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Probing the core–mantle boundary beneath Europe and Western Eurasia: A detailed study using PcP

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SUMMARY

We use PcP (the core reflected P phase) recordings of deep earthquakes and nuclear explosions from the Gräfenberg (Germany) and NORSAR (Norway) arrays to investigate the core–mantle boundary region beneath Europe and western Eurasia. We find evidence for a previously unknown ultra-low velocity zone 600 km south-east of Moscow, located at the edge of a middle-size low shear- velocity region imaged in seismic tomography that is located beneath the Volga river region. The observed amplitude variations of PcP can be modelled by velocity reductions of P and S-waves of −5% and −15%, respectively, with a density increase of +15%. Travel time delays of pre-and postcursors are indicating a thickness of about 13 km for this ultra-low velocity region (ULVZ). However, our modelling also reveals highly ambiguous amplitude variations of PcP and a reflection off the top of the anomaly for various ULVZs and topography models. Accordingly, large velocity contrasts of up to −10% in V_P and −20% in V_S cannot be excluded. In general, the whole Volga river region shows a complex pattern of PcP amplitudes caused most likely by CMB undulations. Further PcP probes beneath Paris, Kiev and northern Italy indicate likely normal CMB conditions, whereas the samples below Finland and the Hungary–Slovakia border yield strongly amplified PcP signals suggesting strong CMB topography effects.

We evaluate the amplitude behaviour of PcP as a function of distance and several ULVZ models using the 1D reflectivity and the 2D Gauss beam method. The influence of the velocity and density perturbations is analysed as well as the anomaly thickness, the dominant period of the source wavelet and interface topographies. Strong variation of the PcP amplitude are obtained as a function of distance and of the impedance contrast. We also consider two types of topographies: undulations atop the CMB in the presence of flat ULVZs and vice versa. Where a broad range of CMB topography dimensions lead to large PcP amplitude variations, only large ULVZ undulations generate significant amplitude scattering. Consequently, this indicates that topography effects of anomalies may mask the true medium parameters as well as the ULVZ thickness. Moreover, there might be a possibility of misinterpreting the precursor as PcP, in particular for thin ULVZs.

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1. Introduction

The Earth's lowermost mantle, the D″ region (Bullen, 1949), exhibits seismic structures that span a large range of different length scales. Observations range from very large regions with reduced P- and S-wave velocities beneath Africa and the Pacific (see e.g. Wen et al., 2001; Ritsema et al., 2011; Tackley, 2012 for a recent review) to small-scale scatterers of only a few kilometres size (e.g. Cleary and Haddon, 1972; Hedlin et al., 1997; Wen, 2000; Niu and Wen, 2001; Earle et al., 2011; Mancinelli and Shearer, 2013). Other features include discontinuities near the core–mantle boundary (CMB) with P- and S-wave jumps of a few percent, i.e. the D″ discontinuity, (e.g. Lay and Helmberger, 1983; Weber, 1993; Wysession et al., 1998 for a review; Hernlund et al., 2005) or small-scale patches with strongly reduced velocities and increased densities known as ultra-low velocity zones (ULVZ) (initially described by Garnero and Helmberger, 1995, 1996). Locally dense network of instruments enables the probing of these different structures at the CMB in many regions.

During the past 20 years, several studies have described the presence and absence of the ULVZs (e.g. Revenaugh and Meyer, 1997; Thorne and Garnero, 2004; summarized in McNamara et al., 2010). These studies utilise different seismic probes such

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as waves diffracted around the core, i.e. $SP_{diff}KS$ and $SKP_{diff}S$ (e.g. Garnero and Helmberger, 1995; Thorne and Garnero, 2004), diffracted and scattered arrivals of the core phase PKP (e.g. Wen and Helmberger, 1998b; Thomas et al., 2009) or waves reflecting at the core, e.g. ScP (e.g. Rost and Revenaugh, 2003; Rost et al., 2006). Waveforms of the standard core reflected phases show additional complications caused by discrete ULVZs that give rise to pre- and postcursors of the main wave, which have been examined by e.g. Garnero and Vidale (1999), Reasoner and Revenaugh (2000) and Rost et al. (2006).

Aside from the S-to-P reflections at the CMB (ScP), short-period PcP signals provide a good vertical resolution for thin velocity anomalies, even if analyses are complicated by the low reflection coefficient, particularly for very close source-receiver distances. Initial work on PcP reflection coefficients has been conducted by Buchbinder (1968) and Ibrahim (1971), while beamforming processes and PcP/P amplitude ratios have been determined by Chowdhury and Frasier (1973) and Frasier and Chowdhury (1974). ULVZ studies using PcP phases mainly focus on the Pacific region (e.g. Mori and Helmberger, 1995; Hutko et al., 2009; Rost and Thomas, 2010). Instead of earthquakes, some studies utilised nuclear explosions sampling parts of Siberia (Krüger et al., 1993; Krüger et al., 1995; Thybo et al., 2003; Ross et al., 2004) in regions that are otherwise not accessible. Combining results of these and other studies, McNamara et al. (2010) suggest that ULVZs seem to occur preferably at the edges of large low shear velocities provinces (LLSVPs, e.g. Su et al., 1994), while Williams et al. (1998) show that they might be related to the bases of mantle upwelling locations.

Other deep mantle features such as a thin transition zone (core–mantle transition zone – CMTZ) just above the CMB rather than a true discontinuity have been assumed by Kanamori (1967) and Buchbinder and Poupinet (1973) and could produce additional waveform complexity. Further studies by e.g. Vidale and Benz (1992), Garnero and Jeanloz (2000) and Thorne and Garnero (2004) have discussed such a small-scale CMTZ with thicknesses of less than 4 km as an alternative to ULVZs. Another structure at the CMB, the so-called core rigidity zones (CRZ, Garnero and Jeanloz, 2000) affect only the outermost core boundary but might also give rise to strongly reduced P- and S-wave velocities and related pre-and postcursors to waves such as PcP and ScP (e.g. Buffett et al., 2000; Garnero and Jeanloz, 2000).

ULVZs have often been explained either by iron alloy infiltrations from the core (e.g. Knittle and Jeanloz, 1991; Kanda and Stevenson, 2006; Otsuka and Karato, 2012) or by a residual Fe-enriched mantle material as a final result of an evolved basal magma ocean (BMO) (Wen et al., 2001; Labrosse et al., 2007; Nomura et al., 2011). The amount of partial melt as well as the melt geometry are still under debate (Williams and Garnero, 1996; Wimert and Hier-Majumder, 2012), where even Fe-enriched solid layers may create ULVZs (Wicks et al., 2010; Andrault et al., 2012; Tackley, 2012).

Williams and Garnero (1996) have provided first implications for seismic velocities in the presence of partial melts. They have assumed maximum P- and S-wave contrasts of −15% and −45%, respectively, for melt fraction up to 35%. They also point out that ULVZs should not exceed a thickness of a few 10s of kilometres. Following this, other studies (e.g. Jacobsen et al., 2002; Mao et al., 2006) have investigated the range of velocity reductions by varying chemical compositions including additional iron. Whereas these above mentioned studies are in agreement with Williams and Garnero (1996), Mao et al. (2011) have recently found evidence for much lower velocity reductions and lower density increases.

Our study involves the probing of the CMB below Europe and western Eurasia using PcP amplitudes and waveforms of earthquakes and nuclear explosions. The less extensive coverage of PcP reflection points across Europe, compared to the Pacific region, restricted our study to only a few areas. We carry out a detailed theoretical amplitude study as a function of the source distance (<50°) and different ULVZ models. Here, we show both 1D and 2D synthetic surveys to test cases of different topography of the CMB in the presence of flat ULVZs and topography of the ULVZ itself. Finally, we discuss our findings in relation to P- and S-wave tomography studies as well as CMB topography maps.

2. Methods

Seismic recordings by two different arrays are analysed with array techniques, especially beamforming and vespagrams (e.g. Rost and Thomas, 2002) to enhance weak signals such as PcP at short distances. The instrument response is removed from all individual stations and we measure amplitude ratios of P and PcP in the respective stacked beam traces. All PcP/P amplitude ratios resultant from earthquake data were normalized by the radiation pattern obtained from the Global Centroid Moment Tensor Catalogue (CMT) (e.g. Dziewonski et al., 1981). We compare them to the focal mechanisms by Zhu et al. (1997) for deep Hindu Kush and Tajikistan earthquakes and find good agreement. Nevertheless, strike, dip and rake variations of up to 10° may cause PcP/P amplitude distortions of up to ~20% (Rost and Revenaugh, 2004).

The PcP reflection coefficient is changing considerably within the distance range (Fig. 1a). At about 60° distance the maximum reflection coefficient is reached corresponding to an incidence angle of 65° at the CMB. Comparing different Earth models, we find that differences in PcP amplitudes are negligible (Fig. 1a).

We measure the amplitude ratios of $\frac{\mathrm{PcP}^{d/m}}{\mathrm{P}^{d/m}}$ and $\frac{\frac{\mathrm{PcP}^{d/m}}{\mathrm{P}^{d/m}}}{\frac{\mathrm{PcP}^{ref}}{\mathrm{P}^{ref}}}$, where d and m refer to data and model, respectively. The latter double scaling normalizes the modified (d or m) PcP/P ratios by the ak135 (Kennett et al., 1995) reference values. Both single and double scaled ratios give the same relative change in PcP amplitude compared with P as function of distance. By way of illustration we provide the double scaling since PcP/P values are very small for near distances due to the characteristics of the PcP reflection coefficient (Fig. 1a). Such a normalization reduces the effect of shallow structure at both the source and the receiver site. However, the upper mantle discontinuities might still have a small effect (e.g. Rost and Weber, 2002; Bai and Ritsema, 2013).

Our theoretical study consists of two different approaches to calculate synthetic seismograms: (i) using the well-established one-dimensional full-wavefield reflectivity method (Fuchs and Müller, 1971; Müller, 1985) and (ii) using the two-dimensional Gauss beam method (GBM, Weber, 1988) and the corresponding program Xgbm (Davis and Henson, 1993) allowing for undulating heterogeneities in the lowermost mantle. This advanced ray tracing technique provides, along with the possibility of laterally varying heterogeneities, the selection of single phases such as P and PcP without the related conversions and other phases that would interact with PcP. Non-standard phases such as the pre- and postcursors of PcP can be created through internal reflections, which represent the most important aspect of the GBM modelling approach. It should be noted that the GBM method is limited by its high-frequency approach, where media rapidly varying over one wavelength cannot be modelled, but is appropriate for the models used here.

In both modelling methods, we use 1 Hz wavelets (corresponding to the dominant frequency observed for PcP in nuclear explosion waveforms), radiated from an explosive point source at 130 km depth. This source depth avoids crustal reverberations

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