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Fine-scale structure of the mid-mantle characterised by global stacks of PP precursors

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ABSTRACT

Subduction zones are likely a major source of compositional heterogeneities in the mantle, which may preserve a record of the subduction history and mantle convection processes. The fine-scale structure associated with mantle heterogeneities can be studied using the scattered seismic wavefield that arrives as coda to or as energy preceding many body wave arrivals. In this study we analyse precursors to PP by creating stacks recorded at globally distributed stations. We create stacks aligned on the PP arrival in 5° distance bins (with range 70–120°) from 600 earthquakes recorded at 193 stations stacking a total of 7320 seismic records. As the energy trailing the direct P arrival, the P coda, interferes with the PP precursors, we suppress the P coda by subtracting a best fitting exponential curve to this energy. The resultant stacks show that PP precursors related to scattering from heterogeneities in the mantle are present for all distances. Lateral variations are explored by producing two regional stacks across the Atlantic and Pacific hemispheres, but we find only negligible differences in the precursory signature between these two regions. The similarity of these two regions suggests that well mixed subducted material can survive at upper and mid-mantle depth. To describe the scattered wavefield in the mantle, we compare the global stacks to synthetic seismograms generated using a Monte Carlo phonon scattering technique. We propose a best-fitting layered heterogeneity model, BRT2017, characterised by a three layer mantle with a background heterogeneity strength ($\epsilon = 0.8\%$) and a depth-interval of increased heterogeneity strength ($\epsilon = 1\%$) between 1000 km and 1800 km. The scalelength of heterogeneity is found to be 8 km throughout the mantle. Since mantle heterogeneity of 8 km scale may be linked to subducted oceanic crust, the detection of increased heterogeneity at mid-mantle depths could be associated with stalled slabs due to increases in viscosity, supporting recent observations of mantle viscosity increases due to the iron spin transition at depths of ∼1000 km.

1. Introduction

Mantle convection is the process that drives the interaction of tectonic plates and recycles oceanic lithosphere introduced into the mantle at subduction zones. Most of our knowledge of the present day convective system comes from seismic tomography (e.g. Ritsema et al., 2011; Van der Hilst et al., 1997), which inverts for seismic travel times and waveforms, and has revealed large seismic velocity variations at both the upper and lower mantle boundaries. In particular, tomographic studies have imaged fast velocity features associated with subducted slabs, some of which are continuous from the surface to the core–mantle boundary (CMB) (e.g. Van der Hilst et al., 1997). Such deep subduction is evidence for the whole mantle interacting in one convective system rather than in separate multi-layered cells. In contrast, some studies have also imaged flat lying fast velocity features in the transition zone and mid-mantle (e.g. Sigloch and Mihalynuk, 2013), suggesting there may be some barriers to these downwellings such as an increase in viscosity just below the transition zone (e.g. Forte and Mitrovica, 2001) or as deep as 2000 km (Justo et al., 2015) due to the iron spin transition.

Subducted slabs partly consist of basaltic crust, which has a different composition to that of mantle peridotite. The crust deforms slowly over time in reaction to convection related stresses (Stixrude and Lithgow-Bertelloni, 2012) leading to long-lived heterogeneity that preserves the path taken by subduction. These heterogeneities have scale lengths on the order of ∼10 km and are below the current resolution levels of global tomography models (>100 km). Thus other seismic methods, such as analysis of the high frequency scattered seismic wavefield (Sato and Fehler, 1998),

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have to be employed to map these heterogeneities and analyse their properties (e.g. Rost et al., 2006). Since subducting plates are sensitive to barriers to flow, we may expect higher density of heterogeneities at boundaries of convection cells. These barriers might only influence thermal convection and the uniformity of mixing, and therefore may not be obvious in tomographic images. To provide additional temporal constraints on subduction processes, the crustal component of slabs can be traced using seismic scattering approaches.

Most previous seismic scattering studies have tried to characterise heterogeneity in the deep or whole mantle and different, often contradicting, distributions of heterogeneity in the mantle have been suggested. Some evidence has been put forth in support of heterogeneities distributed evenly throughout the mantle (Earle and Shearer, 2001; Hedlin et al., 1997; Hedlin and Shearer, 2000; Mancinelli and Shearer, 2013; Margerin and Nolet, 2003a; Shearer and Earle, 2004). In contrast, models with radially varying heterogeneity have also been proposed. Many of the models prefer strong heterogeneities concentrated in the lowermost mantle (Bataille and Flatté, 1988; Cleary and Haddon, 1972; Doornbos, 1978; Niu and Wen, 2001; Tono and Yomogida, 1996) but others suggest a reduction in heterogeneity in the lowermost mantle is necessary (Shearer and Earle, 2004). Furthermore, Hedlin and Shearer (2000) found that models are not well constrained and multiple models can explain the same data. The lack of agreement may result from modelling the whole mantle simultaneously without independent constraints on the upper and mid-mantle heterogeneity structure.

In this study we use precursors to the PP arrival to characterise global averages of heterogeneity since we feel PP precursors provide unique insight into mid-mantle structure that cannot be achieved with other seismic probes (e.g. Bentham and Rost, 2014; Rost et al., 2008; Shearer and Flanagan, 1999). We create global and regional seismic stacks and build on the modelling procedure established by Shearer and Earle (2004) by quantifying the model misfit and systematically searching for the best fitting heterogeneity model. We consider models with constant heterogeneity in the mantle and also increase model complexity by varying heterogeneity with depth to gain insight into the resultant effect of different scattering distributions on the PP precursory wavefield.

We characterise heterogeneity from the lithosphere to the mid-mantle using global signatures of the high frequency PP precursory wavefield. Through stacking of a large global dataset we identify radial changes in heterogeneities, and established whether lateral variations of heterogeneities exist through grouping data into two hemispheres. The heterogeneity structure in the lithosphere and mantle is characterised through forward modelling of the scattered wavefield using a 1D Monte Carlo phonon method (Shearer and Earle, 2004) and the resulting synthetic envelopes are compared to the observed global stacks. The PP precursory wavefield is analysed and modelled for a range of distances, attempting to resolve the depth dependence of the scattering giving rise to the precursory energy. We generate more than 150 models of radial scattering heterogeneity and show that the heterogeneity parameters can be constrained when systematically varied. To limit the size of the parameter space examined in the forward modelling we only explore contributions from four different lithospheric layers within a fixed thickness of 100 km. Additionally, we focus on the contribution from the mantle by considering radial variations in scattering scale length and Root Mean Square (RMS) velocity perturbations, and find the best fitting model overall has depth varying velocity perturbation.

2. Global stacking of PP

2.1. Data

We create stacks of the seismic wavefield recorded by 193 seismometers (Fig. 1). Most of the stations used are part of the Global Seismic Network (GSN) (Albuquerque Seismological Laboratory (ASL)/USGS, 1988; Scripps Institution of Oceanography, 1986) with supplementary stations from the USArray Transportable Array (TA) (IRIS Transportable Array, 2003); Canadian National network (CN), POLARIS network (POL) and Canadian Northwest Experiment (XN) added to improve coverage. These networks are selected due to their appropriate distance range from regions of high earthquake activity. Vertical broadband data for 600 earthquakes (Fig. 1) are obtained from the Incorporated Research Institutions for Seismology (IRIS) database. Earthquakes are selected from 2003 to 2012 with depths from 0 to 100 km, magnitudes (Mw) larger than 5.8, and epicentral distance between source and station from 70° to 120°. The chosen distance range extends the range used in previous studies of scattered PP precursors (Bentham and Rost, 2014; Rost et al., 2008; Wright, 1972). The extended distance range analysed in this work allows us to detect heterogeneities within a larger depth range of the mantle. For an epicentral distance of 70°, PP turns at about 850 km depth and for 120° PP turns at 1550 km depth (see Suppl. Material, Fig. S1) allowing good sampling of the uppermost lower and mid-mantle. Therefore variations in the character of PP in stacks across this distance range should be linked to properties of the mantle between 850 km and 1550 km. Furthermore PP precursors arrive with slowness similar to the PP arrival (Rost et al., 2006), it is likely that the precursors travel to similar depths as PP (see Suppl. Material, Fig. S1). However some scattered arrivals may have scattered multiple times (Shearer, 2007) and/or have travelled out of the great circle plane, thus travelling with deeper or shallower depths than PP.

2.2. Pre-processing

Data are re-sampled to 100 samples per second and filtered using a two way bandpass filter with corner frequencies at 0.5 Hz and 2.5 Hz. This frequency band is chosen as it is sensitive to the small-scale (10 km) spatial wavelengths in lower mantle (Shearer and Earle, 2004) and beneficially, the high frequency noise is removed. The envelope time function of each trace is calculated to obtain phase independent amplitudes for stacking. The stacking of noise can be reduced by ensuring the mean of the noise is zero. An estimate of the mean noise level is found using pre-signal noise calculated from 60 s to 35 s before P (or P_{diff}), and this level is then subtracted from the complete time series before stacking.

We chose to pick observed PP traveltime as the absolute maximum amplitude of the PP waveform using theoretical times as calculated through IASP91 (Kennett and Engdahl, 1991) as a guide. The signal to noise ratio (SNR) of PP amplitude to the amplitude of the noise before P (or P_{diff}) is calculated and traces with SNR less than 5 are removed. The data are organised into 5° distance bins, centred at 72.5°, 77.5°, 82.5°, 87.5°, 92.5°, 97.5°, 102.5°, 107.5°, 112.5° and 117.5°.

2.3. Stacking of PP

Data are aligned on PP and stacked (summed) within each distance bin, normalised by the number of traces and the absolute amplitude of PP (Fig. 2). The number of traces in each distance bin generally decreases with distance, ranging from a minimum of ~500 traces for 117.5° to a maximum of >1000 traces for 72.5° (Fig. 2). The final stacked dataset provides good global coverage