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Dynamical links between small- and large-scale mantle heterogeneity: Seismological evidence

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ABSTRACT

We identify PKP•PKP scattered waves (also known as P′•P′) from earthquakes recorded at small-aperture seismic arrays at distances less than 65°. P′•P′ energy travels as a PKP wave through the core, up into the mantle, then scatters back down through the core to the receiver as a second PKP. P′•P′ waves are unique in that they allow scattering heterogeneities throughout the mantle to be imaged. We use array-processing methods to amplify low amplitude, coherent scattered energy signals and resolve their incoming direction. We deterministically map scattering heterogeneity locations from the core–mantle boundary to the surface. We use an extensive dataset with sensitivity to a large volume of the mantle and a location method allowing us to resolve and map more heterogeneities than have previously been possible, representing a significant increase in our understanding of small-scale structure within the mantle. Our results demonstrate that the distribution of scattering heterogeneities varies both radially and laterally. Scattering is most abundant in the uppermost and lowermost mantle, and a minimum in the mid-mantle, resembling the radial distribution of tomographically derived whole-mantle velocity heterogeneity. We investigate the spatial correlation of scattering heterogeneities with large-scale tomographic velocities, lateral velocity gradients, the locations of deep-seated hotspots and subducted slabs. In the lowermost 1500 km of the mantle, small-scale heterogeneities correlate with regions of low seismic velocity, high lateral seismic gradient, and proximity to hotspots. In the upper 1000 km of the mantle there is no significant correlation between scattering heterogeneity location and subducted slabs. Between 600 and 900 km depth, scattering heterogeneities are more common in the regions most remote from slabs, and close to hotspots. Scattering heterogeneities show an affinity for regions close to slabs within the upper 200 km of the mantle. The similarity between the distribution of large-scale and small-scale mantle structures suggests a dynamic connection across scales, whereby mantle heterogeneities of all sizes may be directed in similar ways by large-scale convective currents.

1. Introduction

The high frequency (∼1 Hz) seismic wavefield provides evidence of kilometre scale structure within the Earth (Cleary and Haddon, 1972). Seismic energy that is not explained by wave propagation in smoothly varying velocity models of the Earth has been attributed to reflections and scattering from sharply contrasting volumetric heterogeneities and roughness on interfaces (Chang and Cleary, 1981). The interaction of the wavefield with discrete, small-scale variations in elastic properties and/or density can divert seismic energy onto new paths, often generating precursors or postcursors (coda) to the main seismic phases that travel in the great circle plane. The size of the scatterers that can be imaged is dependent upon the wavelength that is analysed; for the teleseismic high-frequency P-wavefield above 1 Hz they are typically on the order of 1 to 10 km.

Global imaging of Earth's small-scale heterogeneities is difficult due to the uneven distribution of earthquake sources and seismic receivers, and the low amplitude of the scattered signals involved. Scattering can be studied using single stations, but with this approach the location of the scattering heterogeneity can be ambiguous (Wen, 2000). Alternatively, seismic arrays, i.e., 3 or more closely located sensors, can resolve the incoming direction of scattered waves, thus it is possible to deterministically locate heterogeneities (Thomas et al., 1999; Rost and Earle, 2010; Frost et al., 2013). In the last few decades a number of studies have

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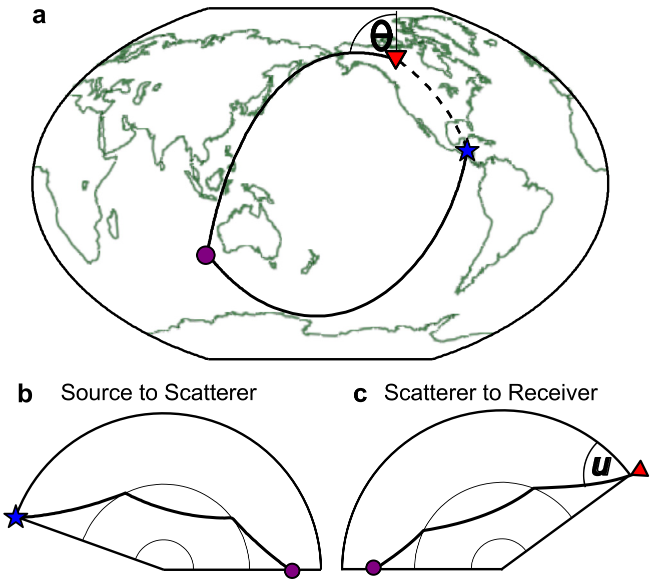

Fig. 1. PKP•PKP (P′•P′) example path. **(a)** A P′•P′ path from the source (star) to a scattering point in the mantle (circle) and then to the receiver (triangle). P′•P′ travels along two great-circle paths (solid lines) to and from the scattering point, off the great-circle path between the source and receiver (dashed line). PKP ray paths from **(b)** source to scatterer (PKP$_{\mathrm{ab}}$) and **(c)** scatterer to receiver (PKP$_{\mathrm{bc}}$). The two PKP legs may be symmetric or asymmetric (as in this case) and can scatter from any depth in the mantle from the CMB to the surface. Rays observed at the surface arrive from a specific direction known as the back-azimuth, θ, measured relative to North, or the relative back-azimuth measured from the GCP, and from a vertical incidence angle, referred to as the slowness, u.

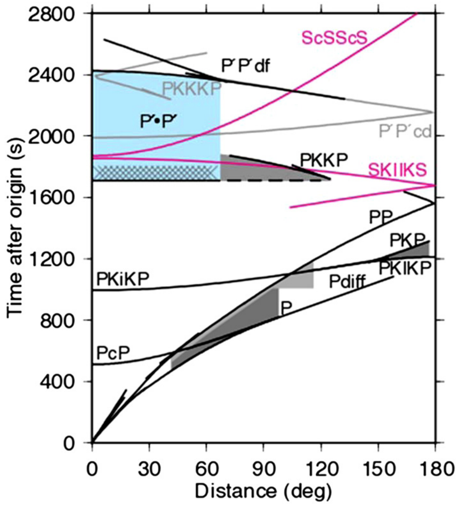

Fig. 2. Travel-time curve displaying P′•P′ and other scattered phases in the high-frequency seismic wavefield. Black lines mark major P-wave phases. The blue region marks the time and distance region investigated for P′•P′ waves in this study. Hatched region marks time and distance region investigated for PK•KP in Frost et al. (2017). Grey and pink lines mark the P- and S-waves, respectively, that may contaminate the P′•P′ study region. Other P- and S-waves are not shown for clarity. Differently shaded grey regions denote time and distance regions previously investigated for other scattered waves. Adapted from Rost et al. (2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

started to unravel the distribution of small-scale heterogeneities of Earth's mantle. Hedlin et al. (1997), and later Mancinelli and Shearer (2013) studied the depth distribution of heterogeneity within the mantle through analysis of PKP pre- and postcursors recorded at single stations. Using a stochastic Rayleigh–Born scattering approach, Mancinelli and Shearer (2013) developed a global model of scattering heterogeneity containing 0.1% root-mean-square velocity variations in the deepest 1200 km of the mantle with heterogeneity scale sizes ranging from 2 to 30 km.

This work is complemented by studies that deterministically map small-scale scattering heterogeneity within the upper and lower mantle. These studies have noted lateral variations in heterogeneity distribution, as well as variations in amplitudes of scattered waves. Scattered P-to-P (P•P, where the "•" represents the location of scattering) and P-to-S (P•S) waves are sensitive to heterogeneities in the upper half of Earth's mantle; they have been used to map scattering heterogeneity in regions influenced by recent subduction (Kaneshima and Helffrich, 1998; Bentham and Rost, 2014). Scattering in the lowermost mantle has also been observed to vary laterally (Waszek et al., 2015). Strong scattering has been observed in regions beneath mantle hotspots (Wen, 2000), near small, regional ultra-low velocity zone (ULVZ) structures (Yao and Wen, 2014), beneath subduction zones (Miller and Niu, 2008), and near the edges of LLSVPs (Frost et al., 2013). A near-global study of PK•KP – a PKP wave that is back-scattered in the lower mantle onto a second PKP path – suggests a spatial correlation between scattering and LLSVP edges in the lowermost 300 km of the mantle (Rost and Earle, 2010; Frost et al., 2017).

The volume of the mantle that can be investigated for scattering heterogeneity is controlled by the specifics of the seismic probe. PK•KP can be used to investigate the lower mantle close to the CMB (Chang and Cleary, 1981; Rost and Earle, 2010; Frost et al., 2017). The direct wave PKPPKP (also called P′P′) results from a PKP wave (P′) reflecting from the underside of the surface, back into the Earth as a second PKP wave, along the great-circle path (GCP). This phase can be preceded by scattered energy called PKP•PKP (P′•P′), caused by back-scattering of PKP at any depth in the mantle (Rost et al., 2015). Like PK•KP, P′•P′ has an unusual scattering geometry (Fig. 1) and can scatter from locations off the GCP, and the P′ segments need not be symmetric to each other. P′•P′ is the continuation of PK•KP towards the surface, thus this phase is able to sample the whole mantle from CMB to crust (Fig. 2). We extend our earlier work and investigate the mantle upwards from the CMB to the surface to deterministically map the vertical and lateral distribution of scattering heterogeneities throughout the mantle. In contrast to other scattering probes, the unusual (and versatile) raypath geometry of P′•P′ allows the study of previously unsampled regions of the Earth.

The internal structure of the Earth and the nature of mantle convection are inherently connected across scales (e.g. Tackley, 2015). The distribution of large-scale mantle structure as imaged by seismic tomography has been investigated using thermo-chemical geodynamic models, which indicate that downwelling of cold, dense slabs at subduction zones moves and shapes the hot, convecting piles of seismically slow material at the CMB, forming the Large Low Shear Velocity Provinces (LLSVPs) (McNamara and Zhong, 2005; Li et al., 2014; Domeier et al., 2016). The LLSVPs, if compositionally distinct, may modulate mantle dynamics through thermal instabilities that result in mantle plumes that rise up causing hotspot volcanism (Thorne et al., 2004; French and Romanowicz, 2015). Furthermore, calculations suggest that mantle plumes may be spatially correlated with the LLSVPs (Thorne et al., 2004; Doubrovine et al., 2016). Geodynamic modelling of thermo-chemical structures in the deep mantle indicates that small-scale heterogeneities (as small as kilometre-sized) can be passively transported in the large-scale flow (Brandenburg and van Keken, 2007; Li et al., 2014; Mulyukova et al., 2015). Furthermore, geochemical analysis of intraplate volcanism suggests that heterogeneities situated in the deep Earth may be transported to the surface by entrainment in mantle convection (Williams et al., 2015). Therefore, there is compelling evidence that the distribu-