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Seismic evidence for Earth's crusty deep mantle

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ABSTRACT

Seismic tomography resolves anomalies interpreted as oceanic lithosphere subducted deep into Earth's lower mantle. However, the fate of the compositionally distinct oceanic crust that is part of the lithosphere is poorly constrained but provides important constraints on mixing processes and the recycling process in the deep Earth. We present high-resolution seismic array analyses of anomalous P-waves sampling the deep mantle, and deterministically locate heterogeneities in the lowermost 300 km of the mantle. Spectral analysis indicates that the dominant scale length of the heterogeneity is 4 to 7 km. The heterogeneity distribution varies laterally and radially and heterogeneities are more abundant near the margins of the lowermost mantle Large Low Velocity Provinces (LLVPs), consistent with mantle convection simulations that show elevated accumulations of deeply advected crustal material near the boundaries of thermo-chemical piles. The size and distribution of the observed heterogeneities is consistent with that expected for subducted oceanic crust. These results thus suggest the deep mantle contains an imprint of continued subduction of oceanic crust, stirred by mantle convection and modulated by long lasting thermo-chemical structures. The preferred location of the heterogeneity in the lowermost mantle is consistent with a thermo-chemical origin of the LLVPs. Our observations relate to the mixing behaviour of small length-scale heterogeneity in the deep Earth and indicate that compositional heterogeneities from the subduction process can survive for extended times in the lowermost mantle.

1. Introduction

Seismological analyses reveal heterogeneities in Earth's mantle from the surface to the core–mantle boundary (CMB) spanning a wide range of scales. In the upper mantle, seismic tomography shows oceanic lithosphere, on the order of 100s km thick, subducting into the Earth (Grand et al., 1997). The oceanic crust component of the lithosphere is subducted into the mantle at a rate of ∼20 km^3 per year at present-day (Li et al., 2016). The crust has been modelled to advect into the lower mantle (Christensen and Hofmann, 1994), and may represent up to 10% of the mass of the mantle from subduction through Earth's history (Hofmann and White, 1982). Geochemical anomalies in ocean island basalts sourced from the deep Earth suggest that oceanic crust is incompletely mixed into the mantle (Stracke et al., 2003). Meanwhile, tomographic images of the lowermost mantle are dominated by two large, 1000s km scale-length, nearly equatorial and antipodal, structures of reduced seismic velocities (e.g. Dziewonski, 1984), both in S- and P-wave velocity (Vs and Vp, respectively); these are surrounded by zones of higher seismic velocities, which are commonly attributed to cooler subduction-related downwellings. The nature and origin of these LLVPs remains enigmatic but may be related to dense thermo-chemical piles (Garnero and McNamara, 2008) possibly consisting of primordial material (Labrosse et al., 2007), products of chemical reactions with the outer core (Knittle and Jeanloz, 1991), or accumulation of subducted oceanic crust (Christensen and Hofmann, 1994). A purely thermal origin of LLVPs has also been advocated (Davies et al., 2015). Geodynamic models indicate that subduction-related currents shape the thermo-chemical structures into piles that internally convect (McNamara and Zhong, 2005).

Significantly smaller scale heterogeneity has been inferred from high-frequency (∼1 Hz) seismic energy trailing (coda) or preceding (precursors) some seismic waves (Shearer, 2007), due to scattering from volumetric heterogeneities with scales similar to the dominant seismic wavelength (Cleary and Haddon, 1972) (e.g. of order 10 km in the lowermost mantle for 1 Hz waves). While seismic probes differ in their sensitivities to the scale and depth of scattering heterogeneity, scattered waves help to characterise fine scale

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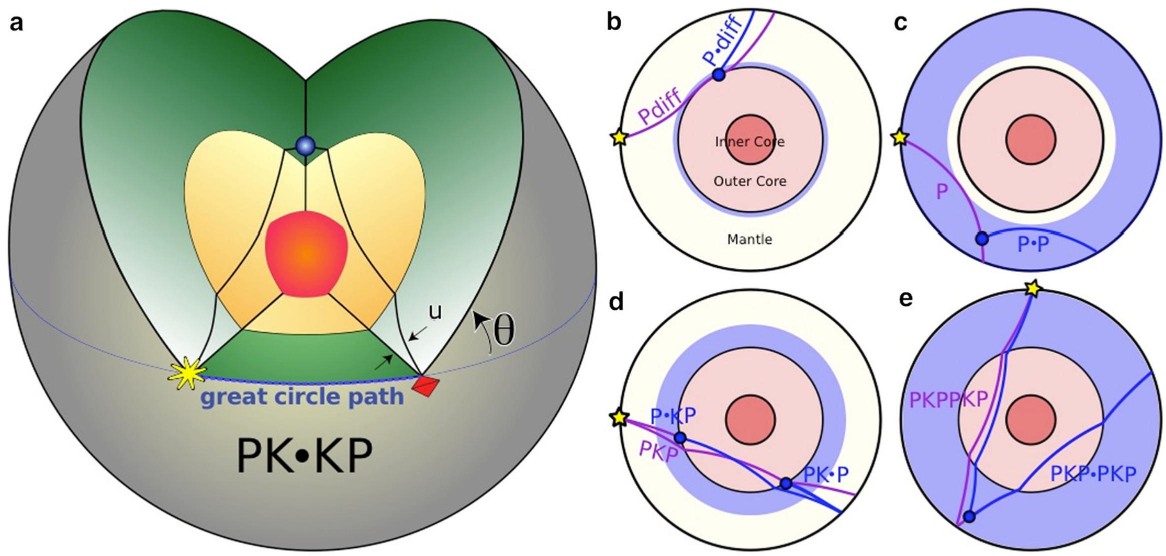

Fig. 1. Raypaths of direct and scattered waves used to map small-scale mantle heterogeneity. (**a**) PK•KP path from an earthquake (star) to a scattering heterogeneity at or near the CMB (blue dot), and to the array (pyramid). The scattered wave travels out of the great-circle path. Other scattered waves used to study mantle structure include (**b**) P_{diff}: a P-wave diffracted along the core–mantle boundary (CMB) and back up to the surface. The wave can be scattered at some distance along the diffracted portion, denoted $P•_{diff}$. Direct and scattered paths (purple and blue lines, respectively), and example scattering location (blue circle) are shown along with the depth range (blue shaded region) that can be studied with this probe. (**c**) P: a direct P-wave, which can be scattered some depth, indicated by •, to another P wave (or S wave, then called P•S) which travels back to the surface, (**d**) PKP: a P-wave which travels through the mantle, outer core, and back up to through the mantle the surface. This wave can be scattered within the mantle, the location of which is indicated by •, either before the wave enters the outer core (P•KP), or as the wave exits the outer core (PK•P), (**e**) PKPPKP: a wave which travels down through the mantle and outer core, up through the mantle and reflects off the underside of the CMB, and returns down through the mantle and up through the outer core and mantle to the surface. A similar wave can be scattered back down through the mantle on the antipodal side and back up to the surface, which can be written as PKP•PKP. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mantle heterogeneity (Shearer, 2007). The radial dependence of scattering has been investigated with PKP waves (P waves that go through Earth's core), which indicate the presence of weak (e,g., Vp perturbations, dVp, of 0.1% RMS), small-scale (6–8 km) heterogeneity distributed throughout the mantle (Mancinelli and Shearer, 2013). These studies present global, radially averaged statistically viable scattering populations but are not able to deterministically locate scattering heterogeneities. Upper mantle regional studies of scattered PP and SS waves (Fig. 1), have deterministically mapped scatterers in subduction zones in the upper and mid-mantle, relating the heterogeneities to subduction processes (Kaneshima and Helffrich, 1998). Lower mantle regional studies using PKP have demonstrated regional deep mantle scattering (Frost et al., 2013; Ma et al., 2016) with strong lateral variations. These lowermost mantle heterogeneities have been attributed to a variety of processes including subduction, plumes, melt processes, and phase transitions. Regional geodynamic models of the upper mantle have demonstrated the role of large-scale convection in generating and manipulating heterogeneity across length-scales (e.g. Korenaga, 2004). While scattering scale-lengths have been previously inferred, the data used are typically band-limited or filtered to high frequency, thereby restricting the constraint on the range of scale lengths that can be deduced. Here we present a seismic probe and method for precise location of scattering heterogeneities near the CMB and simultaneous determination of their dominant scale lengths over a wide spectrum of possibilities.

We use a scattered form of PKKP which first propagates as a P-wave through the mantle, into the core, and back up to the lower mantle (as a normal PKP wave), and then is scattered in the lowermost mantle depth shell back into the core, and then travels through the mantle to the receiver (Rost and Earle, 2010). We refer to this scattered path as PK•KP, where the dot "•" represents the small portion of the path travelled as P-wave from the CMB up into the lower mantle to the scattering location, then back to the CMB. PK•KP may involve out-of-great circle plane scattering and travel along asymmetric source and receiver paths (Fig. 1).

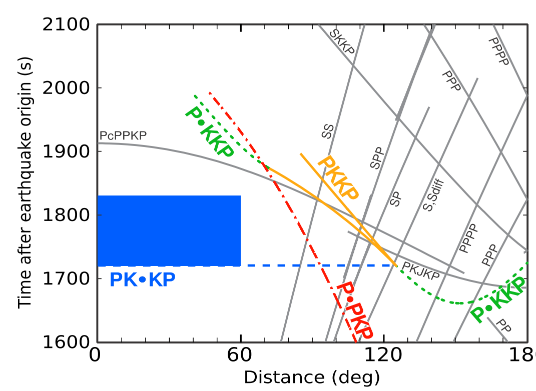

Fig. 2. Travel–time curves of PK•KP and related scattered waves. In the study we use data with source–receiver distances between 0 and 60 degrees and from the first theoretically viable arrival of PK•KP to 110 s after (blue box). Times of other variants of the PKKP path (coloured lines) are also shown (See Earle, 2002 for discussion of other scattered phases). Times of non-scattered waves are shown as grey lines. The blue dashed line depicts PK•KP times at larger distances, which are not used here due to interference with other arrivals. All travel time curves are calculated using IASP91 (Kennett and Engdahl, 1991) and a surface focus earthquake. Figure after Earle (2002). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This probe is especially suited for studying lower mantle heterogeneities because PK•KP arrives in a quiet time-distance window for teleseismic data (Fig. 2), it avoids the source-receiver CMB location ambiguity of PKP scattering (Fig. 1d), it allows deterministic identification of the heterogeneity location, and it allows sampling of an extensive volume of the Earth's mantle (Fig. 3).

2. Data and array-processing methods

While past work introduced the feasibility of this phase for deep mantle heterogeneity detection, analysis was limited geographically and in depth (Rost and Earle, 2010). We collect earthquakes with magnitudes larger than 6.0 occurring in a 17-year period (1995–2012) within 0-to-60° epicentral distance from 13