**Intermittent and lateral varying ULVZ structure at the northeastern margin of the Pacific LLSVP**

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**Summary**

Thin patches with ultra-low velocities have been proposed to exist at the core-mantle boundary (CMB). The detection and mapping of ultra-low velocity zones (ULVZs) are difficult in part by the limitation of source-receiver geometries of seismic phases used in ULVZ modeling. Here we developed a new approach that simultaneously utilizes *ScS* pre- and post-cursor energy to investigate the CMB region for ULVZ structure. We stacked source-deconvolved *ScS* waveforms within 1.5 degree geographic bins to extract *ScS* pre- and post-cursor energy, if present, with *ScS* effectively removed from waveforms. We investigate the CMB beneath the central Pacific Ocean, and evidence for ULVZs is clearly apparent. Geographic bin stacks possessing similar *ScS* precursor-plus-postcursor behavior are grouped using cluster analysis to produce more robust waveforms by enhancing the signal to noise ratios. Synthetic seismograms demonstrate the amplitude and timing of the ULVZ arrivals are sensitive to ULVZ thickness and internal velocities. To pursue local ULVZ properties we processed 13,850 1-D synthetic models with various ULVZ thicknesses and internal properties, using the identical *ScS*-stripping method as with the data. A best fitting model was found for each geographical bin cluster using an amplitude sensitive cross-correlation algorithm. While limitations exist due to 1-D modeling, strong lateral variations are apparent in ULVZ thickness and properties across the large low shear velocity province (LLSVP) margin in our study area. Inside hypothesized LLSVP edges, ULVZs appear to distribute unevenly, suggesting 3D variations of convection currents.

**Keywords:** ultra low velocity zone, ULVZ, core-mantle boundary, large low shear velocity province, LLSVP, *ScS* waves

**1 Introduction**

Over the past 2 decades, dozens of seismic studies have provided evidence for extremely anomalous patches between the solid rocky mantle and molten metallic outer core (see, for example, studies reviewed by Thorne et al., 2004; McNamara et al., 2010). ULVZs are commonly modeled with up to 10% *VP* reduction and 30% *VS* reduction, and varying thicknesses from 5 to 40 km (Garnero et al., 1998; Thorne and Garnero, 2004). A density increase as large as 10% has also been noted (e.g., Reasoner and Revenaugh, 2000; Havens and Revenaugh, 2001; Rost et al., 2005; Rost et al., 2006; Idehara et al., 2007). Lateral dimensions of modeled ULVZs vary widely, from 10’s of km using short period core-reflected waves (e.g., Idehara et al., 2007), to ~900 km using core grazing and diffracted *S* waves (Cottaar and Romanowicz, 2012). Although less than half of the CMB area has been probed, ULVZs tend to be modeled as isolated patches and preferentially near or within lower than average shear velocity regions (Figure 1a). Many ULVZs appear to be in close vicinity to LLSVP margins (Figure 1a).

The origin of ULVZs is not constrained at present, and several hypotheses have been proposed, and include partial melting of some component of the deep mantle (Williams and Garnero, 1996; Berryman, 2000), accumulated silicate sediments from the core (e.g., Buffett et al., 2000), subducted rocks containing banded iron formations (e.g., Dobson and Brodholt, 2005), iron-enriched post-perovskite (e.g., Mao et al., 2006), iron-rich (Mg,Fe)O (e.g., Wicks et al., 2010; Bower et al., 2011), segregated mid-ocean ridge basalt from subduction (e.g., Christensen and Hofmann, 1994), products from the chemical reaction of mantle and core material (e.g., Knittle and Jeanloz, 1991; Garnero and Jeanloz, 2000a), and possibly remnants of a basal magma ocean from an early earth differentiation process (Labrosse et al., 2007; Nomura et al., 2011). Better characterization of ULVZ distribution, properties, and morphology, especially related to surrounding structures (e.g., LLSVP and surrounding mantle), is important to help distinguish between these possibilities.

Thin layering on the core-side of the CMB (e.g., few km) can produce seismic signals that look like those used to image ULVZ structure (Garnero and Helmberger, 1998). Various mechanisms have been proposed to produce a ubiquitous core side layer, including compaction of silicate sediments that accumulate as the core grows (Buffett et al., 2000), or by double diffusive boundary effects of the core and mantle (Buffett, 2010). Isolated core structures may also exist. Rost and Revenaugh (2001) suggested a zone with non-zero *VS* underneath a CMB topographic high, possibly filled by lighter core material. Trade-offs have thus been considered in the seismic imaging of mantle versus core-side layering (as well as models involving some kind of (e.g., “fuzzy”) core-mantle transition (Garnero and Jeanloz, 2000a, 2000b).

The distribution of ULVZs appears to statistically correlate with the surface locations of hotspots (Williams et al., 1998). Additionally, many ULVZs locate near the margins of the LLSVPs (McNamara et al., 2010), which geographically correlate with the surface eruption locations of most Phanerozoic kimberlites and large igneous provinces (Torsvik et al., 2010). Combining this with hot spots being more likely to overly LLSVP margins than elsewhere (Thorne et al., 2004) is consistent with ULVZs being associated with plume generation zones (e.g., Rost et al., 2005) at the edges of the LLSVPs (Williams et al., 1998; Burke et al., 2008); that is, hotspots may originate from whole mantle plumes associated with LLSVP margins with minimal deflection by mantle convection.

High resolution geodynamic modeling shows that convection currents inside lowermost mantle thermochemical piles are able to focus and support these dense ULVZs locally at the boundaries of the piles (e.g., Hernlund and Tackley, 2007; McNamara et al., 2010), consistent with many seismic observations. Li et al. (2015) demonstrate that different possibilities exist regarding the location of ULVZs relative to thermochemical pile margins. If ULVZs are due to partial melt of the thermochemical pile material, they are preferentially away from pile margins where the hottest CMB temperatures are. If ULVZs are due to a unique chemistry that is intrinsically denser than the thermochemical piles, ULVZ material will accumulate at the margin of the pile, but in a non-continuous fashion. If ULVZs are composed of partially molten dense material, dense melt might be suspended due to stirring within ULVZ driven by viscous coupling to convective currents in the overlying mantle, which would result in a positive gradient with depth in VS velocity (Hernlund and Jellinek, 2010), i.e., ULVZ shear velocity being most decreased at the top of the ULVZ. While at least one seismic study is consistent with this (Rost et al., 2006), incomplete CMB coverage and/or poor resolution precludes a definitive description of ULVZ seismic properties.

A number of approaches have been utilized to image ULVZ structure or related phenomena, but center on either reflections (or scattering) of energy from the structure that produce additional arrivals, or anomalous behavior of the phase of interest (travel time and/or waveform) due to the structure. Past analyses have included precursors to *PcP* and *ScP* which reflect off the top of the ULVZ(Vidale and Benz, 1992; Mori and Helmberger, 1995; Kohler and Vidale, 1997; Revenaugh and Meyer, 1997; Garnero and Vidale, 1999; Castle and van der Hilst, 2000; Reasoner and Revenaugh, 2000; Havens and Revenaugh, 2001; Persh et al., 2001; Rost and Revenaugh, 2001, 2003; Rost et al., 2005, 2006, 2010a, 2010b; Idehara et al., 2007; Rost and Thomas, 2010), scattering of *PKP*, *PKKP*, and *SKS* waves from ULVZ structural complexities (Vidale and Hedlin, 1998; Wen and Helmberger, 1998a; Thomas et al., 1999; Stutzmann et al., 2000; Wen, 2000; Ni and Helmberger, 2001a; Niu and Wen, 2001; Zou et al., 2007; Rost and Earle, 2010; Frost et al., 2013), and travel time and/or waveform anomalies of: *ScS* (Ni and Helmberger, 2001b, 2003; Wen, 2001; Simmons and Grand, 2002; Avants et al., 2006a, 2006b; He et al., 2006; Lay et al., 2006; He and Wen, 2009), *SPdKS* (Garnero et al., 1993; Garnero and Helmberger, 1995, 1996, 1998; Helmberger et al., 1996, 2000; Wen and Helmberger, 1998b; Rondenay and Fischer, 2003; Thorne and Garnero, 2004; Thorne et al., 2013; Jensen et al., 2013), S and Sdiff (Cottaar and Romanowicz, 2012), P and Pdiff (Xu and Koper, 2009), *PcP* (Simmons and Grand, 2002; Hutko et al., 2009), *PKP* (Bowers et al., 2000; Luo et al., 2001), and *PKKP* (Rost and Garnero, 2006).

Short period core-reflected data such as *PcP* and *ScP* have proven important for high resolution ULVZ imaging, since they do not have an ambiguity in the location of possible anomalous structure at the core entry-versus-exit regions, as well as having a much smaller Fresnel footprint than many phases (e.g., compared to *Sdiff*, *Pdiff*, or *SPdKS*). The short period data benefit from dense sensor networks or seismic arrays to allow for array processing (thus improving signal-to-noise ratios), but this limits the number of places the CMB can be probed compared to single-station methods. *SPdKS* accounts for the greatest amount of ULVZ detections due to the increased global sampling. However, high-resolution waveform modeling is required to minimize the source/receiver side of path ambiguity (e.g., as in Rondenay and Fischer*,* 2003; Thorne et al., 2013). Double-array stacking of *ScS* data has demonstrated sensitivity to ULVZ structure (Avants et al., 2006b), but *ScS*, typically a clear and strong arrival in teleseismic data, has not been aggressively pursued or exploited as a ULVZ probe.

In this study, we developed a new use of *ScS* as a ULVZ probe to take advantage of the fast growing high quality network datasets (such as EarthScope’s broadband USArray data) which hold potential for greatly increasing CMB coverage for ULVZ investigation. Our focus is to develop and validate the new probe. We present our method and method validation in Section 2, procedures of data processing and geographical bin stacking are introduced in Section 3, and a first order 1D reflectivity forward modeling approach is described in Section 4. In the sections that follow, clear evidence for laterally variable ULVZ structure along the LLSVP margin beneath the northeast Pacific is established.

**2 *ScS* Stripping Method and Validation**

We use *ScS* as a reference phase to search for additional signals reflected from ULVZ layering. As shown in Figure 2a, around the main arrival *ScS*, a ULVZ layer produces a pre-cursor (*SdS*) by reflection off the top of the ULVZ, and a post-cursor (*ScscS*), an *ScS* with an additional internal reflection within the ULVZ,from the underside of the ULVZ top. 1D reflectivity synthetic seismograms (Fuchs and Müller, 1971; Müller, 1985), computed for an epicentral distance of 70° are shown for ULVZ models possessing VP and VS velocity reductions of -10% and 0%, respectively, for a suite of ULVZthicknesses (Figure 2b). Here we see that the *SdS* precursor and *ScscS* postcursor arrivals have similar waveshapes but opposite polarity. Their travel time advance and delay relative to *ScS* are indistinguishable for 1-D models with ULVZ layer thickness less than ~ 100 km (Figure 2c). For thicker ULVZs, the distance between the ULVZ entry and exit locations of *ScscS* is roughly 2 times of that of *ScS,* and the postcursor delay becomes larger than the precursor advance (relative to *ScS*). For a typical ULVZ thickness, e.g., 15 km, the distance between the ULVZ entrance and exit locations of the *ScscS* raypath is about 53 km. Thus for ULVZs that are roughly uniform across a reasonable lateral extent, e.g., 100 km in Rost et al. (2006), this *ScscS* postcursor can be expected. The small error bars in Figure 2c show that the relative travel time variation for *SdS* (relative to *ScS*) over a 15° epicentral distance range is smaller than 1 sec for ULVZ thicknesses less than 50 km. For thicker ULVZ models, this variation increases. Hence we take the precaution of avoiding stacking records spanning distance ranges larger than 15°.

Given the symmetric characteristics of pre- and post-cursors (i.e., symmetric arrival time relative to *ScS* and similar waveforms with opposite polarity), we employ a new method to enhance possible ULVZ-generated energy: the Flip-Reverse-Stack (“FRS”) technique (Figure 3). In FRS, each trace is cut at the peak of *ScS*; the first half of the trace leading up to the *ScS* peak is flipped in polarity and reversed in time then added to the second half of the original trace. Fig. 3a shows the process for a synthetic seismogram computed for a ULVZ model. The resulting FRS trace demonstrates that (a) *ScS* is effectively removed from the waveform, and (b) the ULVZ arrivals are constructively summed, and thus enhanced (see thick black trace in Figure 3a). The FRS method is similarly shown for a data record in Figure 3b: the *ScS* signal is removed leaving an enhanced energy pulse ~ 3 sec following the former *ScS* peak location. We denote this combination of ULVZ pre- and post-cursor as *SU,* to indicate it as a ULVZ-born phase. Figures 3c and 3d show data examples with and without *SU* signals, respectively. Hence the FRS technique enables us to explore the geographic distribution of *SU* signals to investigate ULVZ properties.

To test the sensitivity of *SU* in FRS traces to ULVZ properties, we apply the FRS method to a large suite of synthetic seismograms for a range of 1D ULVZ models. The following ULVZ parameters were varied: *S*-wave velocity reduction (VS)*P*-wave velocity reduction (VP), density increase (**)and ULVZ thickness (*d*). Figure 4 shows the dependency of time delays of the peak of *SU* relative to the peak of *ScS* as well as *SU* amplitude variations relative to *ScS* (before *ScS* was removed by FRS) for different model parameters. Figure 4a varies *VS* while other ULVZ parameters are fixed (d=15 km, =10%, and *VP* =-10%). The peak time of *SU* increases gradually from about 2 to 4 sec, as *VS* decreases from -2% to -30% (left panel in Figure 4a). Amplitude ratios of *SU* and *ScS*, however, show a dramatic increase from about 0.2 to 0.5 as *VS* decreases from -2% to -10%, after which, the ratio remains at around 0.6 while *VS*decreases from -10% to -30% (middle panel of Figure 4a). The third column in Figure 4a shows synthetic *SU* traces at 70º for different *VS* models. Figure 4b shows the amplitude of *SU* (and hence the *SU*/*ScS* amplitude ratio) increases with increasing density (**while the *SU* time is unaffected. We also test the dependency of *SU* on ULVZ thicknesses variations (Figure 4c). The peak time of *SU* increases sharply from 0 to 10 sec as the ULVZ thickness increases from 2 to 30 km. This demonstrates the timing of *SU* relative to *ScS* has the strongest sensitivity on ULVZ thickness. The *SU*/*ScS* amplitude ratio increases with increasing ULVZ thickness: the ratio increases dramatically for the first 10 km of ULVZ thickness and then flattens at around 0.7 for greater ULVZ thicknesses. The *SU* peak time and amplitude do not depend on ULVZ *VP*structure (Figure 4d).

From these synthetic tests, we see that the *SU* peak time is most sensitive to ULVZ thickness, but also shear velocity reduction; these two parameters represent a common trade-off encountered in seismology. Figure 5 illustrates this trade-off, which is strongest for ULVZ thicknesses > 20 km. As seen in Figure 4, smaller thicknesses show *ScS*-*SdS* differential times are more sensitive to the ULVZ thickness. The constant time contours were calculated from synthetics made for a suite of ULVZ thicknesses and shear velocity reductions.

**3 Dataset and Processing**

**3.1 Data Collection and Pre-processing**

We collected shear wave data from 6 intermediate-to-deep focus Fiji-Tonga earthquakes displaying impulsive source shapes and strong signal-to-noise ratios (SNRs) of dominant phases compared to the background energy before the first arriving shear wave. The majority of our dataset is recorded by densely distributed broadband seismometers of the USArray network in North America (Figure 6) deployed by the EarthScope project (http://www.earthscope.org). Table 4.1 lists event information as reported by the National Earthquake Information Center (NEIC). Initially, we obtained displacement component seismograms by instrument response deconvolution, then rotated traces to the great circle reference frame to obtain radial and transverse components of motion. A band-pass filter from 1 to 67 sec was applied in attempt to minimize long period energy associated with instrument deconvolution (Figure S1b). This bandpass filter gives rise to the long-period negative amplitude signal before *S* and *ScS* (Figure S1a),which can affect the FRS processing. To mitigate this, we deconvolved instrument responses, then worked with velocity seismograms, which show much less deconvolution-induced long-period noise (bottom traces, Figure S1b), Every record is then individually inspected. We do not include records at distances where *ScS* and *S* merge in time (near 84 deg or so). Our final data set consists of 984 recordings of *ScS* referenced to direct *S* on the transverse component of motion*.* The entire data set spans a distance range from 71° to 84°, and densely samples the lowermost mantle beneath the central Pacific, southeast of the Hawaiian hotspot (Figure 6b).

We chose earthquakes for which *S* and *ScS* are predicted to be similarly within a strong part of the SH radiation pattern. Radiation patterns for *P* and *SH* components of motion were computed using the Centroid Moment Tensor (CMT) solution for each event obtained from the global CMT database (<http://www.globalcmt.org>); *S* and *ScS* lower hemisphere radiation pattern piercing locations are shown in Figure 6c. For every event, *S* and *ScS* are in the same radiation quadrant without crossing a nodal plane, thus we do not expect differential polarity effects on *S* and *ScS*. Visual inspection of the data corroborated the same-polarity predictions of the SH focal mechanisms.

**3.2 Empirical Source Construction and Deconvolution**

Empirical sources of *S* and *ScS* are separately constructed for each event through an iterative stacking technique, where the phase of interested is windowed, then aligned by cross-correlation, and then summed iteratively to produce an estimate of the source wave shape. The *S* (and *sS* if present) phases are masked (zeroed in amplitude) to preclude their possible contamination to the *ScS* source construction. Similarly, *ScS* and *sS* phases are masked for *S* source construction. For simple sources, *S* and *ScS* empirical sources on velocity seismograms have an upswing followed by a downswing (Figure 7a). The standard deviation about the mean shape of *ScS* is larger than S, reflecting the fact that *S* is larger in amplitude than *ScS*, as well as *S* not having significant energy arriving before it in time. *ScS,* however,can have pre- and post-cursory energy from D” phenomena, including ULVZ structure (e.g., as in Figures 3 and 4).

We pursue deconvolution to remove the *ScS* empirical source stack shape from individual seismograms to sharpen *ScS,* and to equalize *ScS* shapes between events. But if faint energy from ULVZ structure is present before *ScS* arrivals, deconvolution of the *ScS* stack may inadvertently remove the ULVZ-born energy from the deconvolved *ScS* signals (i.e., the very energy we seek to study). To mitigate this possible effect, we proceed with a method to deconvolve the *S* empirical source stack from *ScS* seismograms. However, while very similar in shape to *ScS* (and containing the same source effects, see Fig. 7), *S* is typically not exactly the same width as *ScS*. A slightly broader *ScS* may arise from attenuation in D”, for example,from the hot thermal boundary layer at the base of the mantle. In some cases, *ScS* is narrower than *S*. We adjust *S* to look more like the main up and downswing of *ScS* by stretching or compressing *S* in time (see Figure 7b). We retain the adjusted S empirical source that best correlates with the *ScS* empirical source. The best-fitting time-stretched (or -squeezed) *S* source shape for each event is then deconvolved from *ScS* phases, and the unstretched S is deconvolved from S phases. Deconvolutions are done using the water-level deconvolution method (Clayton and Wiggins, 1976; Stefan et al., 2006). After deconvolution, empirical sources are rebuilt, and the new source shapes of *S* and *ScS* become simpler Gaussian-like pulses (Figure 7c). ­ This procedure of using S for deconvolution circumvents removing any ULVZ signal that may be hidden in *ScS* source shapes.

The deconvolution process removes source effects from each event to yield a uniform population of Gaussian-like waveforms, which permits stacking waveforms from different events (e.g., in geographically oriented stacking schemes). The water-level deconvolution method has two parameters that affect the width and frequency content of the result: (1) a cut-off amplitude (“water-level”, WL) in frequency domain where frequencies below this level are set to WL to avoid zero-division in the spectrum of interest; and (2) a Gaussian width parameter (in seconds), whereby the width of the Gaussian at half of the peak amplitude is specified, i.e., the full width at half maximum (FWHM). We experimented with combinations of both parameters, and for *S* and *ScS* in our dataset, and found that the parameters WL=0.01 and FWHM=3 sec were optimal for most events (examples are shown in Figure S2a). Smaller values of FWHM result in more ringing in the deconvolved traces. For one event (2008/11/08), a larger FWHM value (4.5 sec) was necessary to suppress noise in the deconvolution.

**3.3 Geographic Bin Stacking**

We organize the *ScS* CMB reflection locations into overlapping bins with 1.5º radius (thus, bin radius is roughly 100 km at the CMB). Bin locations are adjusted to the geographical center of the *ScS* bounce points within each original bin location. Figure 8a displays the adjusted bin locations for our study area. The FRS technique is applied to all source-deconvolved *ScS* records, and the resulting FRS traces are stacked in each bin possessing more than 10 records. We stacked FRS traces using an iterative linear weighted stacking approach as follows. First, a cross-correlation coefficient (CCC) is computed for each *ScS* compared to the *ScS* empirical source stack (before *ScS* stripping). Traces are thus referenced in time by their *ScS* best correlating to the *ScS* empirical source stack. All pre-stack FRS traces inherit this time reference. A pre-stack weight is defined for each FRS record from a combination of the pre-FRS signal-to-noise ratio (SNR), a cross-correlation coefficient between each FRS trace and the stack of FRS traces, and a Gaussian location weight, the latter being a Gaussian function of distance between *ScS* bounce location and the bin center. The SNR is defined as the ratio of the peak amplitude of *ScS* and the peak amplitude of noise within a 15 sec window ahead of the S phase. Records are discarded that possess low SNR (<2) and CCC (<0.1) between FRS traces and the FRS stack. A bootstrap resampling (n = 200) of seismograms within each bin is also performed to evaluate uncertainties associated with each stack shape (Figure 8b). Energy of every bin stack falling above the bootstrap 95% confidence interval is displayed in Figure 8c. The bootstrap test shows robust and strong positive energy in the southwest and southeast regions, slightly negative polarity energy in the northwest region, and relatively low amplitude signals elsewhere.

Strong waveform similarities are observed for several of the bin stacks in Figure 8c. Using a clustering algorithm, we identify similar shaped bin stacks for stacks that have strong *SU* energy, resulting in grouping bins into 7 distinct clusters. New FRS stacks are computed from all traces of contributing bins within each cluster, again using the same bootstrap-stacking algorithm (Figure 8d). The larger number of records in each bin significantly reduces the variability in the bootstrap resampling, and stacks are more robust. The lateral dimension of the new clustered bins varies from ~200-350 km. Next, we explore local ULVZ structures to explain the FRS cluster traces.

**4 Modeling**

**4.1 Bin Clusters**

The regionally clustered FRS bin stacks of Figure 8d differ in character, e.g., from large positive FRS pulses (bin clusters 1 and 2) to the first pulse being a negative downswing (bin cluster 7), and thus present the opportunity to explore different local ULVZ models for these locations. The lateral scale of the individual cluster regions is roughly between. The *ScS* Fresnel Zone for ~10 sec period waves (e.g., < 100 km) is much less than the cluster region sizes (200-350 km). Thus, as a first step towards characterizing ULVZ structure to explain our data, we pursue 1-D models to reproduce the dominant character of the individual FRS bin cluster stacks. We seek to investigate first-order differences in ULVZ structure between the 7 regions of Figure 8d..

**4.2 Reflectivity Models**

13,850 Synthetic seismograms were computed using the 1-D reflectivity method (Fuchs and Müller, 1971; Müller, 1985). We constructed ULVZ models for the following four categories: (1) a single ULVZ layer; (2) a two-layer system: a ULVZ and an overlying less anomalous low-velocity zone (LVZ) layer; (3) a three-layer system: a ULVZ, an overlying high velocity zone (HVZ), and a LVZ that overlies the HVZ; and (4) a single HVZ layer. For each category, four different sets of ULVZ properties are considered: (1) -30% *VS*, -10% *VP*, +10% ; (2) -45% *VS*, -15% *VP*, +10%  (3) -15% *VS*, -5% *VP*, +5%  and (4) -10% *VS*, -10% *VP*, +10% . Linear gradients of velocities with respect to depth are also explored for the four ULVZ structural categories, since it affects the amplitude of reflections. For model categories (2) and (3) above, we consider three different LVZ velocity properties: (1) -3% *VS*, -1% *VP*, 0% ; (2) -5% *VS*, -2% *VP*, +1% ; and (3) -7% *VS*, -3% *VP*, +1% . The velocity structure assumed for the HVZ is +3% *VS*, +1% *VP*, and +1% . Here we note that the elastic parameters resulting in this grid search approach may have specific material property implications, which we do not explore here. The majority of all the models have thickness increments of 2 km, resulting in our testing ULVZ, LVZ, and HVZ maximum layer thicknesses of 24, 50, and 50 km, respectively. For all models, synthetic seismograms are calculated for every 1 in epicentral distance.

We process synthetic seismograms following the same procedures as we do with data: we convert synthetics from displacement to velocity, empirical sources of *S* and *ScS* are produced, and the best stretched/squeezed *S* source is determined that matches *ScS* then deconvolved from each seismogram using the water-level method. To avoid any possible distance-dependent effects of pre- versus post-cursor timing relative to *ScS* (associated with HVZ and LVZ models and distance-dependent amplitude variations of ULVZ models, see Figure S3), for each bin cluster, we stack FRS residuals of synthetic seismograms matched to each observed seismograms epicentral distance. In addition, the weighting parameters (SNR, CCC, and Gaussian weight) of each data trace within each cluster are applied directly to the distance matched synthetic seismogram to account for possible amplitude differences introduced by the weighting scheme used with the actual data.

**4.3 Best-fit 1-D ULVZ models**

After creating bin-cluster stacks using the synthetics from all models (in the exact same fashion as with the data), we utilize a cross-correlation scheme to find the best-matching model for every cluster made from data (i.e., those in Figure 8d). Since both amplitude and waveshape in the bin-cluster stacks potentially contain essential ULVZ information (thickness, internal properties, and multiple layering), we utilize an amplitude sensitive cross-correlation algorithm to seek the best matching synthetic model. After cross correlating the observed and synthetic bin cluster stacks, we modify the cross-correlation coefficient by an empirical weight that takes into consideration the similarity in waveshape, as well as peak amplitudes. The weight is a product of the difference between the area beneath a synthetic waveform (*Asynthetic*) and area beneath a bin cluster waveform (*Aref*), of area under the curve and a similar difference between the maximum synthetic peak/trough amplitude (*Psynthetic*) with that of a cluster trace (*Pref*), as follows:



The multiplication of the cross correlation coefficient with the above weight helps to account for small amplitude structures (e.g., as in bin clusters 6 and 7).

The resultant best-matching 1-D ULVZ structures for all the clusters are displayed in Figure 9. For clusters 1, and 2, models with a 20 km thick ULVZ are found to match the main positive polarity peak in timing and amplitude. While the bin cluster stacks 1 and 2 were unique from each other, they are not markedly different in their shape, and accordingly the solution models are essentially similar. The downswing that follows the main peak is not matched in bin clusters 1 and 2. This feature might be due to a reflection off high velocity layering above our model space of exploration, e.g., 100 km or higher, which we do not pursue here. Three-dimensional structure may also contribute to the later arriving downswing (discussed more in the Discussion Section). Trade-offs between ULVZ thickness and velocity reduction exist, which is punctuated by the different ULVZ reductions and thicknesses in the solution models. Among best-fit models are linear gradient models at the top of the ULVZ layering sequence (Figure 9).

Bin clusters 3 and 4 are in the southeast of our study area (Figure 8d). Synthetics from best-fit models match the observed bin-clusters fairly well, with a thinner ULVZ layer than for clusters 1 and 2 to the west, and additionally overlain by a high velocity layer, and an LVZ overlying that (Figure 9). For bin-cluster 3, a range of models fit the observations as well as the best-fit model (especially in regards to the LVZ at the top of the layering sequence); for bin-cluster 4, a somewhat smaller range in models fits the observations. The bin cluster stack 5 has a similar shape and character as bin cluster 4, but the peak amplitude is lower, and resulting good-fit models are more variable, with some having and some lacking an LVZ layer overlying the HVZ. Some of the good-fit models are similar to the models of clusters 3 and 4. The character of bin-cluster 6 (located to the north of bin-cluster 5) has a small positive pulse followed by a negative pulse. The best-fit model is similar in character to that for bin cluster 3. However, the character of the 2nd half of bin clusters 3 and 6 are quite different (which is not a part of the signal that our models discriminate against very well). Interestingly, to the north of clusters 1 and 2, bin cluster 7 initiates with a negative peak, which is best-matched by a model with a high velocity layer on top of a negligibly thin ULVZ.

Except for bin clusters 1 and 2, a common characteristic among the best-fitting models is a high velocity layer above the ULVZ, which accounts for the slight downswing immediately after the ULVZ-induced positive peak. The best-fit models also demonstrate clear evidence for lateral thickness variations in ULVZ structure. Bin-clusters 1-4 have best-fit models with Vs=-30%, as does bin-cluster 6; bin-cluster 5 (located close to bin-clusters 3 and 4), has a Vs=-30% good-fit model that resembles the best-fit model for bin-cluster 4 (Figure 9). We thus take the thicknesses of the best-fit Vs=-30% models for bin-clusters 1-6 (omitting bin-cluster 7, since it is effectively an LVZ, not a ULVZ), and plot these along with the LLSVP margin in Figure 10. The LVZ region for bin-cluster 7 is shown as a hatched zone (in the northwest of the study region). The preferred location of the large ULVZ of Cottaar and Romanowicz (2012) is located outside of our study area to the west, but they noted possible alternative locations that extend into our study area (regions 6a and 6b in Figure 1). This is where we have the LVZ of bin cluster 7, and regions which either lack ULVZs or where they are thinner than our detection level (~ 5 km). The general absence of ULVZ structure in the northwest of our study region (Figure 10) is consistent with the large ULVZ in Cottaar and Romanowicz (2012) situated in their preferred location. The Courtier et al. (2007) study models multiple ScS reverberations, and do not directly model ULVZ structure, but not ULVZ presence may explain some data features. Thus, while we indicate their ULVZ beneath Hawaii in Figure 1 (region 5), it can in fact (if necessary for their data) be to slightly to the west or southwest to coincide with the Cottaar and Romanowicz (2012) preferred location, given the Fresnel zone size of their ScS waves.

The thicker ULVZ structure of bin clusters 1 and 2 map the furthest inside of the LLSVP (according to the Vs =-0.8% contour in the S20RTS model). Bin cluster 6 maps outside the -0.8% contour, which may mean that ULVZ structure is indeed outside the LLSVP, or that the LLSVP margin is not confidently mapped at this location and might in fact be slightly to the northeast.

As noted in Figure 1 (regions 1-4), several studies have presented evidence for ULVZ structure in the area of our bin clusters 1 and 2. Figure 10b presents velocity depth profiles of several studies, and compares them with our preferred model for bin clusters 1 and 2 (dashed blue line, Figure 10b). **[[ADD DETAILS HERE**. Region 1 is 3 studies. Do all three present that model in fig 10b? I know why the Mori model might disagree, since it was a PcP study, right? Thus we have more sensitivity to S. What about Kohler? Etc etc. Please provide the details of the different models, and try to reconcile why our result is so very different. This is very very important. There are 2 aspects to why something may disagree. You can consider my discussion of Cottaar and Romanowicz as an example, and the Courtier et al also, as an example: we can either consider their data and its Fresnel zones, and/or where they sample. But we **cannot** just present it and show such discrepancy and not talk about it. Ok? This modification will require information to be added to Figure 10b caption (and maybe the figure itself), and of course text here.**]]**

**5 Discussion and Implications**

**5.1 Assumptions and uncertainties**

In this paper, we developed a new method to strip out the main *ScS* phase and enhance subtle ULVZ-generated reflected energy, if present, in FRS traces. These were then geographically clustered, re-stacked, and assigned best-fitting regional 1-D ULVZ models. One of our primary objectives was to test this technique for identifying ULVZ structure, with an emphasis towards identifying lateral variations in ULVZ structure. This method appears fairly stable, and thus represents an addition to the collection of ULVZ-detecting seismic waves, especially because *ScS* is a well-recorded seismic wave and typically easily observable for most deep earthquakes with M>6. However, several uncertainties exist, and are discussed here.

One source of uncertainty comes from the deconvolution process. Since every seismogram may possess a unique frequency content and noise level, the deconvolution process has the potential to amplify a certain frequency band, resulting in an elevated noise level after deconvolution (Figure S2). Consequently, seismograms with lower *ScS* amplitudes appear to have much higher noise level after deconvolution. Through trial and error, we optimized deconvolution parameters to suppress noise while making the resultant waveform narrow. We also suppressed biases introduced by deconvolution effects by weighting each seismogram by a signal-to-noise ratio measured after deconvolution. Our goal was to stack data from different events, thus deconvolution allowed us to equalize the signals pre-stacking. Using large datasets helps to suppress the effects of any given record on the stack results.

Strong variations in ULVZ thickness over lateral scales shorter than our geographic bin clusters might contribute scatter and variability to FRS stacks of the bin clusters. For example, the distance between the center of clusters 2 and 4 is ~ 350 km at the CMB, over which our best-fit model ULVZ thicknesses change from 20 km (bin clusters 1 and 2) to 14 km (bin clusters 4 and 5, Fig. 10a). The ULVZ thickness change between these two models may certainly be more acute: if comparing individual bin stacks for bin 14 and bin 15 (Figure 8b), where the distance is less than 100 km, the FRS stacks are different (and bin 14 may represent some transition from the behavior seen at bin 13 and its neighbors to the east, e.g., FRS stacks of bins 15 and 7, etc.).

Bin cluster 3 is close to bin clusters 4 and 5, and best-fit with a much thinner model, 5 km thick. ULVZ structural changes over short lateral distances is not unusual, and this level of variability is comparable with the lateral variations in thickness inferred from past studies (e.g. Rost et al., 2005; Idehara et al. 2007). If significant ULVZ thickness changes over short lateral distances are present (e.g., < 100 km), which of course includes the possibility of tilted or other 3-D structures, the ULVZ pre-cursor and post-cursor arrivals (Figure 2) may fail to be symmetric about *ScS* (and/or absence), resulting in a number of possibilities, including broadened or even multi-peaked FRS traces (if multi-peaked, with weaker amplitudes). The resultant best-fitting 1-D model could thus have a weaker and thinner ULVZ, leading to an underestimation of ULVZ properties. Multiple bumps are in fact present in the FRS of bin cluster 3 (see Figure 8d and Figure 9). Our 1-D approach does not resolve if ULVZ structure at the location of bin cluster 3 may be a transitional (e.g., tilted) structure or true variability in the form a strong reduction in ULVZ thickness from the bin clusters 4 and 5 to the east.

Bin clusters 3, 4, 5 and 6 have very complex 3-layer best-fit velocity structures for the lowermost 100 km: their ULVZs are overlain by HVZ and LVZ layering (Figure 9). These complex velocity structures might be caused by a number of possibilities, which include complexities associated with local accumulation of chemical heterogeneities (Wen and Helmberger, 1998a; Rost and Earle, 2010; Frost et al., 2013; Li et al., 2014), or possibly discontinuities associated with the post-perovskite phase transition (Hernlund et al., 2005; Lay et al., 2006; Avants et al., 2006a). Alternatively, it is possible that fine-scale heterogeneity along the *ScS* raypath can manifest as complexities in a solution 1D structure, but this possibility requires (*i*) the structure to similarly affect data from different source-receiver geometries as to robustly affect the bin stack, (*ii*) if low in amplitude, the structure is required to produce a pre- and post-cursor to *ScS* that are opposite in polarity and equal in time away from *ScS* to stack coherently, and/or (*iii*) the signal needs to be large enough relative to *ScS* so that its amplitude remains large after the FRS process. These possibilities become more viable if crossing path coverage is poor, and for our study region it is dominated by southwest Pacific events to western US stations. But for our data, multiple sources and rays sample the different bins and shows variability among the bins in our study area (and bootstrap resampling establishes the stacks are robust). We thus argue the source of the waveform variability is indeed structure at the CMB; this is supported by a number of other seismic phases and analyses that place ULVZ structure at the CMB in our study region.

The first positive peak in bin clusters 1 and 2 associated with ULVZ structure is fit well by synthetic models (Figure 9), however, the strong downswing immediately following the peak is poorly predicted. Possible causes include, but are not limited to, the limited parameter space of tested velocity structures above the ULVZ (such as not exploring high enough above the CMB), and unaccounted for, complex yet strong, 2- or 3-D heterogeneities along the raypath. The former might be resolved by exploring a more complete parameter space with larger range of velocity increases and thicknesses of the HVZ. The latter requires 2- or 3-D wavefield modeling, which is left for future work – our focus here has been to establish the FRS method and test its ability to identify local ULVZ structures.

For a given set of 1-D ULVZ properties, the uncertainty associated with determining the ULVZ thickness is roughly within 2 km due to the high sensitivity to thickness of the FRS peak time (Figure 4c). The average noise level relative to the *ScS* peak amplitude is about 0.15 across our whole dataset. Hence, we estimate the detection threshold of our technique for ULVZ thickness to be approximately 5 km, below which, the amplitude of *SU* in FRS traces (and stacks) is comparable to the noise level of our data. Any combination of lower noise level, higher frequency data, or array methodologies may hold promise for pushing this detection threshold to a smaller thickness.

The trade-off between ULVZ thickness and velocity reduction (e.g., Garnero et al., 1998; Thorne and Garnero, 2004) also exists for this ULVZ probe, and hence the velocity reduction of the best-fitting ULVZ models is not uniquely constrained. For example, for bin cluster 1, a ULVZ model with 45% *VS* reduction and thickness of 16 km also fits the data fairly well (Figure 9). However, if the velocity reduction of best fitting models is lessened, combined with thickening the ULVZ, FRS amplitudes diminish, resulting in a poorer fit the data stacks. Thus the thickness-velocity trade-off of the FRS approach may not be as strong as some of the other probes.

Seismic anisotropy is not considered during the data processing and modeling of this study. Lateral variations of anisotropic shear-wave polarization directions have been documented for the lowermost mantle in this region (Russell et al., 1998). Anisotropy can introduce splitting time of *ScS* between radial and transverse components of motion; we do not anticipate this affecting the FRS stripping technique, which only uses the transverse component. Azimuthal anisotropy (e.g., Garnero et al., 2004; Maupin et al., 2005; Wookey et al., 2005; Wookey and Kendall, 2008) may potentially introduce energy around *ScS,* but this should not dominate the FRS process since any SV leakage onto the SH should not be symmetric about *ScS*. Upper mantle anisotropy might similarly have subtle and asymmetric effects on waveforms, but we do not anticipate it strongly affecting the FRS process.

The relative location between our mapped ULVZ structure and the edge of the LLSVP depends upon constraining the location of both. We have represented the location of the edge of the LLSVP in long wavelength tomography by one particular model (Ritsema, 20XX); other models result in the edge location differing by up to 100’s of km (e.g., see Zhao et al., 2015). We do not constrain the LLSVP edge here, nor do we attempt to evaluate its location in the different tomography models. However, we emphasize that the nature of ULVZs, e.g., if they are within the LLSVPs, just at their margins, and/or outside LLSVPs relate to different possible origins of ULVZs. We also note the locations of our mapped ULVZs have been derived using 1-D raypaths (as have many tomography models). But the 3-D heterogeneity of the LLSVP likely causes raypath deflections to some degree. Future work can explore this effect with 3-D ray tracing as well as 3-D synthetics (as in Cottaar and Romanowicz, 2012). Another possible source for waveform distortion is that the edge of the ULVZ might give rise to wave multi-pathing (Rost et al., 2006; Idehara et al., 2007), causing coda energy and thus complex FRS bin stack waveforms; such later arrivals might manifest as velocity structure further up off the CMB in our 1D modeling scheme. Our results (e.g., Figure 10) motivate future work that assesses waveform effects of the 2- and 3-D structure implied from this modeling, which is also implied by high-resolution geodynamic modeling (Li et al., 2014), which we discuss next.

**5.2 Dynamical Implications**

The recent interpretation of LLSVPs being due to thermochemical piles of chemically distinct material (e.g., McNamara and Zhong, 2005; Nakagawa and Tackley, 20XX; Torsvik and XXX, 201X) suggests the highest mantle temperatures exist within the piles. If ULVZs all reside inside of thermochemical piles, the hypothesis of partial melting of LLSVP material would plausibly explain the origin of ULVZs(Williams and Garnero*,* 1996). But if some of the ULVZs are located outside of (and distant from) LLSVPs (as shown in the summary of McNamara et al., 2010), other possibilities should be explored, such as a chemically distinct origin to ULVZs. This includes subducted rocks containing dense banded iron formations (Dobson and Brodholt, 2005), iron-enriched post-perovskite (Mao et al., 2006), segregated mid-ocean ridge basalt from subduction (Christensen and Hofmann, 1994; Li et al., 2014), and iron-rich (Mg,Fe)O (Wicks et al., 2010). These possibilities may permit ULVZs away from regions with lower than average velocities or higher than average mantle temperatures. It is also important to consider the fact that other hypotheses for the LLSVPs exist that do not involve chemical distinction from the rest of the mantle (Davies et al., 2012).

Our study suggests significant lateral variation in ULVZ properties across our study region in the central Pacific. This non-uniform distribution of ULVZs is consistent with ULVZ distribution and thickness variability predicted for dense chemically distinct ULVZ material within chemically distinct thermochemical piles, which predicts ULVZ intermittency and variable thickness and shape along pile edges (Figure 11). A number of geodynamic studies show evidence for ULVZs (chemically distinct or solely thermal in origin) being variable in distribution and thickness (e.g., REFERENCES {help from Mingming/Allen}). The calculation for Fig. 11 (after Li et al., 2015) assumes an initially uniform ULVZ layer, 5 km thick, that is denser than the background mantle (not shown) and thermochemical pile material. The ULVZ material is swept by convection to the thermochemical piles and ends up in non-uniform accumulations near the pile edges. The details of the ULVZ accumulations depend on a number of parameter assumptions in the convection calculation (detailed in Li et al., 2015), so we only focus on the general result, that ULVZs are not expected to be uniform along pile margins, and thickness can be variable, but with some locations having relatively uniform properties over local lateral scales (e.g., 100’s of km). Li et al. (2015) also display the distribution of the hottest temperatures within thermochemical piles, which are displaced away from pile edges inside the piles by some 100’s of km. Thus there is the possibility for interesting combinations of partial melt (in the hottest areas) and chemistry (which can be anywhere the material is swept to), resulting in different ULVZ properties from place to place.

A non-uniform distribution of ULVZs (as in Figure 11) may result in non-uniform entrainment (spatial and temporal) within thermochemical piles, and similarly, into mantle plumes which root at the top of thermochemical piles. Thus, if ULVZs contain incompatible elements that are eventually detected in whole mantle plumes (e.g., Hofmann, 1997; Courtillot et al., 2003; Weis et al., 2011), then we expect entrainment and thus erupted trace element abundances to be variable. Furthermore, the evolution of ULVZs with respect to time might also explain the isotopic variability along the track of one particular hotspot (Weis et al., 2011).

**5.3 Expanded coverage possibilities**

*ScS* on the tangential component of motion is a common and strong phase in earthquake data, and covers a reasonably large distance range with little interference and overlapping with other phases. Thus, the FRS method permits surveying large areas of the CMB, in some cases permitting independent probing of past study regions, in other cases permitting analysis of new regions. Since the FRS method with *ScS* utilizes the transverse component of motion, this new probe provides constraints on ULVZ *VS* structure without dependence on *VP*. Future work should combine this method with those dependent on ULVZ *VP* structure for the same region (e.g., *PcP*).

**6 Conclusion**

We developed a new ULVZ probe to flip-reverse-stack (FRS) source-deconvolved *ScS* waveforms within 1.5-degree radius geographic bins to simultaneously strip out the *ScS* wave and enhance reflected energy associated with ULVZ structure. Geographic bins with similar FRS residual stacks were grouped into clusters to produce robust stacked waveshapes. A bootstrap stacking technique was conducted to test the robustness of each stack. The amplitude and time of the stacked FRS residuals are sensitive to the thickness and the velocity structure of ULVZ according to 1-D synthetic tests. This new probe holds the promise to expand the current CMB study area for ULVZ structure.

ULVZ properties are inferred from forward modeling the FRS bin cluster stacks. We used an amplitude-sensitive cross-correlation algorithm to search for a best-fitting model out of 13,850 1-D synthetic models with various ULVZ thicknesses and properties for each cluster. These best-fitting models depict a map of ULVZ thickness distribution, which indicates lateral variations of ULVZ thicknesses and properties near the hypothesized LLSVP edges. ULVZs appear to be thicker within the LLSVP than outside of it, consistent with a thermochemical nature of the LLSVP. Inside of the LLSVP edges, a thick (~20km) ULVZ patch is located near the southwest corner of our study region, and a thinner (~14 km thick) patch is close to the southeast corner, with no or very thin ULVZ in-between them. This non-uniform distribution suggests strong spatial variations of viscous flow strength within the LLSVP and along LLSVP edges.

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**Supplementary Online Material**

Materials and Methods

Figs. S1-S3

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**Table 1.** Event list

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Date | Latitude (deg) | Longitude (deg) | Depth (km) | Mag. |
| 02 Feb. 2006 | -17.83 | -178.28 | 599 | 5.8 |
| 26 Aug. 2007 | -17.46 | -174.34 | 127 | 5.9 |
| 19 Jul. 2008 | -17.34 | -177.31 | 391 | 6.4 |
| 22 Oct. 2008 | -18.42 | -175.36 | 233 | 6.4 |
| 08 Nov. 2008 | -15.22 | -174.23 | 121 | 5.4 |
| 22 Nov. 2009 | -17.79 | -178.43 | 522 | 5.7 |

**Figure 1.** (left)Lowermost mantle shear velocity heterogeneity from model S20RTS (Ritsema, XXXX) is shown by the shaded blue (higher than average wavespeeds) to red (lower than average speeds) colors. Black box denotes the region of this study, which is enlarged in the panel on the right. Two dVs contours are shown: -0.5% (orange) and -0.8% (red). (right) Six previous ULVZ mappings in our study region are shown by differently colored lines with numbers corresponding to: 1. *Mori and Helmberger* (1995); *Kohler et al.* (1997); 2. *Revenaugh and Meyer* (1997); 3. *Avants et al.* (2006a); *Lay et al.* (2006); 4. *Hutko et al.,* (2009); 5. *Courtier et al.,* (2007); 6. *Cottaar and Romanowicz* (2012): 6a and 6b correspond to ULVZ locations that can explain some aspects of their data to the northeast of their preferred ULVZ location (which is outside our study region). Background is the *VS* tomography model shown in the globe on the left. The orange and red contours are as in the globe on the left.

**Figure 2.** (a) Raypath geometry at 70° epicentral distance for *ScS*, pre-cursor (*SdS*) and post-cursor (*ScscS*) is predicted for a 15 km thick ULVZ with 30% *VS* reduction model relative to PREM (Dziewonski and Anderson, 1981). (b) Synthetic seismograms at 70° are calculated for ULVZs with different thicknesses using reflectivity method. Thick gray lines highlight the time variation of *SdS* and *ScscS* relative to ULVZ thickness. (c) Absolute differential travel times of *SdS* and *ScscS* relative to *ScS*, denoted as |T*ScS-SdS*| and |T*ScscS-ScS*| respectively, are calculated for ULVZ thicknesses up to 100 km, which illustrates the symmetry between pre-cursor and post-cursor relative to *ScS*. Gray error bar stands for the time difference of *SdS* between 70° and 85° to illustrate the pre-cursor time variation with respect to distance for different models.

**Figure 3.** Examples of the flip-reverse-stack (FRS) technique. (a) Application of FRS to a synthetic seismogram from a 20 km ULVZ model (epicenter distance = XX deg, source depth = XXX km) produces a FRS trace with a simple positive peak (denoted as phase SU) that is twice the amplitude of individual pre- or post-cursor. The seismogram is cut at the *ScS* peak into a front part (black dashed line) and a back part (solid black line).The front part is flipped in polarity and reversed in time, then added to the back part, which yields the FRS trace (thick black line) with *ScS* stripped out.The remaining constructive sum of the *SdS* and *ScscS* ULVZ arrivals is denoted *SU*. (b) Similar to (a), with the FRS method applied to a data record from an event on 19 July 2008, recorded by EarthScope station Z16A. This record results in an FRS trace with SU peak relatively close to time zero, suggesting a thin ULVZ layer. (c) and (d) show some data examples of FRS traces with and without SU peaks, respectively. The traces in (c) and (d) are scaled according to the plotted size of the *ScS* amplitude in panel (a). [[ISSUE: the ScS peaks in panel a and panel b of Figure 3 are different sizes. They should be the same, and thus the FRS traces accordingly scaled. This is important (read fig caption) because I state the panels c and d are scaled according to the ScS in panels “a and b”. please fix according to what is correct (since I don’t really know how c and d are scaled. Note: I shaded the SU pulses in (c) to be like that in a and b. here, I assumed a zero line. please look at the original FRS pulses to make sure I didn’t do horribly bad!]]

**Figure 4.** Tests of FRS residual peak time and amplitude variations with respect to ULVZ *VS*, , thickness, and *VP*. (a) ULVZ *VS* model tests. We applied FRS technique to synthetic seismograms from ULVZ models with varying *VS*, but fixing , *VP*, and thickness at 10%, -10% and 15 km, respectively. We measured the peak time and amplitude of FRS residuals for synthetics at 70° in epicentral distance (source depth = XXX km). The left and middle panels show the variation of FRS peak time and amplitude with respect to *VS*, respectively. The right panel shows the FRS residuals corresponding to PREM model and ULVZ models with different *VS*. (b) FRS tests for ULVZ  models where *VS,* thickness, and *VP* were fixed at -30%, 15 km and -10% respectively.(c) FRS tests for models with different ULVZ thicknesses, but fixing *VS,*  and *VP* at -30%, 10%, and -10%, respectively. (d) FRS tests for ULVZ *VP* models with *VS,* thickness, and  fixed at -30%, 15 km, and 10%, respectively.

**Figure 5.** The trade-off relationship between ULVZ *VS* and ULVZ thickness for the arrival time of precursor *SdS* relative to *ScS* at 70° is shown (contours) for ULVZ models with different *VS* and thickness (source depth in the synthetics was XXX km). Contours are plotted in black lines with *SdS* relative time labeled.

**Figure 6.** (a) Geometry of the phases *S* and *ScS* are shown in cross-section. (b) Raypaths (blue) predicted by the PREM model connecting events (red stars) and stations (black triangles) are shown. Small red dots in the middle of the raypaths show *ScS* reflection locations on the CMB. Thick light-green lines denote the plate boundaries. Small box around the events depicts region enlarged in panel (c), which shows the lower hemisphere *P* and *SH* radiations patterns predicted from the CMT source information provided by Ekstrom (2XXX) (colored “beach balls”). For each event (red star), the P radiation pattern is shown with two SH radiation patterns: one with the predicted *S* wave piercing points (lower left), and one with the *ScS* piercing points (lower right) – piercing locations shown as black dots, and show that all events have *S* and *ScS* away from nodal lines. The thick light-green line is the plate boundary. Events are listed in Table 1.

**Figure 7.** (a) Empirical source stacks (black solid lines) of velocity seismograms for *S* and *ScS* are plotted for the August 26, 2007 event. Gray shading represents one standard deviation associated with the stack time points. Numbers on the right denote number of records used to construct empirical sources. (b) *S* empirical source (dashed line) is stretched by 112% to fit the *ScS* empirical source (solid black line). (c) Empirical source shape (black solid line) of deconvolved seismograms for *S* and *ScS* are plotted with respect to time. Gray shading and numbers to the right are as in (a). See text for more detail.

**Figure 8.** (a) 1.5 degree radius geographical bins (black circles), bin centers (blue crosses), and *ScS* CMB reflection locations (red dots) are plotted; only bins with > 10 records are shown. (b) Bootstrap stacks (black traces) with 95% confidence levels (orange bounding traces) are plotted for all bins. Bin locations are blue crosses, and numbers correspond to bin number. (c) Positive energy (dark red) below the 95% confidence level and negative energy (blue) above the 95% level are plotted for each bin location (blue crosses). (d) Bins with similar bootstrap stacks are grouped into 7 clusters. Colors of bin circles correspond to individual clusters. Blue crosses denote bin cluster centers.. Bootstraped stacks (black traces) and 95% confidence levels (orange traces) are also plotted.

**Figure 9.** *(left column)*Cluster FRS bin-stacks (thick black lines) plus bootstrap resampling stack bounds (gray shaded area denotes the 95% confidence level) are plotted with the best-fitting model FRS (dashed blue lines), along with FRS predictions from any model with weighted cross-correlation correlations within 90% of that of the best fitting model (dotted orange lines). Numbers in the upper left corner correspond to cluster numbers. (*right column*) Velocity models of PREM (black line), best fitting model (dashed blue line), and the good fitting models shown in the left panels (orange dotted lines) are plotted with respect to the height above the CMB for the seven clusters.

**Figure 10.** (a)ULVZ thickness distribution map of this study. The black triangle denotes the location of the main island of Hawaii. Thick red dashed line is a contour line of -0.8% *VS* (as in Fig. 1, Ritsema 2XXX) . Colors of circles stand for thickness of ULVZs (see text for more detail). (b) For the region of bin cluster 1 (see Fig. 8d), our best fitting velocity model (dashed blue line) is plotted along with models from previous studies sampling the same region. Numbers correspond to the studies as in Fig. 1: 1. *Mori and Helmberger* (1995); *Kohler et al.* (1997); 3. *Avants et al.* (2006a); *Lay et al.* (2006); 4. *Hutko et al.,* (2009).

**Figure 11.**  ***(For Mingming and Allen to add the description here)***

**Figure S1.** (a)*S* and *ScS* stacks (black lines) of displacement seismograms are plotted for the August 26, 2007 event, with arrows indicating the artifact introduced by bandpass filtering (namely, the negative polarity ramp leading up to the arrival). Tan shading represents one standard deviation associated with each stack. (b) Tests of instrument deconvolution effects. An example of the non-instrument deconvolved velocity trace is plotted in black, aligned on the *S* wave arrival time predicted by PREM. Arrival time of the PREM predicted *ScS* time is plotted in the black line. Instrument deconvolution to displacement and velocity tests are conducted using the transfer command in SAC. Line colors correspond to different low-pass shoulder frequencies, assuming the same low-pass cut-off frequency, high-pass shoulder frequency, and high-pass cut-off frequency at 0.001, 1e+5, and 1e+6 HZ, respectively.

**Figure S2.** (a) Examples of water-level deconvolution for different Gaussian function widths used in the method are shown for an example event and station, specified by the full width at half maximum (FWHM) parameter.For this example (Event MONTH DAY, YEAR, station XXX), the water-level parameter is WL=0.01. The optimal deconvolution occurs for FWHM=3.0 sec. We deconvolve the *S* source shape (black dashed line) that was stretched to match the *ScS* empirical source from the original trace (blue solid lines). The resultant deconvolved traces (black solid lines) are shown. The original trace (blue records) is plotted with each deconvolution for comparison. (b) Water-level deconvolution for the event on November 8, 2008, where the optimal water-level deconvolution occurs for FWHM=4.5 sec.

**Figure S3.** (a) Travel times of *SdS* and *ScscS* relative to *ScS* are calculated for LVZ models with thicknesses up to 100 km and *VS*=-3%, *VP*=-1%. Gray error bar stands for the time difference of *SdS* between 70° and 85° to illustrate the pre-cursor time variation with respect to distance for different models. (b) Travel times of *SdS* and *ScscS* relative to *ScS* for HVZ models with varying thickness and *VS*=3%, *VP*=1%. Symbols and error bars are as in (a). (c) Distance dependence of the FRS amplitude ratio relative to *ScS* is plotted for a model with 15 km thick ULVZ with parameters: *VS*=-30%, *VP*=-10%, and *=+*