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INVESTIGATION OF A LOWER MANTLE SHEAR WAVE TRIPLICATION USING A BROADBAND ARRAY

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Abstract. SH signals recorded by an array of four broadband (Benioff 1-90) instruments, run by Caltech, are inspected for evidence of a lower mantle shear wave velocity discontinuity previously detected using WWSSN data. Deep focus earthquakes beneath Argentina span the distance range 78° to 82° from the array, where the triplication in the travel time curve produced by the discontinuity is expected to result in an arrival between the direct shear wave, S, and the reflection off of the core-mantle boundary, ScS. The SH data for these events do show evidence of the arrival; however, the broadband signals also show significant receiver structure complexity. Empirical receiver functions are determined for each station by stacking observations for events in South America closer than 75° from the array. Incorporating these receiver functions into the synthetic modeling demonstrates that lower mantle shear velocity models with a discontinuity fit the observations better than models without one.

Introduction

The core-mantle boundary is the largest chemical discontinuity in the earth, and a detailed understanding of its velocity structure is important for models of the thermal history and dynamics of the core and mantle. The lowermost 250 km of the mantle (D" region) is known to be a region of anomalously low shear velocity gradients and lateral heterogeneity (Bullen 1949; Cleary, Porra and Read 1967; Hales and Roberts 1970).

Most recent seismological studies of this region have attempted to resolve the velocity gradients in the D" layer using long period diffracted arrivals (e.g. Doornbos and Mondt 1979; Mula and Müller 1980). A recent study by Lay and Helmberger (1983), using direct body wave phases recorded on short- and long-period WWSSN and CSN (Canadian Seismic Network) stations, indicates the existence of a lower mantle S wave triplication in the travel time curve produced by a 2.75% shear velocity discontinuity about 280 ± 30 km above the core-mantle boundary. This triplication can be directly observed on SH components of displacements from intermediate and deep focus earthquakes in the distance range 75° to 95°. In this paper we conduct an investigation of SH and ScSH phases recorded by a small array of four broadband three-component instruments deployed in Southern California. These data are strongly influenced by receiver structure, but are shown to be consistent with, and supportive of the model proposed by Lay and Helmberger (1983) for the velocity structure above the core beneath central America.

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Data

The separation of seismic energy into short- and long-period recording channels performed by most analog networks often delimits the information that can be extracted about source complexity and earth structure from body wave signals. There is increasing impetus to utilize broadband data. A very limited amount of broadband three-component data is available, and the existing stations tend to be widely distributed. The broadband array that we have used in this study consists of four 3-component long period Benioff stations run by Caltech. The stations are PAS (34.15N,118.17W), TIN (37.05N,118.23W), RVR (33.99N,117.38W), and BAR (32.68N,116.67W), which are distributed over 400 km in Southern California. The instruments have a broadband frequency response (pendulum period T_p=1 sec, galvonometer period T_g=90 sec), which makes them particularly attractive for body wave studies of earth structure. The response characteristics of the Benioff instrument are compared with those of the short- and long-period WWSSN and long-period (T_p=30 sec,T_g=90 sec) Press-Ewing instruments in Figure 1a. A typical SH arrival, recorded on the Benioff (LP) instrument, is compared with the same arrival recorded by the Press-Ewing instrument. The broad band instrument provides much better resolution of distinct phases in the coda of the arrival. The array presently runs at a low gain and is analog recorded, which limits its usefulness to teleseismic events with m_b>5.7. The data in Figure 1b clearly indicate the potential of broadband records for improving our understanding of earth structure and earthquake source complexity; however, it is clear that receiver structure and earth noise are of greater concern than for longer period recordings.

Several source regions with deep focus earthquakes are located in the distance range 70° to 95° from the array, including those in Argentina, Tonga-Fiji, and the Sea of Japan. This distance range is optimal for detecting fine velocity structure in the lower mantle, also deep events generally produce simple waveforms, free of surface interactions, which simplifies analysis of the signals. An extensive data search was conducted through the Benioff records for deep events in the three source regions mentioned above for the period 1963-1984. While several events with suitable magnitudes and source complexity have occurred in Tonga, the SH radiation to Southern California was nodal in almost all cases; and deep events beneath the Sea of Japan generally were too small to produce clear recordings. South American events provided sufficient data to establish re-

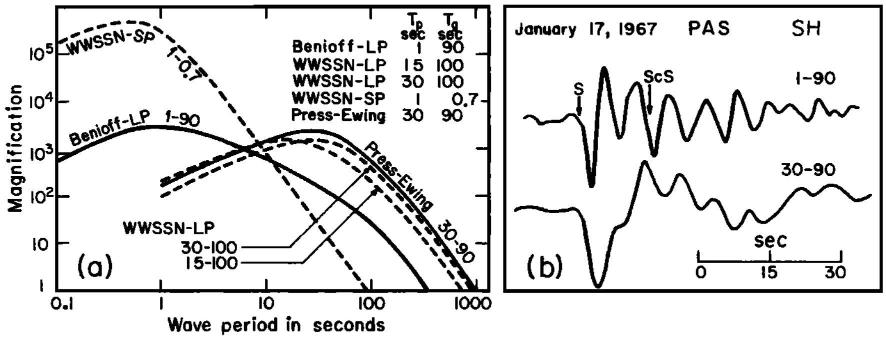

Figure 1. (a) Comparison of the amplitude responses of the long-period Benioff WWSSN and Press-Ewing instruments. (b) SH arrivals recorded at Pasadena on the Benioff (LP) and Press-Ewing instruments for a deep focus earthquake (d=586 km) in Argentina at a distance of 80.3°.

ceiver complexity as well as to seek the presence of the lower mantle triplication. Five deep focus events in Argentina, out of the seven events analyzed by Lay and Helmberger (1983), produced suitable records for the distance range 75° to 82°. These events all have stable SH radiation patterns to North America and have simple, impulsive waveforms across the North American array of WWSSN stations. The Benioff records from these events were digitized and the SH data were analyzed.

SH signals from the Argentine event of January 17, 1967 (d=586 km), which has very simple P and S wave signals at other stations and azimuths (Lay and Helmberger, 1981), are shown in Figure 2. The middle column shows synthetic seismograms produced using generalized ray theory for the Jeffreys-Bullen (JB) velocity structure of Press (1966) (Figure 3). The timing and relative amplitude of arrivals of S and ScS, which is the reflected shear wave at the core-mantle boundary, is roughly matched, though the ScS observations are somewhat larger than predicted. There is an arrival between S and ScS observed at all stations, which is not predicted for the JB model, and which changes in relative timing as the distance increases. The moveout of this phase indicates that it is not a source arrival, but results from either a deep reflection in the mantle or from systematic receiver structure. The right hand column shows synthetic SH waveforms for model SLHA (Figure 3) of Lay and Helmberger (1983), which has a 2.75% shear velocity discontinuity 251 km above the core beneath Central America. The triplication resulting from this structure produces the arrival between S and ScS which has a moveout similar to that of the arrival in the data. Note that the predicted ScS-S differential time is well matched at BAR, but is slightly too long at larger distances, for both models. The arrivals following ScS at RVR, PAS, and TIN are not coherent from station to station and thus indicate the substantial contributions of near receiver structure. The records observed for the other deep events are quite similar to those shown in Figure 2, with simple S and ScS arrivals and coherent intermediate phases. In order to interpret these data it is clearly necessary to attempt to account for receiver structure.

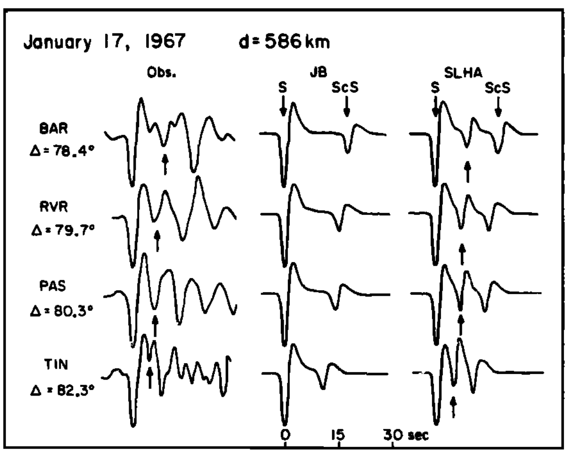

Figure 2. SH data (left) and synthetic seismograms for the JB (middle) and SLHA (right) velocity models for the January 17, 1967 event. The amplitudes are normalized.

Discussion

Detailed shear velocity structures beneath the Benioff stations are not available, though some studies of the PAS receiver structure have been

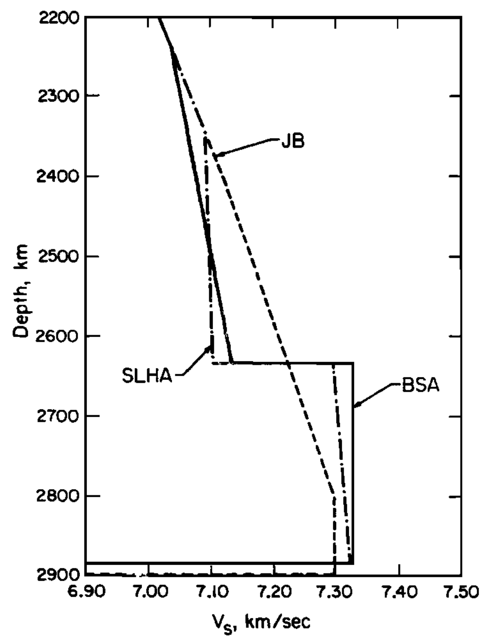

Figure 3. Shear velocity models for the D" region.

performed (Lee and Langston,1983). Establishing deterministic structures requires excellent ray arameter and azimuthal coverage, which is impossible to obtain for these receivers, so we have adopted a simple empirical approach to account for first-order features of the receiver contribution to the SH signals. Intermediate and deep focus earthquakes in South America along the great circle between Southern California and the Argentine source region, but at closer distances to the array, were inspected. Events with simple source functions, low levels of seismic noise, and strong SH arrivals were digitized. Recordings from events at distances from 55° to 75°, which vary only slightly in ray parameter, were then stacked by aligning them on the first peak arrival and summing the traces. An example of this procedure is shown in Figure 4, where 6 PAS recordings are summed. The sum clearly reflects the common characteristics of the traces, which are due to receiver structure. The limited number of traces available precludes more sophisticated time series analysis procedures for estimating the receiver function, and the stability of our procedure is readily apparent. The summed trace thus consists of an "average" simple earthquake source function; the broadband instrument response; an average attenuation operator; and an average receiver function for each station at the same azimuth and approximate ray parameter as for the deep Argentine observations. These traces are used as source functions in the modeling below. The summing procedure yielded a simple receiver structure for BAR, slightly ringing complexity for PAS (Figure 4) and RVR, and higher frequency arrivals for the TIN coda.

When generalized ray theory synthetics are generated using the empirical source functions described above, both the mantle response and first order effects of the receiver structure are included. Figure 5 shows a comparison of SH observations in the triplication range at BAR with synthetics for the JB model computed using the empirical BAR source function. In addition to the S and ScS phases, the JB model synthetics have an

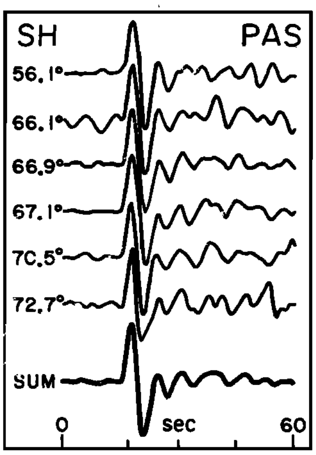

Figure 4. SH seismograms with normalized amplitudes observed at Pasadena from intermediate and deep focus earthquakes in South America at pre-triplication distances along the great circle between Southern California and the Argentine source region.

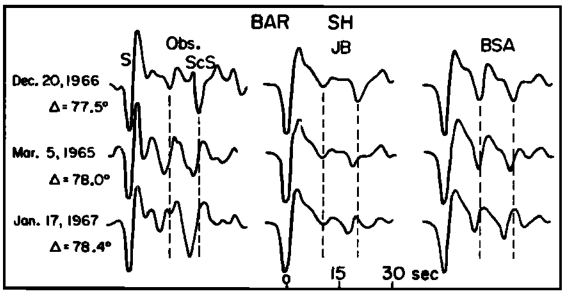

Figure 5. SH observations at BAR and synthetic seismograms with the empirical BAR source function for the JB and BSA models.

intermediate arrival produced by receiver structure, which is apparent about 10 seconds after the S arrival. This is a small phase, but it is close in timing to the intermediate arrivals observed between S and ScS. However, the observations show a systematic moveout of both the ScS and intermediate arrivals, whereas only ScS moves out for the JB synthetics. The right hand column shows synthetics for a lower mantle shear velocity model (BSA) (Figure 3) that was slightly modified from that presented for the Argentina-to-North America paths (SLHA) by Lay and Helmberger (1983). The modifications simply increased the velocity gradient above the discontinuity and decreased the velocity gradient below it, resulting in a better fit to the observed ScS-S times. Other modifications of SLHA could achieve the same effect. The triplication Scd arrival overlaps the receiver structure arrival but has a moveout very close to the observed behavior. The moveout of this intermediate phase clearly indicates that it is not produced by receiver structure, and the synthetics with the lower mantle triplication match the observed behavior. Clearly, not all aspects of the observed waveforms have been modeled. Most of these discrepancies are due to the individual source complexity of the deep events which has not been accounted for. The amplitude of ScS varies in the observations as well, which appears to be the result of interference between ScS and a crustal reverberation (Note the small bump just ahead of ScS at 77.5° which interferes with the downswing at 78°). This interaction with the receiver function clearly complicates interpretation of secondary arrivals, and would be difficult to detect using narrow band instruments.

Figure 6 shows additional comparisons of observations and synthetics for the JB and BSA models. In this case,the station is PAS, which is similar to RVR in having strong observed reverberations following ScS. These reverberations are quite well accounted for in the synthetics which include the empirical receiver functions. The JB model synthetics have clear S and ScS arrivals, though the ScS-S time is slightly too large, as is true for model SLHA. Once again, the receiver structure produces a reverberation between S and ScS, close in timing to the observed arrival. The fortuitous occurrence of this crustal arrival at different relative times, for BAR and PAS, could easily be mistaken for lower mantle structure if only a few observations for each station were available. However, for RVR and TIN, receiver structure does not produce arrivals at the right times to account for the observations in Figure 2. A

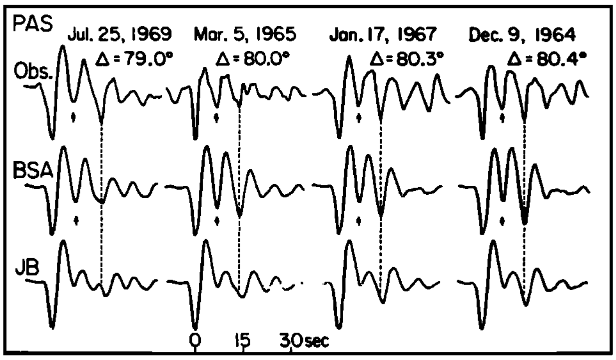

Figure 6. SH observations at Pasadena and synthetic seismograms with the empirical PAS source function for the BSA and JB models.

receiver arrival between S and ScS is expected for TIN, but several seconds later than the observed arrival. Synthetics for model BSA are shown in the middle row of Figure 6. Note that the ScS-S times for model BSA match the observations, and that the relative timing and amplitudes of the first three cycles are more accurately modeled than by the JB synthetics. The interaction between the crustal reverberations and the triplication and ScS arrivals produces amplitude interference that complicates refining the lower mantle models, based on the relative amplitude behavior.

The good time resolution of the Benioff data did enable the slight modifications of model SLHA described above, for a systematic mismatch in ScS-S differential times was observed across the array that could not be detected with WWSSN long period recordings. However, the limited spatial extent of the array constrains the possible model space only slightly more than that found, using WWSSN data, by Lay and Helmberger (1983). While they used long period narrow band instruments, the wide spatial distribution provided good ray parameter constraints. A larger network of three component broad band stations would maximize our ability to model the D" region.

Conclusions

SH observations from five deep focus earthquakes beneath Argentina recorded by four broadband three component instruments in Southern California provide additional evidence for a shear velocity discontinuity in the lower mantle. While these data alone would not suffice to discover such a feature, they do allow for corroboration of it. The timing and amplitude of a systematic arrival between S and ScS in the range 78^o to 82^o is generally consistent with the triplication produced by a 2.75% shear velocity discontinuity 250 km above the core. A slight systematic mismatch between the observed ScS-S times and predictions of model SLHA (Lay and Helmberger,1983) is detected, using the superior time resolution of the broadband data over that for WWSSN instruments. This permits some refinements of the lower mantle shear velocity model to be made. The importance of receiver structure complexity in broadband data is demonstrated and an empirical stacking procedure is used to account for this complexity in the synthetic modeling. Source and structure studies using such data must account for receiver complexity as far as possible to avoid misinterpretation of the signals.

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