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UPPER MANTLE CONVERTED WAVES BENEATH THE NARS ARRAY

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Abstract. Several registrations of teleseismic events on the NARS array show a phase which can be identified as a P to S conversion at the 670-km discontinuity beneath western Europe. Variations in the amplitude and arrival time of the so-called Ps phase are observed for different azimuths. A single station/multiple event stacking technique was applied to the data to determine the consistency of the phase. The results are indicative of amplitude, arrival time, and slowness variations of the converted phase on a local scale. These observations are most logically explained by a model with depth variations of the 670-km discontinuity of the order of 20 km over a distance of 200 km.

Introduction

It is important to establish the exact nature of the 670-km discontinuity. Several body wave studies have been carried out to investigate the character of the upper mantle transition zone between 400 and 700 km more closely (see for references e.g. Lees et al., 1983). Lees et al. (1983) have related this seismological evidence to compositional models of the upper mantle transition zone. The large reflection coefficient of the 670-km discontinuity as inferred from body wave studies implies both chemical and phase changes according to the authors. However, as pointed out in a recent paper by Muirhead (1985), the main evidence for a sharp discontinuity comes from precursors to the P´P´ phase. These precursors, which are identified as P´670P´ phases (underside reflections from the 670-km discontinuity) have amplitudes of 10 to 20% of the P´P´ phase on short period seismograms. Cleary (1981) and Muirhead (1985) argue that these precursors might also be explained by scattered P3KP phases. Thus, evidence as provided by converted body waves, is needed to determine the character of the 670-km discontinuity.

The aim of this study is to investigate the character of the 670-km discontinuity beneath western Europe with the aid of P to S converted body waves. The data which are used for this study are teleseismic registrations on the broad-band NARS array (NARS: Network of Autonomously Registrating Seismographs). Since the converted phases which originate under the array sample the 670-km discontinuity very locally, it is possible to investigate whether there are any lateral variations in the 670-km discontinuity with these phases. The configuration of the NARS array with 14 stations located on the west-European Platform, is in this respect very suitable for this purpose.

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Data

The Ps phase, the P to S converted phase from the upper mantle under the station, appears in the coda of the direct P wave. For the teleseismic events studied here ($\Delta > 65^\circ$) it arrives 65-70 s after the direct P phase when converted at a depth of 670 km. Its polarity is that of an SV wave and it will therefore primarily be registrated on the radial component of the seismogram. Because the Ps phase is a phase of low amplitude, arriving in the coda of the P phase, it will only be recognized under optimum conditions.

The data used for this study are registrations on the NARS array. This array consists of 14 digital, 3-component, broad-band recording stations which are located in western Europe along a line of 2600 km (Dost et al., 1984; see fig. 4). The stations were installed between 1982 and 1984. This means that some stations have been in operation for a longer period than others and, consequently, have a larger data set. Data have been selected for an optimum signal-to-noise ratio for the Ps phase: registrations of strong (m_b >5.8), teleseismic ($65^\circ < \Delta < 100^\circ$) events with simple source time functions and sharp P onsets. The best data were obtained from deep (>400km) events, but for this study seismograms from events of varying depth (10-650km) have been used.

Observations

About 10% of the 72 selected seismograms showed a distinct phase with SV polarity, with an arrival time of 65-70 s after the direct P phase and with a waveshape comparable to that of the direct P. Three examples of such registrations are shown in fig. 1. These phases could be identified as Ps phases from the 670-km discontinuity because the following criteria were met. The particle motion is that of an SV wave with most of its energy on the radial component. The nonlinear filter which multiplies the radial with the vertical component produces a negative amplitude which is again indicative of an SV arrival. The waveshape is similar to that of the unconverted P phase and the phase is enhanced when the signal is cross-correlated with the waveform of the direct P phase. The arrival time of 65-70 s after the P phase indicates that the depth of conversion corresponds to that of the 670-km discontinuity. No other P to SV converted wave can explain these observations since other reflected and converted phases with the same arrival time have amplitudes which are much smaller than those observed.

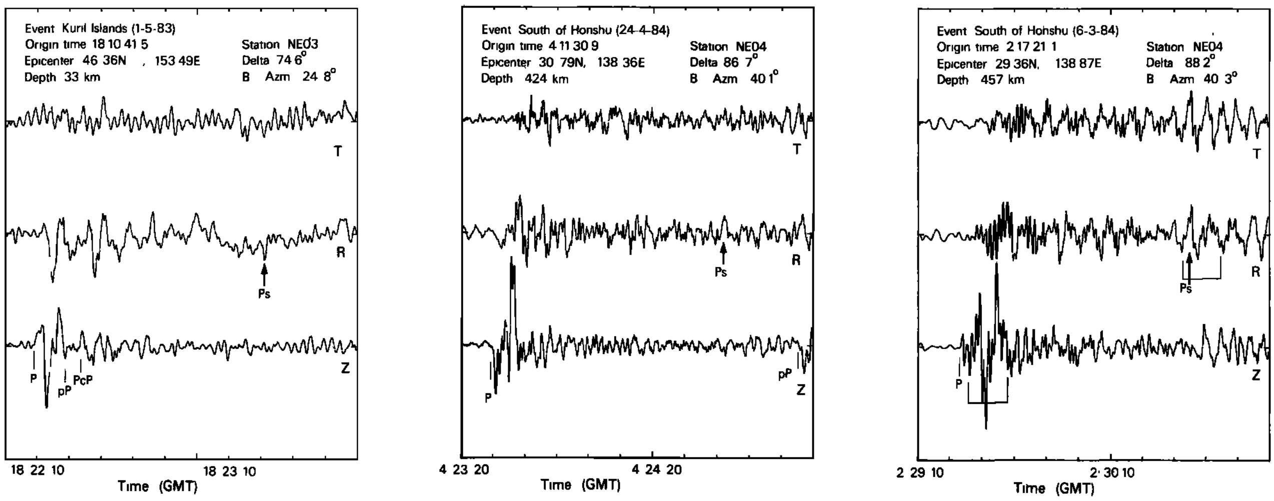

Fig. 1. Vertical (Z), radial (R), and transverse (T) components of registrations with phases identified as Ps. (Event information is from the PDE).

The Ps phase is usually difficult to detect due to the high level of noise in the P wave coda. Phases with amplitudes which are at least 10% of that of the P can commonly be recognized. A registration with an exceptionally high amplitude on radial and transverse component is shown in fig 1c. The source-time function can be clearly recognized at 66 s after the direct P on the horizontals. An analysis of the selected data showed that the phase identified as Ps showed large amplitude variations, and on several good quality records it appeared to be absent or of very low amplitude.

Amplitude variations of upper mantle converted phases have also been observed for other conversions elsewhere. Faber and Mueller (1980, 1984) noticed amplitude variations in the Sp phase recorded in stations in the U.S., and in the precursors to S, SKS and ScS phases on long-period seismograms of the Graefenberg array. They explained their results by large scale and local variations in the sharpness of the mantle transition zone. Variations in the amplitude of the Sp phase from a discontinuity at a depth of 451 km under LASA have been observed by Baumgardt and Alexander (1984). They noticed that the Sp phase from the 670-km discontinuity could only be intermittently recognized. The same observation was made by Barley et al. (1982) and Bock and Ha (1984) in their studies of near source S to P converted phases. They explained this feature by variations in the radiation pattern of the analyzed earthquakes.

The elusive nature of the Ps phase on registrations on the broad-band NARS array necessitated a closer study of the statistical significance of the presence of the Ps phase. The method adopted for this purpose is a single station stacking technique. In this method normalized seismograms from different events registrated at a single station are stacked along lines of equal $dT/d\Delta$. The normalization involves a correlation of the 3 components (vertical, radial and transverse) of each seismogram with the waveshape of the direct P phase on the vertical. The data are then displayed in a τ-p-diagram, in which p represents the differential slowness, the slowness with respect to the direct P phase. Fig. 2 presents the results of the stacking procedure for events registered at station NE04 with a back azimuth between 36 and 71°. The pivot distance in

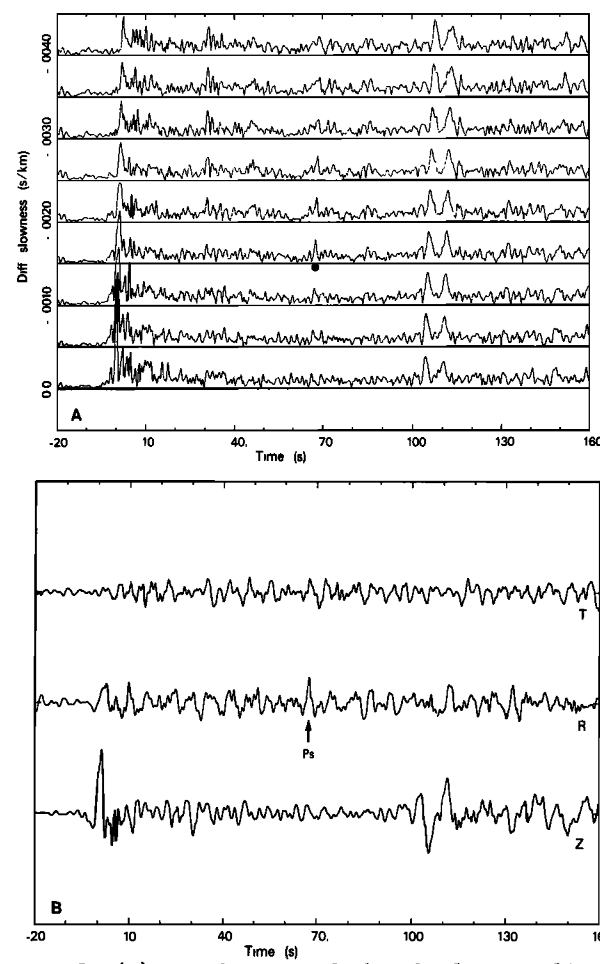

Fig. 2. (a) τ-p diagram of the absolute amplitude of the stack of station NE04. (b) 3 components of the stack with a differential slowness of -0.0015 s/km. (7 Events: Delta: 76.9-99.3°, Back azimuth: 36.3-71.0°, Focal depth: 18-651km)

the figures is 80°. The predicted arrival time and slowness of the Ps phase according to the model 1066B are indicated by a dot in the τ-p-diagram of fig. 2a. The observed stacked phase has an arrival time and slowness which correspond to the Ps phase of the model 1066B, and its SV-polarity is clear from fig. 2b. The amplitude is roughly 20% of the direct P phase. This is an extraordinarily high value when compared to the Ps/P amplitude ratio of 8% computed for models such as 1066B and PEM, which have velocity increases of 8-10% and density increases of 6-7% at a depth of 670 km. Such an anomalously high amplitude is not observed at the same station (NE04) for events from another azimuthal window (20°-35°).

Fig. 3 shows the results of the stacking procedure for 6 stations of the northern part of the NARS array. These stations were the only ones for which we had enough data to obtain reliable results from the stack. All events are within the epicentral distance range of 69-99° and focal depths vary from 10 to 651 km. High amplitudes of the Ps phase from the 670-km discontinuity are observed in station NE04 (azimuth: 36-71°) and station NE05 (azimuth: 20-87°). There are no indications of the presence of a Ps phase with a Ps/P amplitude ratio exceeding 5% for the stations NE02, NE03, NE06 and NE08 for the azimuthal windows specified, although the number of registrations for station NE08 is small. The stacked seismograms of the stations NE04 and NE05 on which the Ps phases are clearly present indicate small variations in the arrival time and estimated slowness of the converted phase between the two stations.

These observations can only be explained in terms of lateral variations in the upper mantle structure under western Europe. Fig. 4 shows the parts of the 670-km discontinuity and upper mantle which are sampled by the registrations. Bold lines depict the locations of the P to S conversion and the two extremely bold arcs indicate the locations from which high amplitude Ps phases are observed.

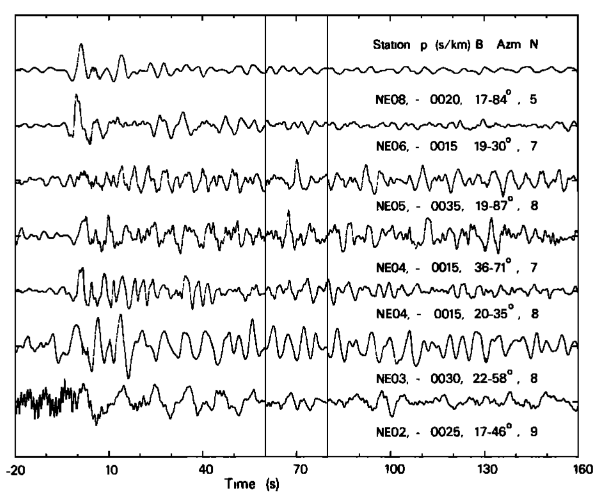

Fig. 3. Radial component of stacked seismograms. Station name, differential slowness, back azimuth and number of registrations are given at the right end of each trace.

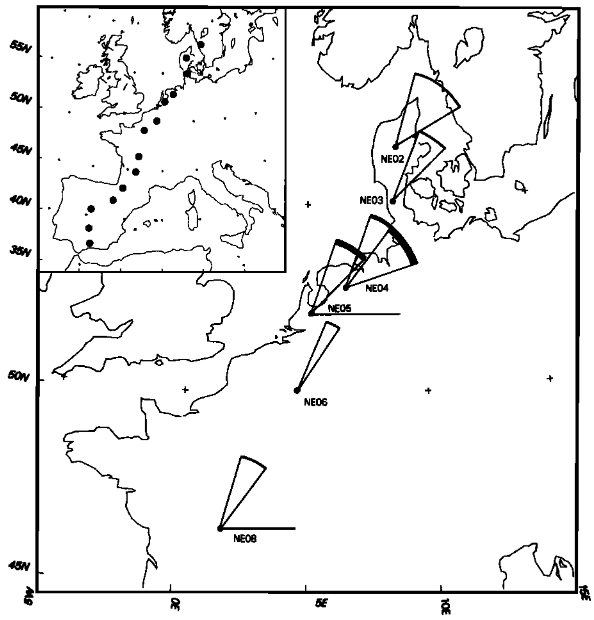

Fig. 4. Projection onto the Earth's surface of parts of the upper mantle sampled by the Ps data. Bold lines indicate the location of conversion. Insert shows the location of stations NE01-NE14 of the NARS array.

Discussion and Conclusion

The most important conclusion to be drawn from the observations in this paper is that the amplitudes of Ps converted phases show large variations on a local scale. There are two possible explanations for this observation. The first one is that there are lateral variations in the sharpness of the discontinuity. However, none of the currently accepted petrological models can explain Ps phases with amplitudes which exceed that of P by more than 10%. A second more plausible interpretation is that focussing and defocussing structures in the upper mantle account for the observed differences. Variations in the depth of the 670-km discontinuity are most effective in producing amplitude variations in the Ps phase. A back-of-the-envelope calculation, assuming reasonable velocities and an ideal lens-like shape of a bulge in the 670-km discontinuity shows that this bulge should have a radius of curvature of about 1300 km to double the amplitude. This means that depth variations of 15 km over a distance of 200 km are needed to account for the observed amplitude differences. Similar values are obtained when we want to explain the observed variations in the arrival time of the Ps phase. The stations NE04 and NE05 which are 200 km apart show a time difference of the Ps phase of about 3 s, which requires a change in depth of the 670-km discontinuity of roughly 30 km. Thus, a model which involves large local scale variations of the 670-km discontinuity accounts for the observed amplitude and arrival time variations of the Ps phase. It should be noted that the focussing and defocussing effects of the 670-km discontinuity are much larger for the converted Ps phase than for the P wave due to large refraction of the Ps wave across the discontinuity.

Furthermore, the effects can be different for the two waves, since the two rays are separated by 150 to 250 km at a depth of 700 km for teleseismic events. Other anomalous structures in the upper mantle may also contribute to differences in the amplitude, arrival time and slowness of the Ps phase. However, the influence of depth variations of a 400-km discontinuity, or of variations in the thickness of a low velocity zone are much smaller than that of the 670-km discontinuity.

Unfortunately, the limited amount of data make it impossible to interpret the results from this data set in a more quantatative way. However, the data allow one other conclusion to be drawn with certainty: The 670-km discontinuity is locally extremely sharp since observed undulations in the P wavetrain of about 1 Hz can also be recognized in the Ps phase (see fig 1c). This means that waves with a wavelength of 10 km at a depth of 670 km "feel" the discontinuity as a sharp transition.

The results of this study are comparable to other studies of upper mantle converted phases in the fact that large amplitude variations are observed. The amplitude variations observed in this study are indicative of local scale variations in the upper mantle. Large scale variations may also be present as pointed out by Faber and Mueller (1984), but these cannot be resolved with the NARS array data set which is presently available. A model which includes variations in the depth of the 670-km discontinuity could also explain the observed amplitude variations and the intermittent character of the P′670P′ phases. This means that phases identified as P′670P′ might be a selection of high amplitude, focussed P′670P′ waves. The reflection coefficient inferred from these data alone may therefore be overestimated by Lees et al. (1983), although their conclusions are not invalidated by this study.

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