ScP; a probe of ultralow velocity zones at the base of the mantle

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Abstract. The core-reflected phase *ScP* is a sensitive probe of the properties of an ultralow velocity zone (ULVZ) at the base of the mantle. In synthetic experiments, a ULVZ with large depressions in *P* and *S* velocities results in *ScP* having two diagnostic precursors and one later arrival, whose timing depends on ULVZ V_P, V_S, and thickness. Amplitudes of the additional arrivals can be large if ULVZ shear velocity has extreme reductions, such as 30% and greater. Some data examples are presented for southwest Pacific events recorded at short period and broadband arrays in Hawaii, which show evidence for a ULVZ. Resolving all three additional arrivals will help in addressing the strength and ratio of V_S and V_P reductions in ULVZ, and thus the issue of partial melt.

Introduction

Deep mantle structure, including volumetric heterogeneity, sharpness of the core-mantle boundary (CMB), attenuation, scattering properties and wavespeed anisotropy have been studied for several decades with core-reflected energy [e.g., *Kanamori*, 1967; *Chowdury and Frazier*, 1973; *Vidale and Benz*, 1992; *Krüger et al.*, 1995]. Upper mantle effects are typically minimized by comparing the core-reflected phase to direct *S* or *P*. Wide-angle CMB reflections have also proven valuable as a reference for reflections off lowermost mantle interfaces, such as off the top of *D″* [e.g., *Lay and Helmberger*, 1983; *Weber and Davis*, 1990]. Similarly, observations of a precursor to *PcP* is one line of evidence for an ultralow velocity zone (ULVZ) [*Mori and Helmberger*, 1995; *Revenaugh and Meyer*, 1997].

While evidence for ULVZs is abundant, especially in the central Pacific, strong trade-offs exist in ULVZ properties, such as between ULVZ thickness and velocity reduction, as well as the ratio between *S* and *P* velocity depressions within the layer [see *Garnero and Helmberger*, 1998]. The resolution of *S*-to-*P* velocity reduction ratio within a ULVZ is critical to evaluate the possibility of partial melt as the layer's origin [*Williams and Garnero*, 1996; *Revenaugh and Meyer*, 1997; *Vidale and Hedlin*, 1998; *Wen and Helmberger*, 1998] versus an origin due to chemistry alone [*Manga and Jeanloz*, 1996].

One particular phase, *ScP* (Figure 1a), can provide constraints on shear velocity in a ULVZ, which relates to the issue of partial melt in the layer. In this paper, we show how a ULVZ can produce two precursors and a postcursory arrival to
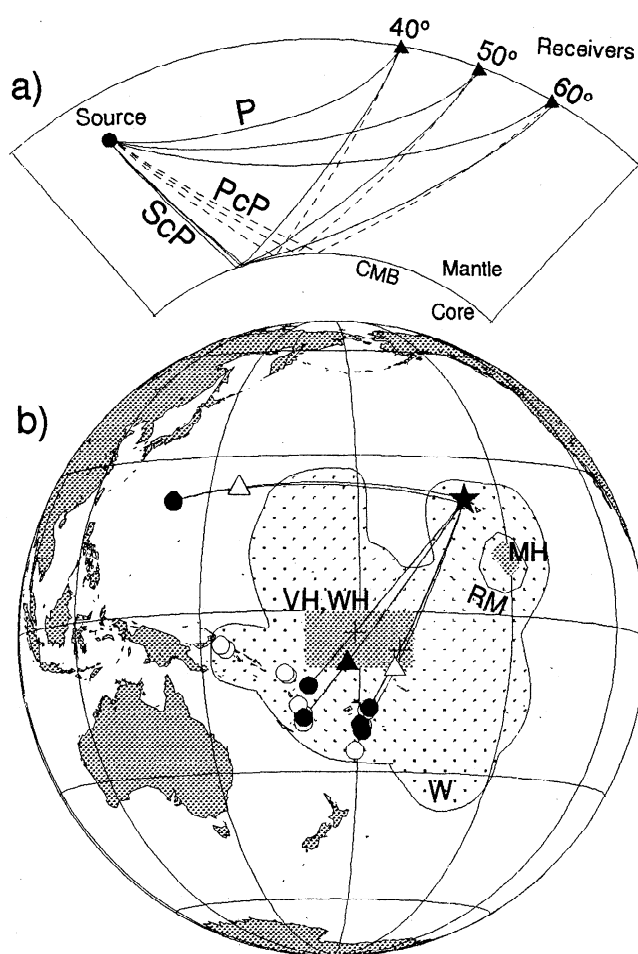
ScP. If detectable, these will provide constraints on the relationship of the *S*-to-*P* velocity reductions in a ULVZ. Preliminary data stacks show evidence for one of the additional arrivals, compatible with a thin ULVZ.

Figure 1. (a) Geometric ray paths of *ScP* (solid) and *PcP* (dashed) for a 500 km deep earthquake source. (b) Ray path geometry of *ScP* data used in this study: Solid circles are earthquakes with usable *ScP* data, open circles are events too noisy in the *ScP* time window to analyze (or no *ScP* observed). Great circle paths are shown for events with clear *ScP*; *ScP* CMB bounce points are denoted for the following behavior: *ScP* precursor apparent (solid triangle), no *ScP* precursor (open triangle), precursor study not unambiguous due to possible noise contamination (cross). Regions of previous study are also denoted: VH=*Vidale and Hedlin* [1998], WH=*Wen and Helmberger* [1998], MH=*Mori and Helmberger* [1995], RM=*Revenaugh and Meyer* [1997], W=*Williams et al.* [1998]. The star corresponds to the location of the Hawaiian Array.
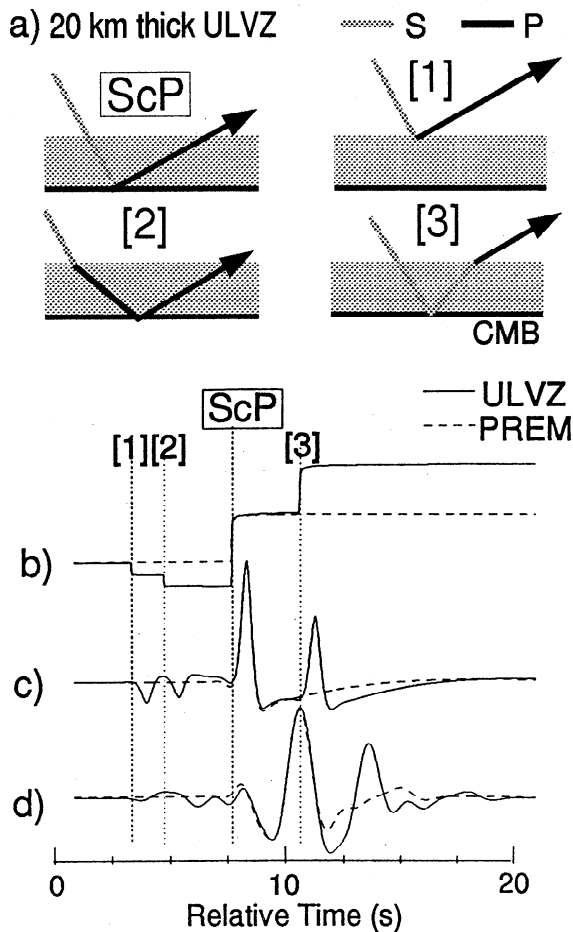
a) 20 km thick ULVZ

Figure 2. ScP arrivals due to a 20 km thick ULVZ with P and S velocity drops of 10% and 30%, respectively. (a) Ray path geometries. (b) Empirical source from a stack of P-waves. (c) Generalized ray method [e.g., see Helmberger, 1983] constructed Green's function at 60° epicentral distance, for the ULVZ (solid) and PREM (dashed). (d) Displacement synthetic for (c). (e) Empirical source of (b) convolved with displacement synthetic of (d). Numbered vertical lines correspond to numbered phases in (a). All traces normalized in time and amplitude to ScP. (See text for details).

ScP and Additional Arrivals

ScP is ideal for studying localized CMB regions (Figure 1); CMB reflection points are localized for a 20 deg span in epicentral distance compared to PcP for the same distance range. Additional ScP arrivals due to a ULVZ are shown in Figures 2a-2e. Figure 2a displays the ray path geometries of ScP and three additional arrivals: [1] an S-to-P reflection off the top of the ULVZ; [2] an S converted to P upon entry of the ULVZ; and [3] an S-wave reflected off the core, then converted to P upon exiting the ULVZ. In the lower box of the figure are: an empirical source (Figure 2b) from a stack of P-waves that do not traverse the lower mantle from a deep Fiji event recorded at the Hawaiian short-period array (50 stations over roughly 100 km x 100 km); the empirical Green's function for PREM and a 20 km thick ULVZ with P and S drops of 10% and 30%, respectively, at 60° epicentral distance (Figure 2c), followed by a displacement synthetic of the Greens' function, low pass filtered at 1 Hz (Figure 2d); and finally a convolution of the empirical source and the displacement synthetic (Figure 2e). Large density increases are not presented in this paper, but

were shown effective at increasing amplitudes of SPdKS arrivals [Garnero and Helmberger, 1998]. The dashed trace in all cases is that for PREM [Dziewonski and Anderson, 1981]. The theoretical displacement trace of Figure 2d clearly shows the two precursors and one postcursory arrival. Once convolved with a realistic P-wave source (Figure 2e), the arrivals are not as distinct, and could be contaminated by noise preceding ScP. For this reason, stacking large numbers of records [e.g., Vidale and Benz, 1992; Revenaugh and Meyer, 1997] is likely to be necessary for confident determination of precursory (or postcursory) energy.

ScP Data and Modeling

Stacks of short-period array data permit inspection of ScP for any possible additional arrivals. Vidale and Benz [1992] demonstrated that ScP has as sharp an onset as direct P for the path from Alaska to California, and concluded that the CMB is locally sharp and flat (thus, no ULVZ). Southwest Pacific earthquakes recorded at a short-period and broadband array of stations in Hawaii (Figures 3a-3d) enable us to sample the area beneath the central Pacific that was previously depicted as having a ULVZ in patches [e.g., Garnero and Helmberger, 1996]. In our analysis of 17 events from that region (Figure 1b), a wide variety of waveform behavior was observed. Two events with stable ScP showed no clear precursory energy (as Figure 3a and 3b, one event showed a clear ScP precursor, 4 events either contained too complex or weak ScP for any reliable analysis, and 11 events showed no evidence for ScP.
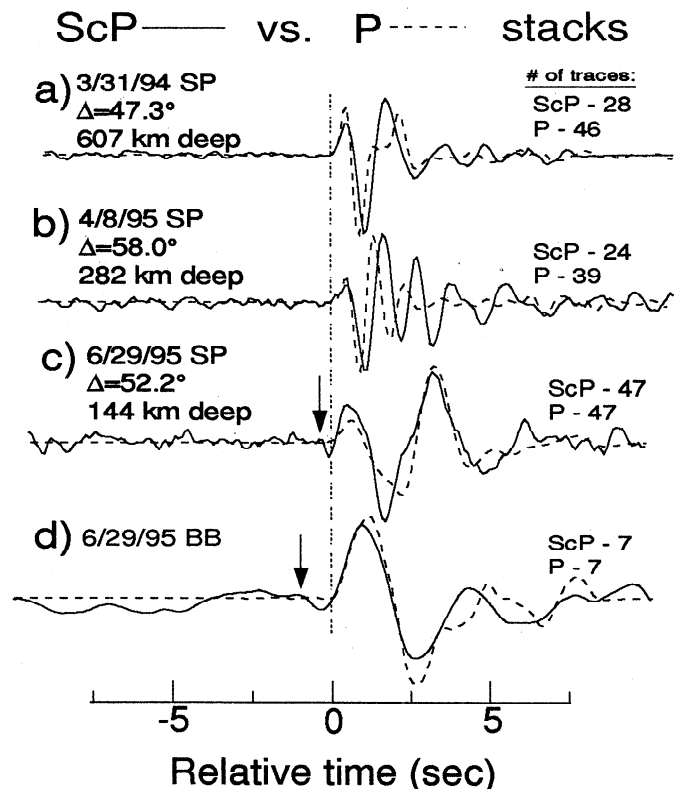

Figure 3. Stacks of ScP (solid traces) and direct P waves (dotted traces) recorded in Hawaii. (a)-(c) Short period stacks, and (d) broadband stacks. Arrows indicate precursory energy before ScP. All traces normalized in time and amplitude to ScP prior to stacking. The number of recordings used in the stacks are indicated in the upper right of each trace.

either due to high noise or low *ScP* amplitudes. Figures 3c and 3d show short-period and broadband *ScP* stacks, respectively, for a New Hebrides event having a small negative polarity precursor. (*ScP* stacks of fewer records than for *P* indicate lower *ScP* amplitudes than *P*, where some noisy *ScP* records were omitted from the stack). *ScP* paths for the 6/29/95 event reflect off the CMB near the zone that *Vidale and Heldin* [1998] noted as having large *PKP* precursors (inferred as due to a basal zone of partial melt). One of our stacks that lacks precursory energy to *ScP* also bounces off the CMB in this region (Figure 3a), and may indicate strong lateral variations.

The broadband stack of Figure 3d is compared to predictions from various ULVZ models in Figure 4. The top set of traces are the data stack (solid) and the PREM prediction (dashed). As the ULVZ thickness is increased from 0 to 10 km, precursory energy becomes more pronounced in the synthetics; also, the 10 km thick ULVZ with the 30% *S* drop has a significant postcursor. For the range of parameters displayed in the figure, the observed precursor is best matched by the 5 km thick ULVZ with 10% and 30% *P* and *S* reductions, respectively. However, given the possible contamination due to noise, this fit is not significantly better than the 10:10,10 model. Choosing more extreme velocity reductions would result in a thinner ULVZ layer [see *Garnero et al.*, 1998].

As shown in Figure 2, two precursors result from models having strong *S* reductions. Our data set does not clearly define the absence or presence of two *ScP* precursors, most likely due
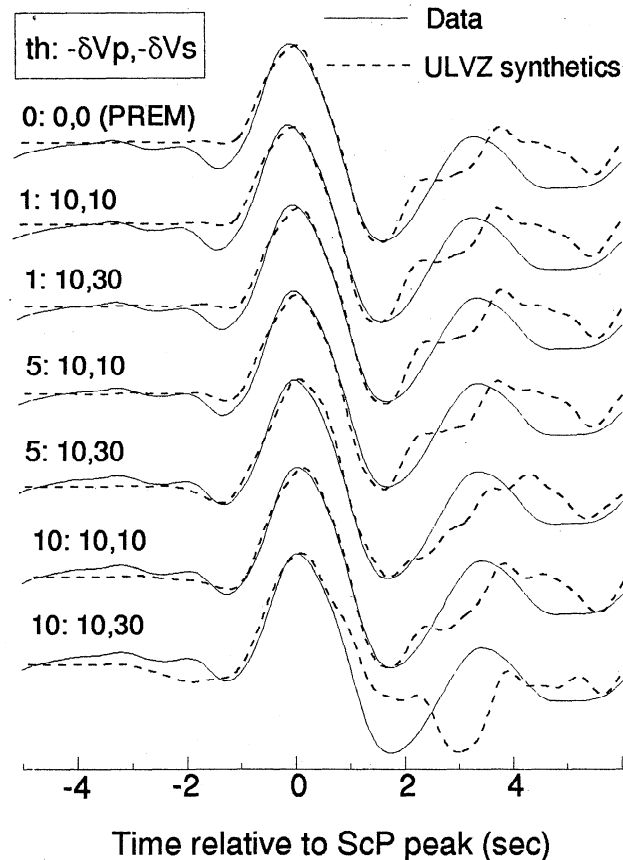
Figure 4. Generalized ray synthetics (dotted) compared to the data trace of Figure 3d (solid). Numbers in upper left are ULVZ thickness (th), *P* velocity drop (δV_P), and *S* velocity drop (δV_S). The observed *P*-wave stack (Figure 3d) was used as an empirical source, and convolved with ScP Green's functions. All traces normalized in time and amplitude to *ScP*.
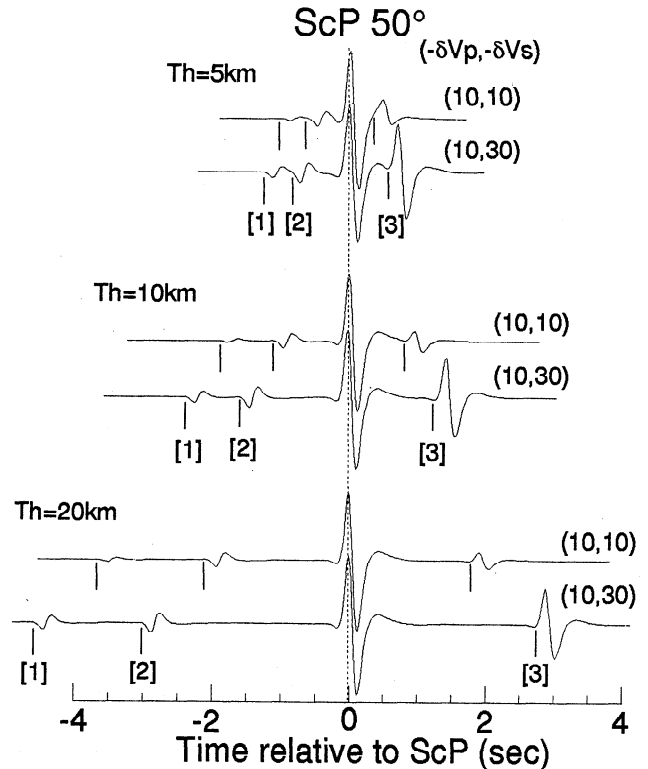
Figure 5. *ScP* and additional arrivals (numbered according to Figure 1) at 50 degrees distance, for different ULVZ thicknesses and velocities. The velocity traces are for a point source, and low pass filtered below 3 Hz. All traces normalized in time and amplitude to *ScP*.

to limitations in our data quality (and possibly data bandwidth). Stacking data from strong, simple, and impulsive sources with appropriate SV radiation should help shed light on this important point, and similarly, with detecting the postcursor. Nonetheless, important rules of thumb can be gained from the predictions. Figure 5 shows synthetics for a ULVZ with thickness of 5, 10, and 20 km, with 1-to-1 and 3-to-1 δV_S-to-δV_P reductions (all with δV_P of -10%). The onsets of the two precursors and the single postcursor are noted, using the same numbering notation as in Figure 2a. Some important characteristics are as follows: (a) the amplitude of arrivals [1] and [3] are strongly dependent on the *S* drop in the ULVZ; (b) the separation between arrivals [1] and [2] depends solely on ULVZ V_P and thickness; and (c) the separation of *ScP* and arrival [2], as well as the separation between *ScP* and arrival [3], depends on ULVZ V_P, V_S, and thickness. Therefore, high-quality stacks of *ScP* may help to provide kinematic constraints on the ratio of *S*-to-*P* wave speeds in the ULVZ, which relates strongly to the phenomena of partial melt in the layer [*Williams and Garnero*, 1996; *Holland and Ahrens*, 1997].

Discussion and Conclusion

We have demonstrated the potential utility of *ScP* in directly assessing the issue of partial melt in the ULVZ. At present, only indirect evidence has been put forth [e.g., *Revenaugh and Meyer*, 1997; *Vidale and Hedlin*, 1998; *Wen and Helmberger*, 1998]. Important uncertainties remain, such as (a) the trade-off between ULVZ velocity and thickness; (b) ULVZ structural features, such as gradients at the top of the ULVZ, or even a transition zone between the mantle and core; and (c) more complex ULVZ structure such as topography and lateral

variations [*Wen and Helmberger*, 1998]. However, for each case, stacks of *ScP* will provide important constraints not obtainable with solely *PcP* and precursors, due to a stronger dependence on V_S and V_P.

In this note we have not considered effects of other factors, such as a D" discontinuity, anisotropy, extreme attenuation, or CMB topography. These features and their small scale variations may certainly perturb short-period energy, which we are unable to address at present. However, *ScP* and the additional arrivals travel nearly identical paths, so we expect such contributions to be small.

Some of our data sampling the southwest and central Pacific lacks coherent precursory energy to *ScP*, a region where Fresnel zones from long period *SPdKS* data argue for a ULVZ (Figure 1b, "W" zone). This suggests the possibility of strong small scale variations in ULVZ structure [as suggested by *Vidale and Hedlin*, 1998; *Wen and Helmberger*, 1998], e.g., of order 100 km and less. Coupling together information from *ScP* and *PcP* precursors for large data stacks may provide important evidence for or against partial melt in regions previously mapped as having a ULVZ. However, noise effects must first be ruled out.

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