Using ScP precursors to search for mantle structures beneath 1800 km depth

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[1] If either two stratified geochemical reservoirs or a mineralogical phase change in perovskite exist in the mantle, the boundary between the geochemical layers or mineralogical phases may lie at a depth between 1800 km and the core-mantle boundary (CMB). We searched for the *ScP* precursors (*S*-to-*P* reflections) that would be generated at the boundary by stacking hundreds of short-period, vertical component teleseismic waveforms from the dense Pacific Northwest Seismic Network (PNSN). PNSN recorded clean *ScP* phases and saved the *P* to *ScP* time window for four earthquakes. We estimate our detection threshold to be impedance contrast >4%. None of the data show evidence of sharp structure between 1800 km and the CMB, suggesting that a sharp seismic discontinuity does not exist between 1800 km and the CMB under the Gulf of Alaska and Mexico: any discontinuity would need to be diffuse, have large topography, or have a small impedance change. While not conclusive, this observation is consistent with an Earth model lacking a global boundary separating geochemical reservoirs and lacking a phase change in this depth range. *INDEX TERMS:* 7203 Seismology: Body wave propagation; 7207 Seismology: Core and mantle; 8121 Tectonophysics: Dynamics, convection currents and mantle plumes; 8124 Tectonophysics: Earth's interior—composition and state (1212). **Citation:** Castle, J. C., and R. D. van der Hilst, Using ScP precursors to search for mantle structures beneath 1800 km depth, *Geophys. Res. Lett.*, *30*(8), 1422, doi:10.1029/2002GL016023, 2003.

1. Introduction

[2] It is now widely accepted that perovskite ($Mg_{.9}Fe_{.1}$-SiO_3, $CaSiO_3$) and magnesiowüstite ($Mg_{.9}Fe_{.1}O$) are the main constituents of Earth's lower mantle [*Liu*, 1979]. Seismological evidence for slabs of subducted lithosphere sinking into the lower mantle strongly argues against strict stratification of convective flow at an interface coinciding with the 660-km discontinuity [e.g., *Creager and Jordan*, 1986; *Grand et al.*, 1997; *van der Hilst et al.*, 1997], but other arguments would favor the existence of compositionally distinct domains in the deep mantle (see [*Hofmann*, 1997; *Albarède and van der Hilst*, 2002] for recent reviews). While the currently available seismological, mineralogical, and geochemical data cannot conclusively rule out changes in mantle mineralogy and phase chemistry deeper in the mantle, unambiguous evidence for such features has so far remained elusive.

[3] The presence of a mineralogical phase change in perovskite has been debated, and experimental evidence has been presented both for a break down of the silicate structure near 70 GPa (1700 km depth) [*Saxena et al.*, 1996] and for stability over the entire pressure range of the mantle [*Serghiou et al.*, 1998]. A recent study confirmed perovskite is stabile to at least 90 GPa (2100 km depth) [*Shim et al.*, 2001] - and perhaps to 135 GPa, that is, near core mantle boundary pressure (Shim, pers. comm. 2002); that study also suggested that its structure may change near 1900 km depth, but this awaits confirmation and the potential implications for elasticity are not yet known. On the basis of heat flow arguments and other geophysical arguments *Kellogg et al.* [1999] suggested the existence of radiogenically enriched domains in the lower mantle, but a predominance of internal mantle heating would argue against such a deep structure [*Davies*, 1998]. Key to unraveling these conflicts are seismic observations pertinent to interfac es in Earth's mantle.

2. Precursors to *ScP*

[4] *PcP* and long-period *ScS* waves have often been used to study the CMB and D″ regions. We unsuccessfully searched for precursors to both of these phases. To image small discontinuities we wanted to use large, dense seismic networks. Unfortunately, most large, dense seismic networks record only vertical component seismograms, eliminating the opportunities of observing *ScS* precursors. Searching for *PcP* precursors was also unsuccessful: *PcP* usually contained signal only at high frequencies above 1 Hz making it difficult to align on *PcP* as a reference phase. Additionally, any *PcP* precursors off structures near 2000 km depth are usually masked by the *P*, *pP*, and *sP* arrivals.

[5] Instead, we probed the lower mantle for *S*-to-*P* reflections and conversions recorded at PNSN. PNSN is a short-period, vertical component, dense triggered network of over 140 seismometers; the PNSN data are easily accessible at the Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC). In a separate work, we used PNSN waveform data to search for *S*-to-*P* conversions in the depth range between 800 km and 2000 km [*Castle and van der Hilst*, 2003]. We found no evidence for global structure in that depth range, in agreement with *Vidale et al.* [2001], but were unable to use *S*-to-*P* conversions to image structures at depths >2000 km.

[6] To probe the deepest mantle, we looked for *S*-to-*P* reflections (*ScP* precursors) that would be generated by any structure between 1800 km to the CMB (Figure 1). A

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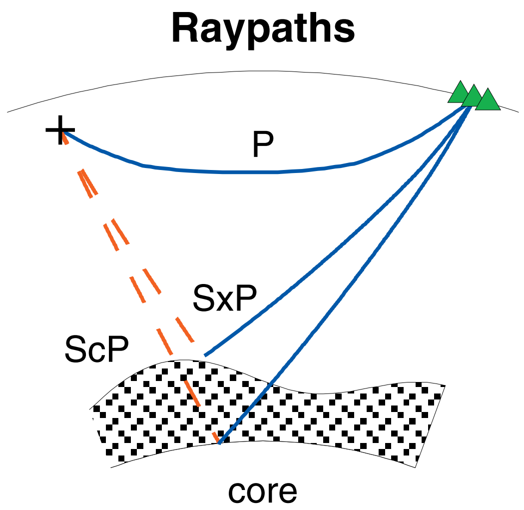

Figure 1. An earthquake at 30°, the *P*, *ScP*, and S_XP raypaths, and a hypothetic enriched geochemical reservoir at the base of the mantle.

seismic discontinuity at 2200 km depth would generate a reflected and converted wave we label $S_{2200}p$. We searched through the PNSN records to find earthquakes in the distance range 20° to 50° for which a clear *ScP* phase was recorded. At larger distances, the *ScP* reflection coefficient becomes post-critical while at shorter distances the reflection/conversion coefficient approaches zero. As PNSN is a triggered network that saves data in selected time windows, PNSN saves *ScP* infrequently and the preceding time window, where a *ScP* precursor would arrive, rarely. Through 2001, four earthquakes were recorded for which the *ScP* waveform was clear and the entire time window from *P* to *ScP* was recorded (Figure 2).

[7] To process seismograms to search for *ScP* precursors, we bandpass filtered the waveforms between an empirically chosen 2–5 s, aligned the waveforms by cross-correlating the filtered *ScP* wave, deleted records with low signal-to-noise ratios, and finally stacked using non-linear phase-weighted stacking [*Schimmel and Paulssen*, 1997]. Higher frequencies are more affected by local structure and thus more difficult to align. As a lower-mantle structure could be non-horizontal, precursors might arrive at slownesses and azimuths other than the predicted values. Taking advantage of the large seismic network, we analyzed waveforms to search for out-of-plane arrivals, stacking the records with respect to time, incident angle, and incident azimuth. Previous work using a similar method has been able to identify signals coming from structures dipping at angles steeper than 30° [*Castle and Creager*, 1998].

[8] Figure 3 shows processed synthetic seismograms. We generated the synthetics using the earthquake and receiver locations from earthquake #1 and used the WKBJ algorithm [*Chapman et al.*, 1988] with the USGS moment tensors [*Sipkin*, 1986], the *Engdahl et al.* [1998] hypocenter locations, the iasp91 velocity model [*Kennett and Engdahl*, 1991] and the PREM density model [*Dziewonski and Anderson*, 1981], both modified to include a 2% jump at either 2000 km (Figure 3A) or at 2600 km (Figure 3B). The synthetics included the *PcP*, *pPcP*, *ScP*, and either $S_{2000}p$ (3A) or $S_{2600}p$ (3B). The plot on the left in Figure 3A is a vespegram and shows the time and slowness of arrivals relative to the *ScP* wave. In every vespegram, we normalized the stacked *ScP* amplitude to 50. The top right figure plots the slowness and back-azimuth of energy arriving in a 25 second window around the *ScP* phase. Similarly, the lower right figure plots the slowness and back-azimu th of energy arriving.

[9] Figure 4 shows vespegrams and back-azimuth/slowness plots for the four earthquakes. In earthquake one, *ScP* is very clear and well constrained in time, azimuth, and slowness. *PcP* and a faint *pPcP* are both also visible. No *S*-to-*P* reflection can be seen at any depth nor is any $S_{2000}p$ visible in the back-azimuth/slowness plot. Earthquakes two and three are not as clean. *ScP* is seen but not as clearly. *PcP* and a faint *pPcP* are both visible in earthquake two; only a very faint *PcP* is observed in earthquake three. The arrival time of *pPcP* in earthquake two is similar to the theoretical arrival time of $S_{2000}p$: *pPcP* but no $S_{2000}p$ is visible in the back-azimuth/slowness plot. A small coherent arrival can be seen from earthquake three stacks just before the $S_{2000}p$ but otherwise no strong large signals exist. Earthquake four shows a very strong *ScP*, *sScP*, *PcP*, and *pPcP* but shows no arrivals that could be considered *S*-to-*P* reflections between 1800 and 2000 km depth.

3. Discussion and Conclusion

[10] In this study of deep interfaces using precursors from PNSN we found only four earthquakes with good record-

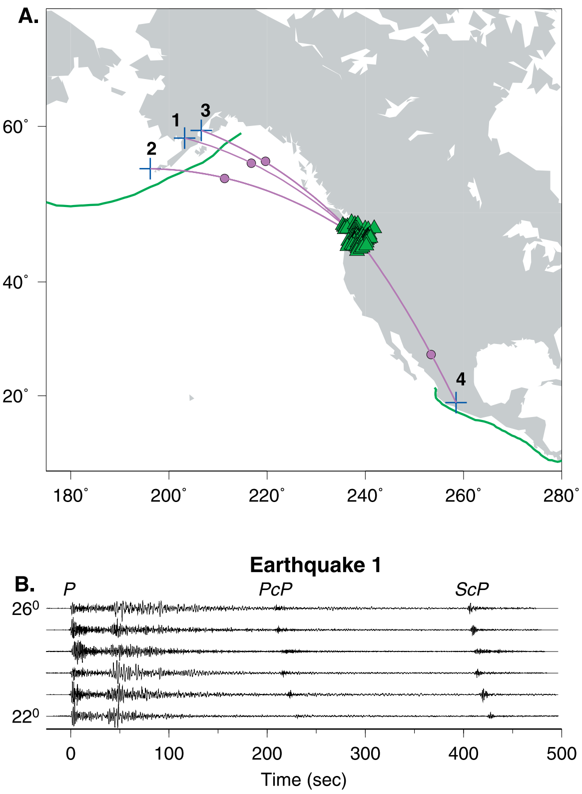

Figure 2. (A) Map of the region of interest. Numbers and crosses mark earthquake locations, triangles mark PNSN station locations, thick lines mark subduction zones, magenta lines mark *ScP* raypaths, an circles mark *ScP* reflection points at the CMB. (B) Six unfiltered seismograms from earthquake #1.

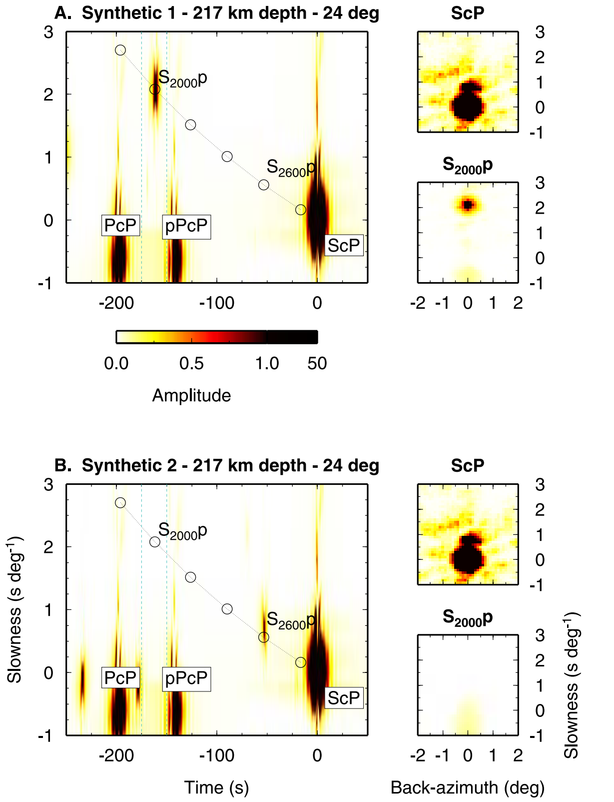

Figure 3. Stacks of WKBJ synthetic seismograms. The model included a 2% jump at 2000 km depth (A) and at 2600 km depth (B). Left: the stacked data of time versus slowness (a vespegram). Circles mark the arrival times and slownesses of *S*-to-*P* reflections off surfaces at 1800, 2000, 2200, 2400, 2600, and 2800 km depth. The *ScP* amplitude in each vespegram is normalized to 50. Amplitudes greater than 1 are colored black. Upper right: the slowness and azimuth of energy arriving in a time window around the *ScP* wave. Lower right: as for above but for a time window around the theoretical $S_{2000}p$ arrival time (dashed lines in the vespegram.

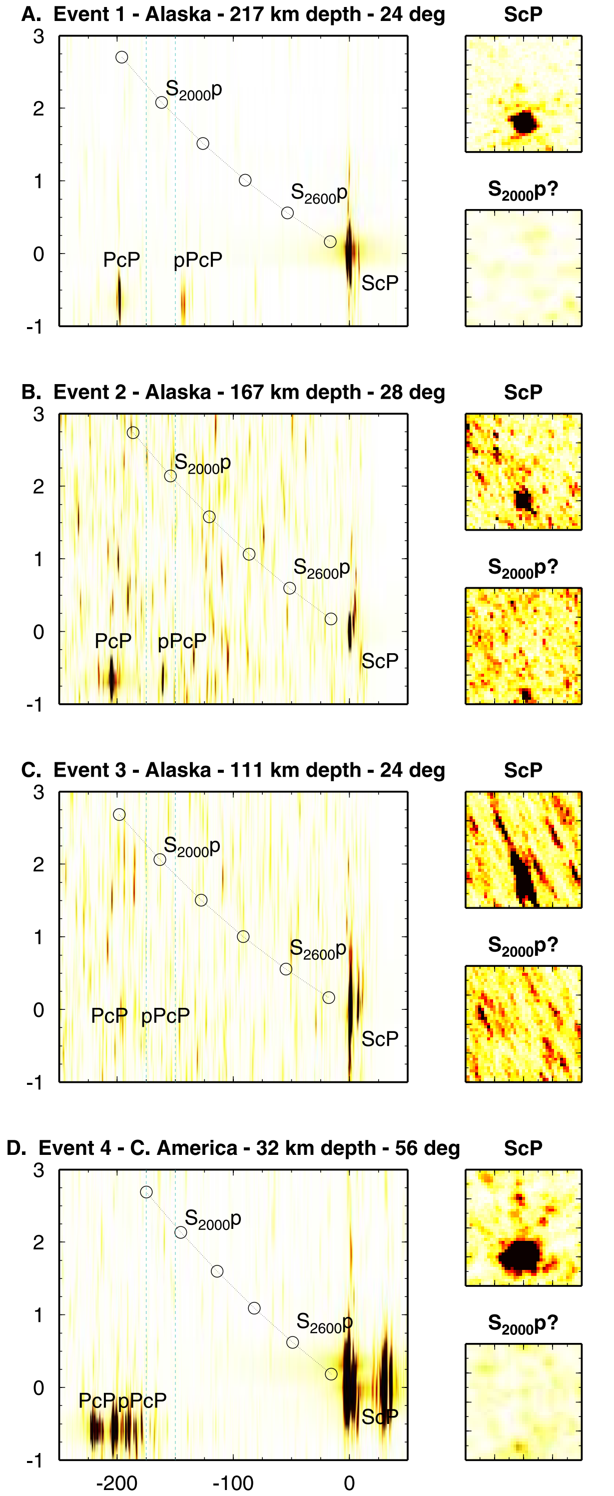

Figure 4. Vespegrams and back-azimuth/slowness plots for the four events. The vespegrams plot the slowness and time of energy arriving at one back-azimuth (along the great-circle path) while the back-azimuth/slowness plots plot the back-azimuth and slowness of energy arriving at the predicted *ScP* time (upper) and $S_{2000}p$ time (lower). The color scale and axes are as for Figure 3. The *ScP* amplitude in each vespegram is normalized to 50.

ings of the *ScP* phase, but none of these show convincing evidence of an *S*-to-*P* reflection in the lower mantle. Indeed, the clean data from earthquakes #1 and #4 give no support that a sharp seismic discontinuity exists anywhere between 1800 and 2800 km depth beneath the Gulf of Alaska and Mexico. Synthetic seismograms suggest we should be able to image structures with impedance contrasts >4% and occurring over a depth interval of less than 30 km. In each vespegram, synthetic and data, we normalized the *ScP* amplitude to 50. Structures causing variation of *ScP* amplitudes independent of any $S_{2000}p$ directly affect expected relative amplitudes.

[11] These observations are consistent with an Earth model without a global discontinuity due to chemical layering or mineralogical phase changes beneath 1800 km depth. The phase diagram for a perovskite phase change is unknown (see, however, *Shim et al.* [2001]), and it is certainly possible that it would occur over a larger depth range than could be detected by the data used here. Furthermore, the analysis presented here is limited due to the small number of earthquakes analyzed and because

geographical regions may not be representative of typical mantle structure. Our results are therefore necessarily tentative, but we expect that more comprehensive studies of *ScP* precursors with dense receiver arrays in other parts of the world (e.g., Japan, western Europe, USArray) could provide conclusive evidence for or against discontinuous changes in elastic properties beneath 1800 km depth in Earth's mantle.

[12] **Acknowledgments.** Figures were created with GMT [*Wessel and Smith*, 1995]. This research was supported by the National Science Foundation.

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