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Topography of upper mantle seismic discontinuities beneath the North Atlantic: The Azores, Canary and Cape Verde plumes

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ABSTRACT

We are mapping the topography of upper mantle seismic discontinuities beneath the North Atlantic and surrounding regions by using precursor arrivals to PP and SS seismic waves that reflect off the seismic discontinuities. Numerous source–receiver combinations have been used in order to collect a large dataset of reflection points beneath our investigation area. We analysed over 1700 seismograms from $M_W > 5.8$ events using array seismic methods to enhance the signal to noise ratio. The measured time lag between PP (SS) arrivals and their corresponding precursors on robust stacks are used to measure the depth of the transition zone boundaries. The reflectors' depths show a correlation between the location of known hotspots and a significantly depressed 410 km discontinuity indicating a temperature increase of 50–300 K compared to the surrounding mantle. For the 660 km discontinuity three distinct behaviours are visible: (i) normal depths beneath Greenland and at a distance of a few hundred kilometres away from known hotspots, (ii) shallower 660 km discontinuity compared with the global average value near hotspots closer to the Mid-Atlantic Ridge, and (iii) very few observations of a 660 km discontinuity at the hotspot locations. We interpret our observations as a large upwelling beneath the southern parts of our study region, possibly due to the South Atlantic convection cell. The thermal anomaly may be ponding beneath the endothermic 660 km phase transformation and likely does not extend through the top of the transition zone as a whole, except for those branches which appear as the thinner upwellings of Azores, Canaries and Cape Verde hotspots at the surface.

1. Introduction

Over the last two decades hotspots have become a subject of interest: detailed information of those anomalous structures can provide a key role in understanding the state of the mantle. Are hotspots the surface manifestation of mantle plumes from the deep Earth? Is a question of critical importance, because it would provide information on the depth origin of those instabilities. Surface hotspots are categorised into three distinct groups considering their formation depth as given by Courtillot et al. (2003): (a) primary plumes with a very deep origin, most probable the D″ layer (i.e., the lowest approx. 300 km of the Earth's mantle, Bullen, 1949), (b) plumes originating from the mantle transition zone between 410 and 660 km depth, (c) Andersonian plumes with a shallow, upper mantle root. Numerous studies have concentrated on investigating origin depths and plume paths of the hotspots of Iceland and Hawaii (e.g., Ballmer et al., 2013; Foulger et al., 2000; Huckfeldt et al., 2013; Li et al., 2000; Montelli et al., 2006; Rickers et al., 2013; Rychert et al., 2013) whereas the origin depth and plume path of other plumes are less well resolved.

A number of studies have obtained evidence of the origin and upwelling paths of plumes using a variety of methods. Global (Montelli et al., 2006; Zhao, 2001, 2007; French et al., 2013) and regional seismic tomography studies (e.g., Allen et al., 2002; Lei et al., 2009; Wolfe et al., 2009; 2011; Tian and Zhao, 2012; Liu and Zhao, 2014) provide images of plume structures that can indicate the depth extent of slow seismic wave velocities. However, the resolution capability of those images in detecting narrow plumes is still under debate (e.g., Nataf, 2000). Investigating the depths of upper mantle seismic discontinuities affected by the intersecting plumes is an alternative approach used to infer the seismic structure beneath hotspots (e.g., Rost and Weber, 2002; Schmandt et al., 2012; Shearer, 2000).

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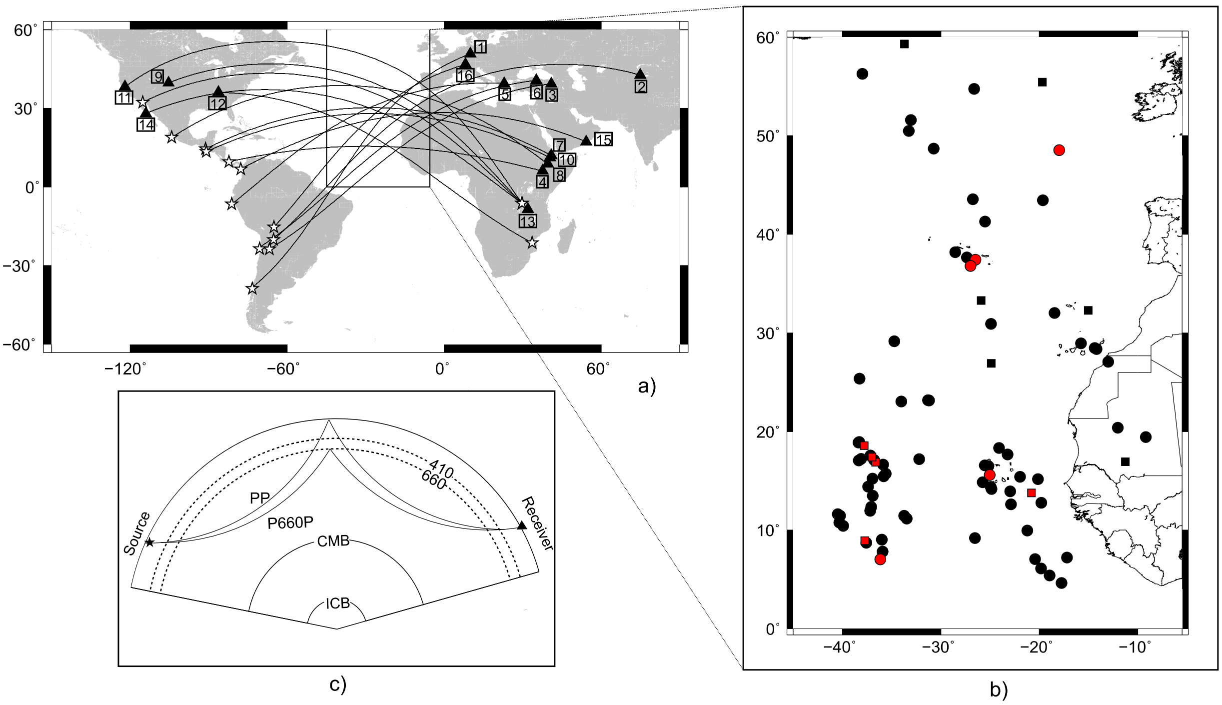

Fig. 1. Investigation area. (a) Source–receiver combinations used in this study. Stars and triangles represent the location of one event per source region and central station of the networks, respectively. The numbers on the map are array numbers as given in Table S3. The great circle path for each source–receiver combination is shown by the line that connects sources and receivers. (b) Location of underside reflections from 410 km (circles) and 660 km discontinuity (squares). Black symbols are used for PP precursors, red symbols show reflection points for precursors to SS. (c) Example ray paths of the waves used here, for simplicity only the PP and P660P ray paths are shown. The P660P wave travels along a similar ray path as PP but reflects at the underside of the 660 km discontinuity. P410P follows a similar path but reflects at the underside of the 410 km discontinuity. CMB: core–mantle boundary, ICB: inner core boundary.

The 410 km and 660 km seismic discontinuities mark the top and bottom boundary of the mantle transition zone (e.g., Bina and Helffrich, 1994; Frost, 2008; Helffrich, 2000), which divide the Earth's mantle into upper and lower parts. Seismic velocity and density jumps in those discontinuities are a property of most 1-D reference Earth models such as IASP91 (Kennett and Engdahl, 1991) or ak135 (Kennett et al., 1995). These two seismic discontinuities are due to the exothermic solid–solid phase transformation of olivine to wadsleyite at approximately 410 km depth (Helffrich, 2000; Katsura and Ito, 1989; Katsura et al., 2004) and the endothermic phase transformation from ringwoodite to perovskite near 660 km depth (Fei et al., 2004; Ito and Takahashi, 1989; Shim et al., 2001), respectively.

Owing to the opposite sign of the Clapeyron slope of these two phase transitions, the mantle transition zone thickness is expected to vary from the global average to a thinner transition zone beneath hotspots and a thicker transition zone beneath subducting slabs (Helffrich, 2000). Some global studies of SS precursors suggest there is no evidence for a ocean/continent dependency of the transition zone discontinuity depths (Flanagan and Shearer, 1998), whereas other SS precursor studies argue for a correlation between thinner transition zones and oceanic regions (Gu et al., 1998). While the 410 km discontinuity seems to be relatively simple and varies mostly with temperature (Andrews and Deuss, 2008; Weidner and Wang, 2000), the 660 km discontinuity seems to be more complex and may have a strong influence on mantle convection and acts as a barrier to up- and downwellings (e.g., Schubert and Tackley, 1995; Shearer and Masters, 1992). Previous studies beneath hotspots mostly find the transition zone to be thinner (e.g., Owens et al., 2000; Shen et al., 1998), while in subduction regions it often seems to be thicker than the global average (e.g., Flanagan and Shearer, 1998; Li and Yuan, 2003; Van der Meijde et al., 2005). Additional complexity of the 660 km discontinuity comes from the possibility that at higher temperatures, i.e., in regions of hot upwellings, the phase transition of majorite–garnet to perovskite becomes dominant (Deuss et al., 2006; Houser and Williams, 2010) and due to its positive Clapeyron slope (Hirose, 2002) implies a deeper 660 km discontinuity depth and therefore a correlation with the 410 km discontinuity in the presence of hot upwellings (e.g., Deuss, 2007).

Recent studies reported different observations of the transition zone thickness beneath the North Atlantic as summarised in Table S1. Helffrich et al. (2010) detected almost normal transition zone thickness beneath the Cape Verde hotspot, which is in contrast to the work of Vinnik et al. (2012) who find a depressed 410 km discontinuity and a raised 660 km discontinuity. A recent study by Silveira et al. (2010) revealed that transition zone thickness does not vary from the standard value in a large region of the Northern Atlantic outside the Azores plateau, whilst Lawrence and Shearer (2006) and Gu and Dziewonski (2002) reported a narrow transition zone in the same region. Since Silveira et al. (2010) benefits from receiver function method and Lawrence and Shearer (2006) employ precursors to SS wave, perhaps some of the discrepancies between their observations may occur due to using different approaches. Chevrot et al. (1999) show that there is no significant correlation between their results of mantle transition zone thickness using receiver functions compared with the study by Flanagan and Shearer (1998), who use SS-precursors. The discrepancy between the two methods is of the order of 8 km (Chevrot et al., 1999). A more recent study by Lawrence and Shearer (2006), argue for a better agreement between the results for the mantle transition zone thickness obtained using SS precursors and those from receiver function method.

In this study, we map the depths and topography of the upper mantle discontinuities within a large area of the Northern Atlantic. We use precursors to the PP and SS waves (Fig. 1) which reflect at the underside of the upper mantle discontinuities. PP and SS precursors have been used previously to map regional