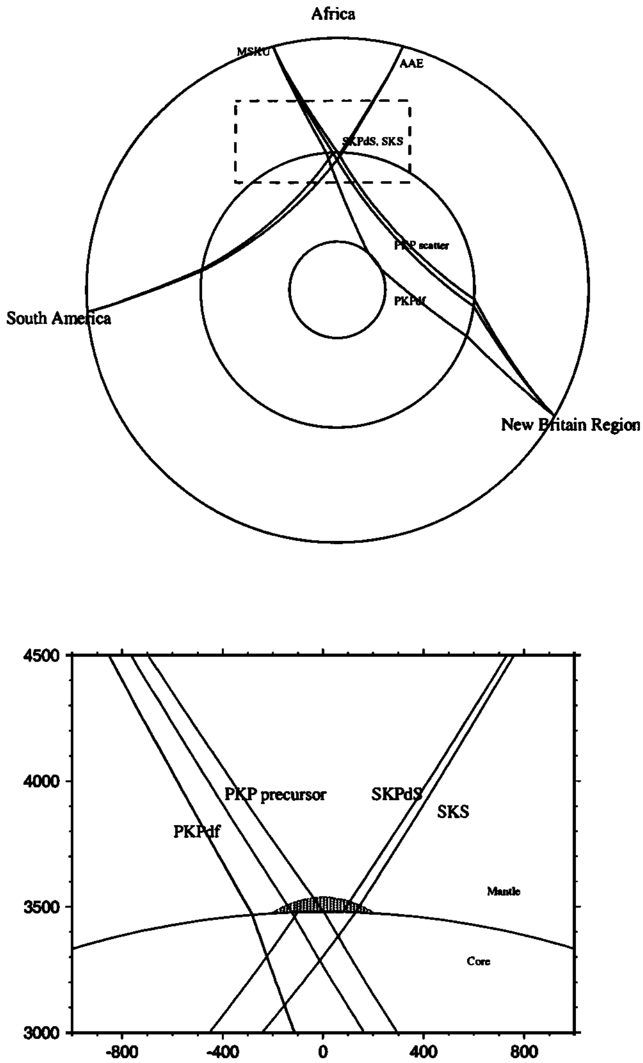

Figure 1. The upper plot displays the ray paths associated with studies of the ULVZ at the core-mantle-boundary (CMB). SKS phases from deep South American events to the African station AAE show distortions caused by the P-diffraction, SKP_dS, which travels along the CMB as indicated, [*Garnero et al (1993)*]. The range where this interference occurs and the severity is controlled by the local CMB structure (lower plot). Note that the two ray paths propagating through the mantle are nearly identical, thus eliminating other complexities. Strong precursors to PKP have been successfully modeled with ULVZ's for path encountering the mid-Pacific upwelling. Here we examine paths from the New Britain Region to the African station MSKU ($\Delta \approx 136°$) which show such anomalous features. The three ray paths displayed indicate the PKP(df) branch sampling the top of inner core and two paths sampling a prospective scaterer.

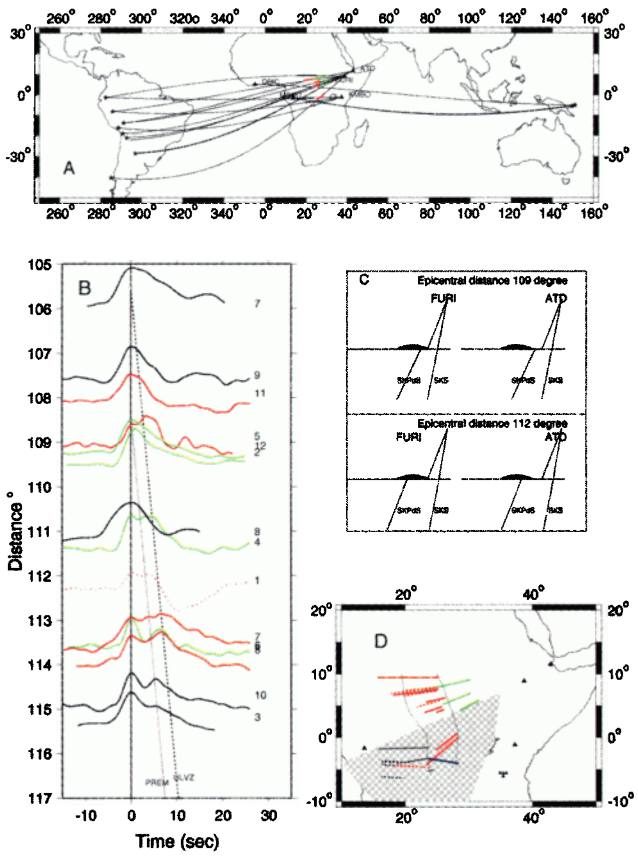

Figure 2. A map of the region sampled is given in (A) along with ray paths sampling the CMB. The SKS + SKP_dS observations in displacement (B); where black (KMBO) appears PREM-like falling on the PREM travel time predictions, red (FURI) displays a strong SKP_dS phase which is delayed in time (dotted, ULVZ), and ATD in green, which appears PREM-like at the ranges less than 110° and anomalous beyond. The dotted red is taken from Part 1 (AAE) where it was successfully modeled with an ULVZ structure. The numbers indicate the South American events producing these seismograms as listed in Table 1. The geometry in C appears to explain the delayed complexity of ATD with simple behaviors at the smaller ranges (109°). The map shown in D summarizes the anomalous CMB segments (red and green) and normal (black). The dotted traces are from Part 1. The blue segments are from PKP precursors sampling the elongated ULVZ structure (as roughly bracketed). The stenciled area is taken from Hedlin and Shear(2000), indicating the position of strongest scatterers observed beneath the African region.

served at AAE (same location as FURI) yield results similar to that seen at FURI in Fig. 2b. Note that AAE has been modeled in Part 1. Also included are segments appropriate for an array of stations in Tanzania. This data is a mixture of normal looking records (PREM-like) to anomalous for a few of the most western stations, which look similar to event 10 for KMBO. We have denoted these as dotted red as some mixture of LVZ and ULVZ structure, Part 1. If such ULVZ exists at this location as claimed above, it should produce obvious effects on the PKP precursor broadband waveforms [*Wen and Helmberger*, 1998b].

Modeling Broadband PKP Precursors

We chose two IRIS stations, MSKU and DBIC, in Fig. 2a to study the PKP core phases in the vicinity of the proposed ULVZ. The paths to DBIC are thought to be sampling PREM-like lower mantle conditions [*Ritsema et al.*, 1999]. and can be used to establish the source characteristics. Station MSKU is at the right geometry with epicentral distances between 134 to 137°, to observe PKP precursors as introduced in Fig. 1. With the source defined from modeling DBIC, we will attribute complexities at MSKU as caused by the CMB crossing zone at the receiver, and consider justification later. The broadband observations of three events are displayed in the upper portion of Fig. 3. The sources were chosen to be impulsive (simple) with parameters given in Table 1. At a distance of 155° (DBIC), the PKP branches are well separated into DF, BC, and AB denoting paths through the inner core, fluid core, and outer fluid core. The phase AB should be phase-shifted by 90° since it is a maximum arrival phase, whereas the DF and BC phases are expected to have

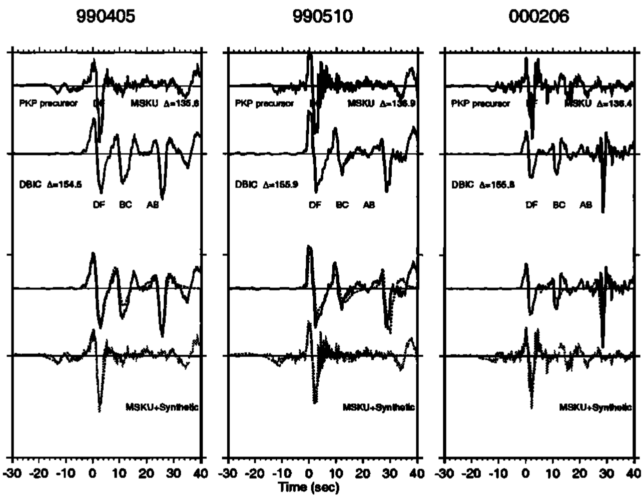

Figure 3. PKP observations (velocity seismogram) from three events in the New Britain Region to Africa at stations DBIC and MSKU. The three branches of PKP containing DF (inner-core), BC (lowermost outer-core), and AB (outer-core) are well separated. These waveforms are modeled by PREM-like models as denoted by dotted synthetics displaying simple source characteristics. The observed DF pulses were used for effective duration and normalized amplitudes. Predictions of the PKP phase before the 144° caustic are simple except for the precursors that are not produced by conventional earth models, and require local sharp lateral velocity structures such as ULVZ for their generation. Their separation in time from PKP indicates their approximate position. A shift in the ULVZ position of 50 km produces about one second change in separation.

Table 1. Events used in this study

No	date	time	lat(o)	lon(o)	depth(km)
1	941020	01:15:16	-39.19	-70.80	164
2	940819	10:02:51	-26.65	-63.38	565
3	980729	07:14:24	-32.31	-71.29	51
4	970902	12:13:22	3.85	-75.75	199
5	971028	06:15:17	-4.37	-76.60	112
6	971128	22:53:41	-13.74	-68.79	586
7	981008	04:51:42	-16.12	-71.40	136
8	991130	04:01:53	-18.78	-69.05	127
9	970123	02:15:22	-22.00	-65.72	276
10	950923	22:31:58	-10.53	-78.70	73
11	950208	18:40:25	4.16	-76.64	69
12	971015	01:03:33	-30.93	-71.22	58
13	980403	22:01:48	-8.15	-74.24	164
14	990403	06:17:18	-16.66	-72.66	87
15	990525	16:42:05	-27.93	-66.93	169
16	950214	15:53:56	-23.29	-67.70	156
17	941212	07:41:55	-17.50	-69.65	151

similar waveforms with the pulse duration representing the source characteristics. This feature is particularly apparent in the middle column (990510). The synthetics were generated with a 2D WKM code [*Ni et al.*, 2000], and fit the data quite well. The observed pulses after AB are probably the surface reflections of pPKP which have not been included in the synthetics. Using these source determinations, we generated the DF predictions at MSKU (Δ = 136°) where the two PKP branches, PKIKP and PKiKP, arrive with nearly identical times. The fits for PKIKP and PKiKP are excellent, but simple models such as PREM will not generate precursors without adding scattering. Synthetics for PREM typically show smooth longer period diffraction signal before PKIKP [*Cormier and Richards*, 1977]. The synthetic precursors displayed here are based on a 2D dome structure, 240 km across, 60 km, and 10% lower P velocity, and located where the SKS/SKP$_d$S modeling predicts, see Fig. 2d (blue lines). The 2D synthetics are based WKM algorithm developed by Ni et al (2000), and these synthetics have been compared with those generated by an analytical-numerical interfacing code[*Wen and Helmberger*, 1998b], and found to be satisfactory.

Discussion

A variety of geometric shapes of anomalous structures were considered in Wen and Helmberger (1998a), and arguments for their existence at the CMB as opposed to the mantle apply equally here. Essentially, the only portion of the earth where the DF path is separated significantly from scattering paths (Fig. 1) is in the lowermost mantle. The issue of receiver-side versus source-side remains problematic. However, if there were a significant anomaly at the source-side, we would expect to see some distortions in the DBIC observations since the CMB crossings are quite close to those of MSKU. Secondly, moving the source about 100 km does not affect the precursor's position, again supporting the receiver-side interpretation. Moreover, the position of the proposed ULVZ as outlined in Fig. 2d is in agreement with strong short-period scattering as reported recently [*Hedlin and Shearer*, 2000]. This relationship between broadband and intense short-period scattering observed here was also observed beneath the mid-Pacific[*Vidale and Hedlin*, 1998]. Thus, it appears that ULVZ's can have a broad range of scale lengths and complexity. This result is in general agreement with local small-scale mantle convection caused by instability of the thermal boundary layer [*Olson et al.*, 1987].

In conclusion, we have delineated a ULVZ extending at least 800 km along the eastern boundary of the Great African upwelling. Its shape is roughly that of a ridge structure with a strong reduction of both S and P velocities of up to 30 and 10%, respectively, as estimated from a combination of SKP_dS and PKP precursors.

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