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LOWER MANTLE VELOCITY INHOMOGENEITY OBSERVED AT GRF ARRAY

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Abstract. GRF broadband array recordings provide strong support for the existence of anomalous *P*-coda phases along the Kuriles - European path first observed using WWSSN data. The data suggest that the phase, termed here *PdP*, arrives 3-5s after the direct *P*-wave and has a slowness 0.7-0.8 s/deg smaller. The latter measurement precludes *PdP*'s misidentification as a source stopping phase, and given the magnitude of the slowness difference, slab multipathing and diffraction are equally unlikely. Because the phase is clearly not observed for all Kurile events and from timing and geometric considerations, crustal reverberations are also untenable as an explanation for *PdP*'s appearance. The hypothesis which best explains the *PdP* arrival time, arrival angle, and waveform is the presence of a 3% velocity jump in the lower mantle approximately 290 km above the core-mantle boundary. Because of the failure of other studies to observe *PdP* under favorable recording conditions, the reflector must be of limited regional extent beneath Northern Siberia.

Introduction

The lowermost 300 km of the mantle has held the interest of Earth scientists at least since the time Bullen designated this region D″ and suggested on the basis of seismic travel time curves that there were present at this depth large gradients in seismic velocities. Much effort has been devoted recently to investigating the seismic structure of D″ because the precision with which one is able to measure the seismic properties of rock at this depth may provide important constraints on mantle geochemical and dynamical models and would thus be of broader interest within the Earth sciences community. An impetus to this surge of interest was the work of *Lay and Helmberger* [1983] who suggested that there was present in more than one geographic location, a 2.75% velocity jump in the *S*-wave velocity at about 300 km above the core-mantle boundary (CMB). They and their co-workers [*Young and Lay*, 1987; *Garnero et al.*, 1988] base their hypothesis principally upon the observation of the phase *Scd* which is produced by a triplication in the traveltime curve that results from an abrupt *S*-velocity increase in the lower mantle.

If such a structure does indeed exist, one would expect to observe a jump in the *P*-wave velocity as well. A number of investigators have searched for evidence of just that and met with mixed success. *Schlittenhardt et al.* [1985] examined the *P*-coda of some very impulsive, moderate-sized earthquakes in the hope of seeing a reflected *P*-wave from the hypothetical discontinuity in a number of regions not studied by Helmberger and Lay. Although they used data of signal to noise ratio (SNR) high enough to detect a signal from a *P*-velocity jump half as large as what Lay and Helmberger report for *S*, they were unable to find convincing evidence to support its existence. Studies of *Pdiff* amplitude decay [*Mula*, 1981; *Doornbos*, 1983] as well as short period *P*-wave amplitudes in the core shadow [*Ruff and Lettvin*, 1984; *Young and Lay*, 1989] suggest a 1.3-1.5% upper limit on *P*-velocity jumps near the CMB.

In contrast to these negative results, *Baumgardt* [1989] reported observations of the *P* reflection sought by *Schlittenhart et al.* [1985], in WWSSN records of some Kurile Islands-Sea of Okhotsk earthquakes recorded at European stations, particularly STU (Stuttgart, FRG). The travel times he measured were well modeled by a *P*-velocity discontinuity of comparable magnitude to the *S*-velocity jump (2.75%) and located at a depth of 344 km above the CMB.

However, there still remain two competing hypotheses which could explain the observations. One is that the anomalous *P*- and *S*-phases are produced by the passage of *P*- and *S*-waves through the strong velocity heterogeneity created by the descending oceanic slab. Evidence of the slab's effect on seismic waveforms, through multipathing [*Silver and Chan*, 1986] and diffraction [*Cormier*, 1985, 1989; *Vidale*, 1987], has been demonstrated. Another hypothesis is that the phases represent energy scattered by small diameter, velocity inhomogeneities near the CMB [*Haddon and Buchbinder*, 1986, 1987]. Scattering from near the CMB can explain precursors to *PKP* [*Haddon and Cleary*, 1974; *Bataille and Flatté*, 1988] and *PKPPKP* [*Husebye et al.*, 1977] waves, and *Haddon and Buchbinder* [1986, 1987] suggest such a mechanism may give rise to the *S*-wave observations in this case.

Unfortunately, studies to date have not been able to measure directly the wave slowness and azimuth, a crucial datum for discriminating between the competing hypotheses. To make such precise measurements, an array of seismic instruments is required. The broadband GRF array is located in southern Germany, not far from Stuttgart where the *P*-coda anomalies have been seen, and is therefore ideally placed to make exactly these measurements. We describe the most important results of our study below.

Data

The data used in this study are recordings from the 13 vertical components of the GRF seismic array. We utilized the same criteria as *Baumgardt* [1989] to select our earthquake sources, namely we sought intermediate- and deep-

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focus events in the Kurile arc which were large enough to yield a signal of good SNR and not too large to obscure arrivals within 10s of direct *P*. No shallow events were considered so that any anomalous phase and conventional depth phases produced at the free surface near the source would be well separated from direct *P* in the seismograms. Therefore, we used no earthquake shallower than 45km. Magnitudes of our sources varied between m_b=5.1-6.6.

Figure 1 shows GRF seismograms for a small, deep event in the Kuriles. That the source lasts a very short time may be seen from the appearance of the direct *P*-wave, which is a single impulse of about 1s duration. Although the individual traces are of modest SNR, the signal may be enhanced by beamforming. The simplicity of the source function is evident in the beam for direct *P* shown in the second trace from the top in Fig. 1.

Travel time computations for an event as deep as this one using radial earth models such as PREM and Jeffreys-Bullen predict no additional phase between direct *P* and *PcP*, the *P*-wave reflected from the Earth's core which arrives approximately 11s after *P*. That there is an additional phase 5s after direct *P* may be seen in a number of individual traces and very clearly in a beam which has the same azimuth as direct *P* and a slowness 0.7-0.8 s/deg less. This is shown in the top trace of Figure 1.

One way of displaying beam energy for many arrival angles is the vespagram, an energy contour plot of slowness versus time for a fixed azimuth. A vespagram for this event for the azimuth corresponding to the Kurile arc is shown in Figure 2. There are two prominent arrivals in the plot. The first is the direct *P* arrival at t=2 s and slowness

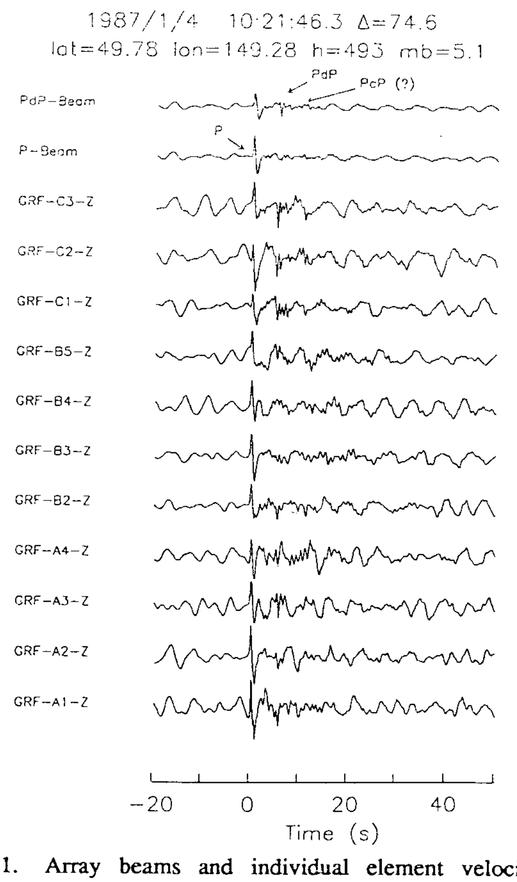

Fig. 1. Array beams and individual element velocity-proportional seismograms aligned on the direct *P* arrival. Elements B-1 and C-4 were not functioning at this time. The traces are summed assuming an arrival angle consistent with a slowness of 5.0 s/deg to produce the *P* beam (second from top) and 4.2 s/deg to produce the *PdP* beam (top trace). Arrows point to our phase identifications.

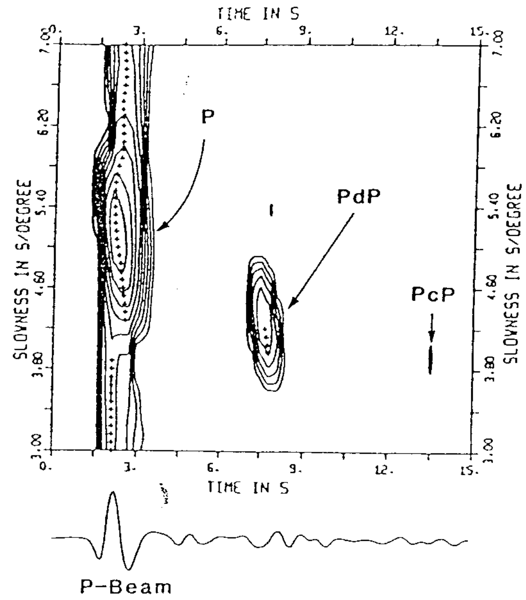

Fig. 2. Contour plot of energy for event in Fig. 1. Plus signs indicate the arrival time of maximum energy at each slowness. Phases corresponding to the maxima are labeled accordingly. The contours extend from 0 to -30 db at intervals of 3 db. The trace at bottom is the *P*-beam filtered to simulate a WWSSN-SP instrument.

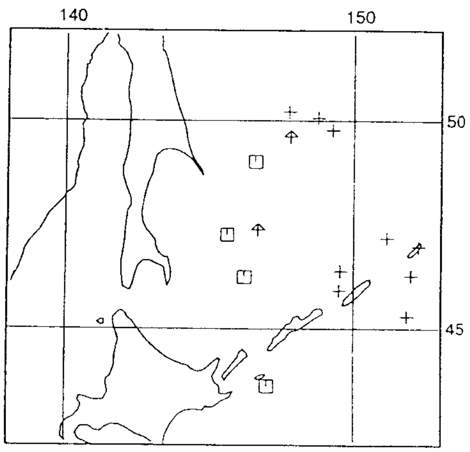

Fig. 3. Origin of events examined in *Weber and Davis* [*submitted*, 1989]. Symbols represent events for which: (+) *PdP* is observed, (□) *PdP* is absent, and (⍏) *PdP* is not observed or is poorly visible but *ScdS* is present. The map is a Mercator projection.

p=5.1 s/deg. The second, which we term *PdP*, has p=4.3 s/deg. (We employ here the nomenclature of *Schlittenhardt* [1986] rather than that of *Baumgardt* [1989].) Barely visible is a third maxima at t=13.5 s and p=3.9 s/deg, which corresponds to that expected for *PcP*.

The example we show here is typical of a number of northern Kurile events recorded at GRF. However, the *PdP* phase is absent for earthquakes occurring in the southern Kuriles. Figure 3 shows a plot of Kurile epicenters we examined for evidence of *PdP*. The geographic correlation of the presence and absence of the phase is fairly clear. The distribution of reflection points in D″ covers a 3° area. Space constraint in *GRL* encourages brevity, and therefore we reserve a more extensive presentation of data examples for an archival journal and will instead dwell now on the possible significance of this result.

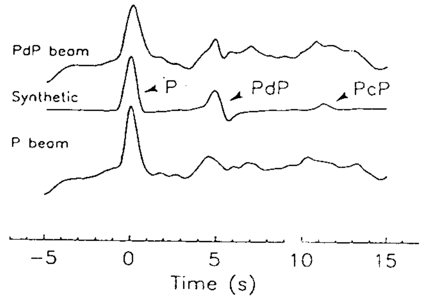

Fig. 4. Three displacement-proportional seismograms for event in Fig. 1. Top and bottom traces are data *PdP* beam and *P* beam respectively. Middle trace is a Gaussian beam synthetic [*Weber*, 1988] computed from model PWDK.

Interpretation

One of the three competing hypotheses for the creation of the *PdP* phase, that *PdP* is produced by the descending oceanic slab, may be ruled out immediately by the measured *PdP–P* slowness difference. When rays corresponding to *P*, *PdP*, and *PcP* are traced back from the observation point at GRF through the PREM or Jeffreys-Bullen earth models toward the Kuriles, the *P* and *PcP* rays cross at a point where the ISC places the source at 493 km depth, but the *PdP* ray does not pass within 1000 km of the hypocenter. Such a wide miss may not be attributed to source mislocation, and even if the slab penetrated here to depths greater than 1000 km as has been suggested [*Creager and Jordan*, 1984, 1986], the *PdP* ray would still not intersect the slab. It is possible to hypothesize a large velocity gradient beneath the slab which would redirect the *PdP* ray into the lower mantle, but this requires a second heterogeneity to deflect it upward again to GRF. We think it is unlikely that heterogeneities of the magnitude required would have remained so long undetected.

A second hypothesis, scattering of waves by small heterogenities in D″, predicts that wave energy will arrive along a distribution of azimuths centered on the great circle connecting GRF to the Kuriles. We consistently observe that *PdP* arrives exactly in the same direction as direct *P*, *i.e.* in the direction of the Kuriles, and the two waves have similar frequency-wavenumber (f-k) spectra. While scattering theory does allow for energy to arrive in this direction, and possibly at this slowness, it is unlikely that this should be so for the entire group of Kurile events whose locations fall over an area several hundred kilometers broad. One would expect to observe off-circle arrivals from scatterers located off the GRF-Kurile path. Furthermore, one would also expect scattering to broaden *PdP*'s f-k spectrum [*Doornbos*, 1988].

The hypothesis we prefer is that there is a 3% *P*-velocity discontinuity 293km above the CMB. Model PWDK [*Weber and Davis, submitted*, 1989], which incorporates these features, is based upon *PdP–P* and *PcP–PdP* differential travel times and predicts well the arrival time, slowness, and amplitude of *PdP*. One other point in favor of PWDK is the shape of the waveform it produces. Figure 4 shows the array *P*-beam (bottom trace) and *PdP*-beam (top trace) bracketing a synthetic seismogram (middle trace) computed for model PWDK using the Gaussian beam method [*Weber*, 1988]. All are proportional to broadband displacement. The arrivals of *P*, *PdP* and *PcP* are labeled on the synthetic trace. The *PdP* wavelet is very close to a pure Hilbert transform of *P* (without the contribution from rays bottoming just below the discontinuity, it would be). The wavelet visible in the *PdP*-beam resembles closely a Hilbert transform in shape and arrives exactly at the time predicted by PWDK.

Discussion

The models PWDK and QM2LME [*Baugardt*, 1989] differ in their placement of the D″ discontinuity by nearly 50 km. This may happen for at least two reasons. The exact arrival time of *PdP* buried in the *P*-coda can be difficult to read particularly when viewed through a WWSSN filter. An error of 0.7s in measurement is all that separates the two models. Given the broader bandwidth and better SNR that GRF array beams afford, we feel the arrival time of *PdP* can be read more accurately than with widely-spaced WWSSN stations.

On the other hand, both models may be correct descriptions of the lower mantle at different geographic points. The reflection points of *PdP* for the events considered by Baumgardt and us are separated by at least 50 km. The appearance of *PdP* at so few stations around the world could be explained if the discontinuity were not a global feature but rather local and within these localities varied a great deal laterally. The *PdP* reflection at the distances at which it has been observed is a post-critical reflection and as a consequence, *PdP*'s appearance on the seismogram is very sensitive to any inclination of the reflecting surface. Nevertheless, a change in depth of 50 km over 50 km horizontal distance is a considerable heterogeneity indeed.

Unfortunately, even with the observations recorded here, it is not yet possible to determine the kind of process which has produced the feature we believe is observed here. A thermal boundary layer is difficult to justify in view of the velocity increase. Another possibility is that this represents slab material subducted into the lower mantle [*Hofmann and White*, 1982]. *Silver et al.* [1989] suggest that 300 km may be an appropriate thickness for a layer of accumulated slab material near thermal equilibrium with its surroundings. Finally *Jordan and Creager* [1987] suggest chemical boundary layers may exist near the CMB.

Conclusions

By measuring the difference in slowness between direct *P* and an anomalous *P*-coda phase *PdP*, we conclude that the source of *PdP* must be the seismic velocity structure of the lower mantle. Causes such as earthquake source complexity, wave effects of the subducting slab, and reverberations within the crust beneath the GRF array may be eliminated on the basis of this observation. The velocity model which best fits the data incorporates a 3% *P*-velocity jump at 293km above the core-mantle boundary. The reflector is very likely of limited geographical extent given that the *PdP* is often unseen under favorable observing conditions. Undulations in the reflector or strong lateral variations in its depth may equally explain its frequent non-appearance. The presence of small inhomogeneities which act as scatterers remains a possible, but unlikely cause.

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