

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

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## Summary

Thin patches of ultra low velocity zones (ULVZs) have been proposed to exist at the core-mantle boundary (CMB). Their detection and mapping are difficult in part by the limitation of source-receiver geometries of ULVZ modeling seismic phases. Here we developed a new approach with an *ScS* stacking algorithm 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. Bins possessing similar *ScS* precursor-plus-postcursor behavior in stacks 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 stacked ULVZ arrivals are sensitive to ULVZ thickness and internal velocities. We processed 13,850 1D 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. Strong lateral variations

are apparent in ULVZ thickness and internal properties across the large low shear velocity province (LLSVP) margin in our study area: ULVZs are thicker and stronger within the LLSVP than outside of it, consistent with that predicted by numerical convection algorithms with chemically distinct LLSVP structures. Inside hypothesized LLSVP edges, ULVZs appear to distribute unevenly, suggesting 3D variations of convection currents.

**Keywords:** ultra low velocity zone, core-mantle boundary, large low shear velocity province, 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 observed to have up to 10%  $V_P$  reduction and 30%  $V_S$  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). Although less than half of the CMB area has been probed, ULVZs are observed to be isolated patches and preferentially located in lower than average velocity regions (Figure 1a). Many ULVZs appear to be in close vicinity to LLSVP margins (Figure 1a).

[[Add this study to you Figure 1. Also, do a quick web of Science (or google scholar?) search for ULVZ to make sure there are not any other studies. [http://seismo.berkeley.edu/wiki\\_br/An\\_unusually\\_large\\_ULVZ\\_at\\_the\\_base\\_of\\_the\\_mantle\\_near\\_Hawaii](http://seismo.berkeley.edu/wiki_br/An_unusually_large_ULVZ_at_the_base_of_the_mantle_near_Hawaii)]]

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 needed 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). Isolate core structures may also exist. Rost and Revenaugh (2001) suggested a zone with non-zero  $V_S$  underneath CMB topographic high, possibly filled by light core materials. Trade-offs have thus been considered in the seismic imaging of mantle versus core-side layering (as well as models involving some kind of core-mantle transition (or “fuzzy”) (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 of most Phanerozoic kimberlites (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 LLSVP margins as whole mantle plumes 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., McNamara et al., 2010), consistent with seismic observations. If ULVZs are composed of partially molten dense material, dense melt might be suspended due to stirring within ULVZ

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**批注 [1]:** There may be other references to add here. This brings me to a question: do u want to add mingming (and allen?) as co-authors? If yes, then we can have mingming bolster all the geodynamics references, and perhaps a nice fig at the end: he has some new 3D calcs that are amazing. Let me know.

driven by viscous coupling to convective currents in the overlying mantle, which would result in a positive gradient with depth in  $V_s$  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*, *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, 2013), 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

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批注 [2]: NOTE: I deleted that text because some of it was redundant, but more importantly, it brings up things (yes, important ones I agree with) that we don't solve with our results. so i want to minimize unkept promises. that language is fine for a thesis, but we might aggravate reviewers by putting it in a pub.

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. Our study region is shown in Figure 1b.

## 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 top (i.e, an internal reflection from the underside of the ULVZ top). 1D reflectivity synthetic seismograms (Fuchs and Müller, 1971; Müller, 1985), computed for an epicentral distance of  $70^\circ$  are shown for ULVZ models possessing  $\delta V_P$  and  $\delta V_S$  velocity reductions of -10% and -30%, 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 models with thin ULVZ layers (Figure 2c). This similarity of pre- and post-cursor arrival time relative to *ScS* is valid for flat ULVZ structures up to  $\sim 100$  km thick. 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

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批注 [3]: I recommend removing the Vs panel on the right. It lacks a Y axis and the fig cap can say the Fig 2B synths are for  $\delta V_P: \delta V_S = -10\%: -30\%$  anyway. I would also remove the "d=15 km" and replace with simply "d". Then, stretch that Fig 2a to be the width of Fig 2B

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批注 [4]: In the figure 2c, change the text that defines the symbols to:  
 $|T_{ScS-SdS}|$  and  $|T_{ScscS-ScS}|$  and define those terms in the figure caption.

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 with 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  $15^\circ$  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  $15^\circ$ .

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). We define a symmetry axis in time from the peak of  $ScS$  and cut the trace there. We flip the polarity and reverse the time of the first half of the trace leading up to the  $ScS$  peak, and add it to the second half of the original trace. 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  $\sim 3$  sec following the former  $ScS$  peak location. **with clear evidence for a ULVZ pulse (Figure 3b).** **[[the previous highlighted text is slated for removal (go ahead and delete it). At present, we show the data has a bump. We do not show it is due to a ULVZ. Tell me: how hard would it be to have a panel C and D for figure 3? The figure layout**

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**批注 [5]:** In Figure 3:

[1] it is hard to see the dashed lines on top of the gray vertical  $ScS$  line. solution: make the dashed lines black.

[2] the word “residual” usually implies something that is left over after a subtraction. Instead, how about “FRS trace”? I am using that in the text.

[3] titles. For (a), add “(PREM)” in the title. For (b) add “(July 19, 2008  $\Delta=80.5^\circ$ )” and in the figure caption, give the station info and the event region (Fiji...) and delete the event info from the figure.

[4] increase font size of time axis numbers & label, and phase labels, and change axis label to “Time relative to  $ScS$  (sec)”

[5] I recommend we name the bump something special instead of the “FRS residual”. And “FRS trace” really refers to the whole record. I will name it:  $S^U$

[6] in the figure, name the phase  $S^U$  (just like other phases are named)



would be a 2x2. Perhaps A, B in row 1. The C panel can be a bunch of FRS traces with the bumps, maybe 8-10 traces, even a mini record section (alternatively, it could be a catalog plot w/ traces equally spaced). The D panel could be exactly as C, but with traces lacking the extra bump. THEN we are set up to say we will now explore the geographical distribution and modeling of these bumps]] We denote this combination of ULVZ pre- and post-cursor as  $S^U$ , to indicate it as a ULVZ-born phase.

To test the sensitivity of  $S^U$  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 ( $\delta V_S$ ),  $P$ -wave velocity reduction ( $\delta V_P$ ), density increase ( $\rho$ ), and ULVZ thickness ( $d$ ). Figure 4 shows the dependency of time delays of the peak of  $S^U$  relative to the peak of  $ScS$  as well as  $S^U$  amplitude variations relative to  $ScS$  for different model parameters. Figure 4a varies  $\delta V_S$  while other ULVZ parameters are fixed (thickness  $d=15$  km,  $\delta\rho=10\%$ , and  $\delta V_P=-10\%$ ). The peak time of  $S^U$  increases gradually from about 2 sec to 4 sec, as  $\delta V_S$  decreases from -2% to -30% (left panel in Figure 4a). Amplitude ratios of  $S^U$  and  $ScS$ , however, show a dramatic increase from 0.2 to 0.5 as  $\delta V_S$  decreases from -2% to -10%, after which, the ratio remains at around 0.6 while  $\delta V_S$  decreases from -10% to -30% (middle panel of Figure 4a). The third column in Figure 4a shows synthetic  $S^U$  traces at  $70^\circ$  for different  $\delta V_S$ . The amplitude of  $S^U$  (and hence the  $S^U/ScS$  amplitude ratio) increases with increasing density ( $\rho$ ) while the  $S^U$  time is unaffected (Figure 4b).

We also test the dependency of  $S^U$  on ULVZ thicknesses variations (Figure 4c). The peak time of  $S^U$  increases sharply from 0 to 10 sec as the ULVZ thickness increases from 2 to 30 km. The  $S^U/ScS$  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  $S^U$  peak time and amplitude do not depend on ULVZ  $V_P$  structure (Figure 4d).

From the synthetic tests, we see that the  $S^U$  peak time is most sensitive to ULVZ thickness and shear velocity reduction; and these two parameters represent a common trade-off encountered in seismology. However, for smaller ULVZ thicknesses (e.g.,  $< 20$  km), the  $ScS-SdS$  differential time shows more sensitive to the ULVZ thickness (Figure 5). 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 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 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 (Figure S1c), allowing omission of the low-pass filter and hence and affects from it. 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 bottommost 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. It is obvious that for every event,  $S$  and  $ScS$  are in the same radiation quadrant without crossing the nodal plane, thus we do not expect differential polarity effects on  $S$  and  $ScS$ .

### 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 interest is windowed, then aligned by cross-correlation, and then summed iteratively to produce an estimate of the source wave shape. The  $S$  and  $sS$  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  $ScS$  on velocity seismograms have an upswing followed by a downswing (Figure 7a). The standard deviation about the mean shape of  $ScS$  is much greater than  $S$ , reflecting the fact that  $S$  is larger in amplitude than  $ScS$ , as well as  $S$  not having any significant energy predicted to arrive right before it in time.  $ScS$ , however, can have energy precede it from D'' phenomena, including ULVZ structure.

We seek a deconvolution approach 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. To mitigate this possible effect, we pursue deconvolving the  $S$  stack from  $ScS$  seismograms. However, while very similar in shape to  $ScS$  (and containing the same source effects),  $S$  is not exactly the same width as  $ScS$ . A slightly broader  $ScS$  may be due to attenuation from the hot thermal boundary layer at the base of the mantle. In some cases,  $ScS$  is narrower than  $S$ . We pursue the approach of adjusting  $S$  to look more

light 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. This procedure circumvents removing any ULVZ signal that may be hidden in  $ScS$  source shape. The best-fitting time-stretched (or -squeezed)  $S$  source shape is then deconvolved from  $ScS$  phases, and the unstretched  $S$  is deconvolved from  $S$  phases, 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 simple Gaussian-like pulses (Figure 7c).

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 have 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 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.

Edward Gamero 4/15/14 16:32

**批注 [6]:** If it is not a total pain in the butt, it might be good to show for all our events the thing that is Fig 7b. It could be supplementary, or we can just add it to this figure. I think the example shown is a bit confusing since the agreement worsens in the first upswing and doesn't get good enough in the downswing. I try to diffuse this in the text, i.e., to reduce it raising reviewer concern...

### 3.3 Geographic Bin Stacking

[[ I rearranged this paragraph to put the FRS stuff before the introduction of stacking within each bin. Otherwise, it reads as if we make ScS stacks, then we make FRS stacks, but never use the ScS bin stacks. If I'm understanding what you did: you don't make ScS bin stacks. You make stacks of the "FRS residual traces". So I rewrote it that way. Ok?]]

We organize the ScS CMB reflection locations into overlapping bins with 1.5° radius (thus, bin radius is roughly 100 km at the CMB). Bin locations are adjusted automatically to maximize the number of records in each bin (Figure 8a). Bin stacks are computed if the number of records is greater than X, which resulted in Y bin stacks being omitted from the grid. The FRS technique is applied to all source-deconvolved ScS records, and the resulting FRS traces are stacked in each bin. We stacked FRS traces using both a phase-weighted scheme (e.g., Schimmel and Paulssen, 1997) (power=2) and a linear stacking approach. The phase-weighted method was less stable, so the phase-weighted stacks are only used to compare with linear stacks to ensure a reasonable concordance. For the linear stacking process, each trace is automatically aligned to the stack trace using cross-correlation and weighted by its signal-to-noise ratio (SNR), cross-correlation coefficient (CCC) and a Gaussian weight, the latter being a Gaussian function of distance between ScS bounce location and the bin center. Records with low SNR and CCC are discarded. A bootstrap resampling (n = 200) of seismograms within each bin is also performed to evaluate uncertainties associated with each

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批注 [7]: I question this step. Shouldn't we adjust bins to put the bin center at the "center of mass" of all the bouncepoints in that bin? Otherwise, don't we chance the following problem?: imagine a LOT of bouncepoints are at the edge of a bin. Then that bin adjusts to include them. But if they are at the edge of the bin, then that particular bin stack will be bias by structure hardly within it. Maybe I'm not understanding this step. Please explain.

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批注 [8]: I added this statement because from your bin numbering scheme, many bins are missing, thus you must have discarded some. Is it because of this criterion? Like the missing bin 29: there are data there, but no bin. We must say why. Or are the data below some SNR/CCC level? Must say why.

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批注 [9]: Why is the PW method bad? Was it the N=2 (power)? If we do not use it, then we should just remove all this text. Or, you can make some supplementary online figure that compares the two methods for different bins. You might consider a suppl online fig that shows all bin stacks (like Nicks SOM fig for all SS stacks in his 2007 science paper).

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批注 [10]: But how do you do the first one? there is no stack yet for that bin. please explain. i don't see any justification in moving the FRS traces in time for the bin stacking. The alignment should be inherited only from aligning ScS traces (within that bin). maybe this is why you would make an ScS stack: to get the relative time shifts for the FRS stacking. if i'm missing something lets have a phone call.

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批注 [11]: Define how you do this.

Edward Garnero 4/15/14 16:32

批注 [12]: Define limits/levels for discard.

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 energy, resulting in grouping bins into 7 distinct clusters; these are stacked again using the same bootstrap-stacking algorithm (Figure 8d). The larger number of records in each bin significantly reduce the variability in the bootstrap resampling, and stacks are more robust. This grouping scheme permits the exploration of geographical systematics of different ULVZ structures responsible for the FRS 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 ULVZ structures in these locations. The lateral scale of the individual cluster regions is roughly between 200-350 km. Being that the *ScS* Fresnel Zone for ~10 sec period waves is much less than this, e.g., < 100 km, as a first approximation we can pursue one dimensional (1-D) ULVZ models to reproduce

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批注 [13]: Clarify: are all the records from all the contributing bins in a given cluster stacked? Or are you just stacking the bin stacks? I think the former is better. Also, see the figure.

the dominant character of the individual FRS bin cluster stacks. The motivation is to investigate first-order differences in ULVZ structures 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)  $-30\% \delta V_S$ ,  $-10\% \delta V_P$ ,  $+10\% \delta \rho$ ; (2)  $-45\% \delta V_S$ ,  $-15\% \delta V_P$ ,  $+10\% \delta \rho$ ; (3)  $-15\% \delta V_S$ ,  $-5\% \delta V_P$ ,  $+5\% \delta \rho$ ; and (4)  $-10\% \delta V_S$ ,  $-10\% \delta V_P$ ,  $+10\% \delta \rho$ . Linear gradients of velocities with respect to depth are also explored for the four ULVZ structural categories, since it affects the amplitude of reflections. The velocity structure assumed for the HVZ is  $-3\% \delta V_S$ ,  $-1\% \delta V_P$ , and  $+1\% \delta \rho$ . Three different LVZ velocity properties are assumed: (1)  $-3\% \delta V_S$ ,  $-1\% \delta V_P$ ,  $0\% \delta \rho$ ; (2)  $-5\% \delta V_S$ ,  $-2\% \delta V_P$ ,  $+1\% \delta \rho$ ; and (3)  $-7\% \delta V_S$ ,  $-3\% \delta V_P$ ,  $+1\% \delta \rho$ . The majority of all the models have thickness increments of 2 km, resulting in our testing ULVZ, LVZ, and HVZ layer thicknesses of X, Y, Z, respectively. For all models, synthetic seismograms are calculated for every  $1^\circ$  in epicentral distance.

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**批注 [14]: Making a note:** be sure the Discussion section considers or mentions that we are aware that we are perhaps making unrealistic materials. Properties (1) and (2) have same density but different velocities, thus the elastic properties (e.g. poisson's ratio) are differing, but we do not propose materials....

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**批注 [15]:** H=high... aren't the velocity values positive, hence + instead of -? Also, I would intro the LVZ properties after ULVZ, then HVZ.



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 the possible amplitude difference introduced by the weighting scheme used with the actual data.

### 4.3 Cross-Correlation Scheme

After creating bin-cluster stacks using the synthetics from all models, 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 waveform in the bin-cluster stacks potentially contain essential information of ULVZ thickness, layering, and internal properties, 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 weight the cross-correlation coefficient by the relative waveform difference of area under

the curve and the relative peak/trough amplitude difference between the synthetic waveform and data. Using the two additional weights helps to properly account for small amplitude structures (e.g., bin clusters 6 and 7).

The resultant best-matching velocity models for all the clusters are displayed in Figure 9. For clusters 1, and 2, models with 20 km thick ULVZ are found to match the main positive polarity peak in timing and amplitude. While the clusters 1 and 2 were uniquely formed, they are not markedly different in their shape, and accordingly the solution models are 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., X km or higher. 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).

Synthetic bin-clusters for best-fit models for clusters 3 and 4 (to the east) match the observed bin-clusters fairly well, with a ULVZ layer 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 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

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**批注 [16]:** Explain this: is it a scheme of OBS-PRED, the compute area under curve of residual? Then how does this manifest as a weight?

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**批注 [17]:** Explain this too: is the a different between max amplitude peak and max amplitude trough, within some time window? Or entire time window? Just like SAC's MarkPTP? Then, how is this used as a weight. At present, a reader cannot reproduce your work, not enough detail.

models are more variable, with some having and some lacking an LVZ layer overlying the HVZ. The character of bin-cluster 6 is 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 2<sup>nd</sup> 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, which is situated near a presumed edge of the Pacific LLSVP (Figure 10). Since the trade-off between velocity reduction and thickness of ULVZ exists, for cluster 5, we plot the ULVZ thickness for a 30%  $V_S$  reduction instead of 45%, the best fitting model. The thicker ULVZs of bin clusters 1 and 2 map inside of the LLSVP (to the south of the Edge line in Figure 10), where temperature is expected to be higher than outside of it (McNamara et al., 2010; Li et al., 2014). Thin (10 km) or below our threshold (5 km or less) ULVZs map outside the LLSVP. Even inside of the hypothesized edge, spatial variations of ULVZ thicknesses are strong. The distance between the center of clusters 2 and 4 is  $\sim 350$  km on the CMB, over which our best-fit model ULVZ thicknesses change from 20 km to 14 km. In fact, the ULVZ thickness change may certainly be more

acute if comparing individual bin 14 and bin 15 (Figure 8b), between which the distance is less than 100 km, comparable with the lateral variations in thickness inferred from past studies (e.g., REFERENCES, Rost et al., 2005).

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批注 [18]: Try to have non-garnero researchers if possible. But u can add the mike thorne work, etc.

**[[Somewhere in the above paragraphs we need to compare our ScS-derived models with results from studies shown in Figure 1. Perhaps one way is to grab any model presented in Figure 1 from past studies, and overlay it in our Figure 9 models, for the cluster where the past study occurred, IF they overlap w/ our bins]]**

## 5 Discussion and Implications

### 5.1 Uncertainties

In this paper, we developed a new method to strip out the main ScS phase and enhance subtle ULVZ-generated reflected energy in FRS traces. These were then geographically clustered, stacked, and assigned best-fitting regional 1-D ULVZ models. One of our primary objectives was to test this technique for identifying lateral variations in ULVZ structure. This method is a nice addition to the collection of ULVZ detection methods, since ScS is a well recorded seismic wave, and easily observable for most deep earthquakes with  $M > 6$ . However, uncertainties with this method are still present, and discussed in this section.

One source of uncertainty comes from the deconvolution process. Since every seismogram may possess a unique frequency content and noise level, the deconvolution process may erroneously 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 brought by these deconvolution effects by weighting each seismogram by a signal-to-noise ratio measured after deconvolution.

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. If significant ULVZ thickness changes or tilted ULVZ surface are present within any bin cluster, the ULVZ pre-cursor and post-cursor arrivals (e.g., Figure 2) would fail to be symmetric about ScS, resulting in a broadened or even multi-peak FRS (with weaker amplitudes) than that of a flat and uniform ULVZ layer. The resultant best-fitting model would thus have a weaker and thinner ULVZ, leading to an underestimation of ULVZ properties. This might be evident in cluster 3 (see location in Figure 8d and cluster modeling in Figures 9 and 10), where a broader but weaker FRS stack might be due to a tilted or variable ULVZ topography: bin cluster 3 is between bin clusters 1 and 2 (modeled to be 20 km thick) and bin clusters 4 and 5 (modeled to be 14 km thick). Furthermore, clusters 3, 4, 5 and 6 have very complex 3-layer velocity structures for the lowermost 100 km, where best-fit models contain a ULVZ overlain by a HVZ and LVZ (Figure 9). These complex velocity structures might be caused any number of possibilities, which include complexities associated with local or layered chemical heterogeneities (SCATTERING REFERENCES e.g., recent frost & rost et al,

some Earle and Rost ref, older wen and helmberger and vidale and hedlin scatterer paper), and discontinuities associated with the post-perovskite phase transition (REFERENCES). Alternatively, it is possible that fine-scale heterogeneity along the *ScS* raypath can mimic a complex 1D structure, but this possibility requires the structure to similarly affect *ScS* from different sources that sample some CMB region. An argument can be made for this being unlikely due to the multiple sources and rays sampling one spot; however, if present, it may affect many analyses for this region. Another possibility 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. These 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).

Although the first positive peak in bin clusters 1 and 2 associated with ULVZ structure is fitted well by synthetic models, the strong down-swing immediately following 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 increase and thickness of 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 within  $\pm 2$  km due to the high sensitivity to thickness of the FRS peak time (Figure 4c). The average noise level relative to  $ScS$  amplitude is about 0.15 across our whole dataset. Hence, we estimate the detection threshold of our technique for ULVZ thickness to be 5 km, below which, the amplitude of FRS 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) 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%  $V_S$  reduction and thickness of X 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.

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 (Garnero et al., 2004; Maupin et al., 2005; Wookey et al., 2005;

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批注 [19]: Clarify: is this for  $ScS=1$  or for  $S=1$  for this citing of .15?

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 should not strongly affect the FRS process.

The relative location between ULVZs and LLSVP edges is relevant for discussion of the nature of ULVZs. The approximate location of edges in long wavelength tomography model (Grand, 2002) is illustrated by the -1% contour line at 2750 km depth in Figure 10. However, the exact location of the LLSVP edge on top of the CMB in this region is poorly constrained. Furthermore, the precise locations of ULVZs are also subjected to variations due to raypath deflections associated with the strong 3D LLSVP structures above ULVZs. This uncertainty could be explored with 3D ray tracing combined with detailed knowledge of mantle velocity structures (e.g., Zhao et al., 1994). If ULVZs all reside inside of the LLSVP edge, the common hypothesis of partial melting of LLSVP material would be plausible to explain the origin of ULVZ (Williams and Garnero, 1996). But if some of the ULVZs are located outside of (and distant from) LLSVPs (as suggested in some studies in Figure 1), other hypotheses should be explored, e.g., 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), 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.

## 5.2 Dynamical Implications

Our study suggests that ULVZs are not uniformly distributed along the LLSVP edge. Thick patches of ULVZs are found in clusters 1 and 2, while relatively thinner ULVZs are found in clusters 4 and 5. In between these patches, cluster 3 shows complicated FRS waveforms that might be caused by multipathing at ULVZ edges (Figure 9), with the possibility of a thinner transitional ULVZ; similarly. Bin cluster 6 shows thinner ULVZ structure. Very weak ULVZ signals are present in cluster bin 7, suggesting thin or no ULVZ there (Figure 8). This non-uniform distribution of ULVZs is consistent with those predicted for dense ULVZ material within chemically distinct thermochemical piles (Li et al., 2014b), which predicts ULVZ intermittency and variable thickness and shape along pile edges (Figure 11).

A non-uniform distribution of ULVZs may result in non-uniform entrainment (spatial and temporal) within thermochemical piles, and similarly, into plumes. 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 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). If the nature of ULVZs is partial melt as suggested by the 3-to-1 reduction of  $\delta V_S$ -to- $\delta V_P$  (Williams and Garnero, 1996; Berryman, 2000), then they should be

present closer to thermochemical pile edges that are the hottest regions as predicted by geodynamic models (McNamara and Zhong, 2005; Tan and Gurnis, 2005). This appears consistent with at least some seismological observations (Figure 1).

### 5.3 Expanded coverage possibilities

$ScS$  is a common and strong phase in earthquake data which 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  $V_S$  structure without dependence on  $V_P$ . Future work should combine this method with those dependent on ULVZ  $V_P$  structure for the same region (e.g.,  $PcP$ ).

## 6 Conclusion

We developed a new ULVZ probe to flip-reverse-stack 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 are grouped into clusters to produce robust stack 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 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 1D synthetic models with various ULVZ thicknesses and properties for each cluster. These best-fitting models depict a map of ULVZ thickness distribution, which indicates strong lateral variations of ULVZ thicknesses and properties proximal the hypothesized LLSVP edges. ULVZs appear to be thicker within the LLSVP than outside of it, consistent with the thermochemical nature of the LLSVP and strong viscous flow along its edges. Inside of the LLSVP edges, a thick (~20km) ULVZ patch is located near the southwest corner of our study region, and a thin (~14) 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 along the LLSVP edges, and also may explain the diverse isotope signature of hotspots.

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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.** (a) Global distribution of ULVZs modified from (McNamara et al., 2010). Black box denotes the region of this study shown in (b). (b) Previous ULVZ detections in our study region are shown in black 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)*. Background is the  $V_S$  tomography model at 2750 km depth (Grand, 2002). Contours for the  $-0.8\% \delta V_S$  are drawn in orange.

**Figure 2.** (a) Raypath geometry at  $70^\circ$  epicentral distance for  $ScS$ , pre-cursor ( $SdS$ ) and post-cursor ( $ScscS$ ) is predicted for a 15 km thick ULVZ with 30%  $V_S$  reduction model. (b) Synthetic seismograms at  $70^\circ$  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) Travel times of  $SdS$  and  $ScscS$  relative to  $ScS$  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  $70^\circ$  and  $85^\circ$  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 produces a FRS residual with a simple positive peak that is twice the amplitude of individual pre- or post-cursor. We divide the seismogram into front (gray dash line) and back

(black solid line) parts using  $ScS$  peak. We then flip the polarity and reverse the time of the front part to add with the back part, which yields the FRS residual (thick black line) with  $ScS$  stripped out. (b) Similar with (a), we apply the FRS to a data record from an event on 19 July 2008, which also gives us a FRS residual with a positive peak but very close to time zero, suggesting a very thin ULVZ layer.

**Figure 4.** Tests of FRS residual peak time and amplitude variations with respect to ULVZ  $\delta V_S$ ,  $\delta\rho$ , thickness, and  $\delta V_P$ . (a) ULVZ  $\delta V_S$  model tests. We applied FRS technique to synthetic seismograms from ULVZ models with varying  $\delta V_S$ , but the same  $\delta\rho$ ,  $\delta V_P$ , and thickness at 10%, -10% and 15 km respectively. We measured the peak time and amplitude of FRS residuals at  $70^\circ$  distance. The left and middle panels show the variation of FRS peak time and amplitude with respect to  $\delta V_S$ , respectively. The right panel shows the FRS residuals corresponding to PREM model and ULVZ models with different  $\delta V_S$ . (b) FRS tests for ULVZ  $\delta\rho$  models with  $\delta V_S$ , thickness, and  $\delta V_P$  fixed at -30%, 15 km and -10% respectively. (c) FRS tests for models with different ULVZ thickness but same  $\delta V_S$ ,  $\delta\rho$ , and  $\delta V_P$  at -30%, 10%, and -10% respectively. (d) FRS tests for ULVZ  $\delta V_P$  models with  $\delta V_S$ , thickness, and  $\delta\rho$  fixed at -30%, 15 km, and 10% respectively.

**Figure 5.** Trade-off relationship between ULVZ  $\delta V_S$  and thickness. We calculate the arrival times of  $SdS$  relative to  $ScS$  at  $70^\circ$  for ULVZ models with different  $\delta V_S$

and thickness. Contours are plotted in black lines with  $SdS$  relative time labeled respectively.

**Figure 6.** (a) Phases used in this study. (b) Raypaths predicted by PREM model connecting events (stars) and stations (black triangles) are plotted in gray. Small diamond shape dots stand for  $ScS$  reflection locations on CMB. Black lines denote the plate boundaries. (c)  $P$  and  $SH$  radiations patterns (color beach balls) are plotted for each event (stars).  $S$  and  $ScS$  piercing locations (black crosses) are plotted on  $SH$  radiation patterns for each event.

**Figure 7.** (a) Empirical source stacks (black solid lines) of velocity seismograms for  $S$  and  $ScS$  are plotted for an event on 26 August 2007. Gray shades are standard deviation associated with stacks. Numbers on the right denote number of records used to construct empirical sources. (b)  $S$  empirical source (dash line) is stretched by 112% to fit the  $ScS$  empirical source (solid black line). The stretched  $S$  (gray solid line) is then used to deconvolve with each trace. (c) Empirical source shape (black solid line) of deconvolved seismograms for  $S$  and  $ScS$  are plotted with respect to time. Gray shades and numbers on the right have the same meaning as in (a).

**Figure 8.** (a) Geographical bins (black circles), bin centers (blue crosses), and  $ScS$  reflection locations on CMB (gray dots) are plotted in our study region. (b) Bootstrap stacks (black trace) with 95% confidence levels (gray trace) are plotted



for all bins with bin number shown beside the bin center (blue crosses). (c) Positive energy below the 95% confidence level and negative energy above the 95% level are also plotted for each bin. (d) Bins with similar bootstrap stacks are grouped into clusters. Colors of bin circles correspond to clusters. The black cross stands for the center of each cluster. Numbers are cluster names. Bootstrap stacks and confidence level are also plotted similarly with (b).

**Figure 9.** Bootstrap stacks (thick black lines) of FRS residuals for all clusters are plotted with respect to time on left column. Thin black lines denote the 95% confidence level. Thick red lines are the best fitting models while thin gray lines are good fitting models with weighted cross-correlation correlations within 90% of that of the best fitting model. Numbers on the upper right corner are cluster names. Velocity models of PREM (black), best fitting model (red), and good fitting models (gray) are plotted with respect to the height above the CMB on the right column for different clusters.

**Figure 10.** ULVZ thickness distribution map of this study. The red triangle stands for the current location of Hawaii Island. Thick black line is a contour line of -1%  $\delta V_S$  of Grand's tomography model at 2750 km deep. Colors of circles stand for thickness of ULVZs.

**Figure S1.** (a)  $S$  and  $ScS$  stacks (black lines) of displacement seismograms are plotted for the same event with arrows pointing out the artifact introduced by bandpass filtering process. Gray shade stands for the standard deviation associated with each stack. (b) Tests of instrument deconvolution effects. An example of the non-instrument deconvolved trace is plotted in black aligned on  $S$  wave arrival time predicted by PREM model. Arrival time of  $ScS$  from PREM prediction is also plotted in dashed black line. Instrument deconvolution to displacement and velocity tests are conducted using transfer command in SAC. Line colors correspond to different low-pass shoulder frequency, 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) **[[PROVIDE STATION, EVENT, Distance info in figure. Also: check that the time axis label is correct]]** For a record at X degrees, examples of water-level deconvolution for different Gaussian function widths used in the method are shown, specified by the full width at half maximum (FWHM) parameter. For this example, the water-level parameter is  $WL=0.01$ . We deconvolve the  $S$  source shape (black dashed line) that was stretched to match the  $ScS$  empirical source from the whole trace (blue solid lines). The resultant deconvolved traces (black solid lines) are shown. The original trace is plotted with each deconvolution for comparison. (b) Water-level deconvolution for a problematic event on 8 November 2008. **This event [[briefly explain why it is problematic. Also, this is the S-wave, right? Why are we showing S? lastly, I**

assume the S empirical source is plotted at its correct time, which is different relative to PREM than this station. If that is not correct, shift the emp src to line up. If I'm correct, fig cap should state that.]].

**Figure S3.** (a) Travel times of  $SdS$  and  $ScscS$  relative to  $ScS$  are calculated for LVZ models with thicknesses up to 100 km and  $\delta V_S = -3\%$ ,  $\delta V_P = -1\%$ . Gray error bar stands for the time difference of  $SdS$  between  $70^\circ$  and  $85^\circ$  to illustrate the precursor 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  $\delta V_S = 3\%$ ,  $\delta V_P = 1\%$ . (c) FRS residual amplitude ratio relative to  $ScS$  is plotted with respect to distance for a model with 15 km thick ULVZ with parameters at:  $\delta V_S = -30\%$ ,  $\delta V_P = -10\%$ , and  $\delta \rho = 10\%$ .