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Strong seismic scatterers near the core–mantle boundary north of the Pacific Anomaly

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ABSTRACT

Tomographic images have shown that there are clear high-velocity heterogeneities to the north of the Pacific Anomaly near the core–mantle boundary (CMB), but the detailed structure and origin of these heterogeneities are poorly known. In this study, we analyze PKP precursors from earthquakes in the Aleutian Islands and Kamchatka Peninsula recorded by seismic arrays in Antarctica, and find that these heterogeneities extend ~400 km above the CMB and are distributed between 30° and 45°N in latitude. The scatterers show the largest P-wave velocity perturbation of 1.0–1.2% in the center (160–180°E) and ~0.5% to the west and east (140–160°E, 180–200°E). ScS–S differential travel-time residuals reveal similar features. We suggest that these seismic scatterers are the remnants of ancient subducted slab material. The lateral variations may be caused either by different slabs, or by variations in slab composition resulting from their segregation process.

1. Introduction

The core–mantle boundary (CMB) is one of the most significant boundary layers within the Earth. This layer and its adjacent regions, especially D″, are key to understanding dynamic processes within the Earth, such as the source of mantle plumes, the fate of subducted slabs, and material and heat exchange between the mantle and core (Young and Thorne, 1987; Wysession et al., 1994; Lay et al., 1998; Garnero, 2000, 2004; McNamara and Zhong, 2005; Lay and Garnero, 2011). Previous seismological studies have found complex heterogeneities near the CMB, such as Large Low Shear Velocity Provinces (LLSVPs) (e.g., Wen, 2001; Ni and Helmberger, 2003; Wang and Wen, 2007; Garnero and McNamara, 2008; He and Wen, 2009, 2012), Ultra-Low-Velocity zones (ULVZ) (Garnero and Vidale, 1999; Rost et al., 2006; Rost et al., 2010; Yao and Wen, 2014), anisotropy (e.g., Kendall and Silver, 1996; Lay et al., 1998; Garnero et al., 2004; Long, 2009), and seismic scatterers (e.g., Cleary and Haddon, 1972; Husebye and King, 1976; Vidale and Hedlin, 1998; Thomas et al., 1999; Hedlin and Shearer, 2000; Cao and Romanowicz, 2007; Vanacore et al., 2010). Although high-velocity anomaly regions are well studied and are commonly attributed to subducted slabs, many regions, because of inadequate sampling by conventional seismic phases, are poorly imaged. In addition, conventional tomographic methods often poorly resolve small-scale structures due to limited frequency content. In this case, unconventional methods, such as those specifically focusing on scattered waves, may provide additional information. For the lowermost mantle, PKP precursors are possible candidates to serve this purpose.

PKP precursors are P waves that are scattered by small-scale elastic heterogeneities in the mantle and/or topographic irregularities on the CMB (e.g., Cleary and Haddon, 1972; Haddon and Cleary, 1974; Doornbos, 1976, 1978; Bataille and Flatté, 1988; Cormier, 1995; Hedlin and Shearer, 2000). Because of the geometry ray-paths of these seismic phases, the scattered P waves can

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precede the core phase (PKIKP) by up to 20 s and are typically best recorded at a distance range between 120° and 142° (Fig. 1). Particular advantages of using PKP precursors are that they are sensitive to heterogeneity at a scale as small as ~10 km, and are not contaminated by the coda of other phases due to their earlier arrival times. There have been successful applications of PKP precursors studies on global scales (e.g., Hedlin et al., 1997; Cormier, 1999; Margerin and Nolet, 2003b; Mancinelli and Shearer, 2013), as well as regional scales (e.g., Vidale and Hedlin, 1998; Wen and Helmberger, 1998; Niu and Wen, 2001; Miller and Niu, 2008; Thomas et al., 2009; Frost et al., 2013). In regional studies that incorporate well-sited arrays of seismographs, greater information about the anomalies, such as their boundary locations and sharpness, may be resolvable.

In this study, we focus on the CMB region to the north of the Pacific Anomaly, a region where tomographic images consistently show large-scale high-velocity anomalies (Li and Romanowicz, 1996; Grand, 2002; Zhao, 2004; Li et al., 2008; Simmons et al., 2010) but where high resolution details are lacking. We use PKP precursors from earthquakes in the Aleutian Islands and Kamchatka Peninsula recorded by recently deployed seismic arrays in Antarctica to locate the scatterers and to investigate their velocity variations. Our results show that the observed precursors are caused by seismic scatterers in the lowermost mantle, and the strengths of these scatterers vary according to their locations. Furthermore, we also analyze ScS–S travel time residuals sampling the same region, and find that the results show similar variation pattern. We suggest that the lateral variations in this region may be caused by heterogeneities from different subducted slabs, or by varying chemical compositions of the slab resulting from their segregation process.

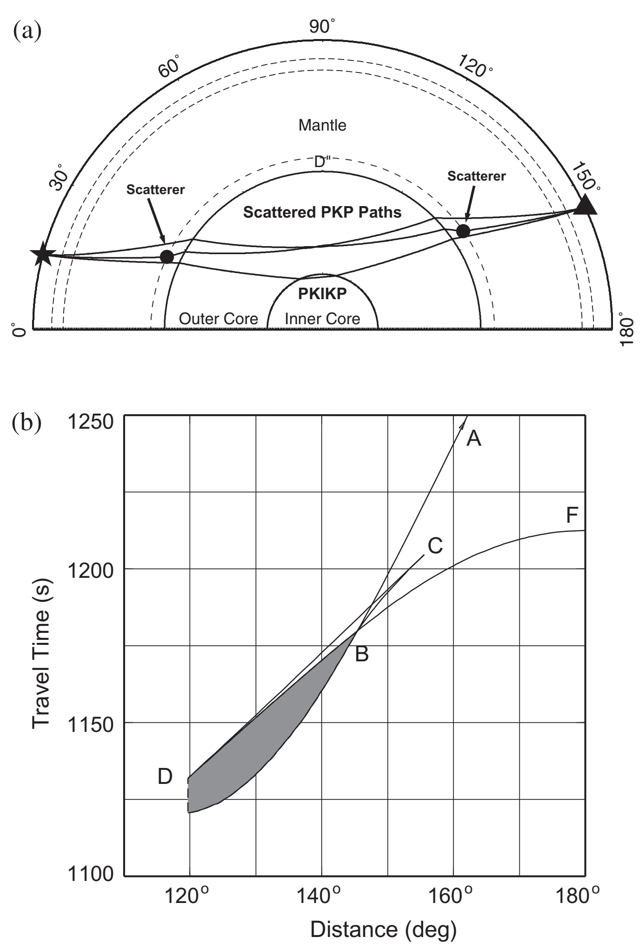

Fig. 1. (a) Ray-paths of PKIKP and scattered PKP waves. The PKP precursors are scattered PKP waves generated by the seismic scatterers (black dots) in the lower mantle beneath the source or receiver. The five-pointed star denotes the earthquake at the surface, and the triangle denotes the seismic station. (b) Travel time curves of four branches of PKP. Due to the unusual ray paths caused by scatterers in the lower mantle, the scattered waves can precede PKIKP by up to ~20 s. The shaded region indicates the possible earlier arrival times for precursors.

2. CMB region heterogeneities from PKP precursors

To constrain small-scale heterogeneities near the CMB beneath the Pacific region, we collected PKP precursor data recorded by Antarctic seismic arrays (GAMSIS and POLENET-ANET array) from earthquakes in the Aleutian Islands and Kamchatka Peninsula (Fig. 2). The GAMSEIS and POLENET/ANET networks consist of temporary and semi-permanent seismic stations deployed in East and West Antarctica beginning in 2008 for understanding the structure and solid-earth ice sheet interactions of the continent (Heeszel et al., 2013; Accardo et al., 2014; Anthony et al., 2015). These new seismic stations provide much improved coverage of the CMB along paths not previously sampled due to sparse global station distribution in the far-southern latitudes. Here we use 59 Antarctic seismic stations (26 in GAMSEIS and 33 in POLENET/ANET) deployed during 2009–2011, and earthquakes with magnitude greater than 5.5 (Table 1) at a distance range of 134–143°. All seismograms are band-pass filtered between 0.5 and 2.0 Hz, and only those with low noise levels and clear precursor signals are selected. PKP precursor travel times and envelope amplitudes are then analyzed to locate the scatterers and to calculate the velocity variations within them.

Fig. 3 shows representative PKP precursor waveforms from earthquakes in three different regions (western, middle and eastern region). The relative amplitudes of PKP precursors in the middle region (central panel) are obviously much larger than those in the other two regions, and are larger than the PKIKP phases at some distances. Investigating the larger sample of earthquakes in each region, we find that the amplitudes have no relation with the earthquake depth (Table 1). By comparing the entry and exit points of PKIKP rays at the CMB (Fig. 2) from these earthquakes, it is found that the exit points of the earthquakes from different regions are intermixed, while the entry points are well separated into different locations.

2.1. Results from PKP arrival times

To determine the exact locations of the seismic scatterers, we adopt Wen's method (Wen, 2000) that utilizes the arrival times of PKP precursors. First, we divide the region of the possible scatterer locations (20–50°N, 140–200°E, and from the CMB to 600 km above the CMB) into six depth ranges with separation of 100 km. In each depth range, the region is further divided into a 1.0° by 1.0° uniform grid of nodes. Then we calculate the scatterer probability and hit count for each node by comparing the predicted and observed precursor arrival times of all earthquakes. The probability at a given node is the ratio of the number of seismic rays whose PKP precursor onsets sample this node over the total number of seismic rays in this study, and the hit count is the number of PKP precursors sampling this node. Detailed information about the method can be found in Wen (2000). In general, the grids with high probability and large hit counts are most likely where the PKP precursors originate.

We calculate the hit counts and probability near the CMB region for both source side and receiver side. We find that, at the same depth, both the hit counts and probability for receiver side are smaller than those of the source side. Considering together the fact