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Anisotropy as cause for polarity reversals of D″ reflections

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ABSTRACT

Recordings of seismic events that sample the deep mantle can test different hypotheses of mantle processes and composition. Seismic reflections from structures in the D″ region — the bottom 200–400 km of the Earth's mantle — can provide information on the velocity contrasts in this region. By studying the waveforms and polarities of the D″ reflections in P and S-waves, we can potentially distinguish between different explanations for the observed structures, such as phase transitions, mineral texture or thermal anomalies. Here we use source–receiver combinations that contain reflections from D″ in two different regions that are both characterised by fast seismic velocities in tomographic models. Beneath the Caribbean a positive S-velocity contrast but negative P-wave velocity contrast across the D″ reflector has been reported previously, consistent with a model of a phase change in $MgSiO_3$. In the second fast velocity region (Eurasia) we detect positive P- and S-wave velocity contrasts in two orthogonal paths crossing in the lowermost mantle indicating a different scenario for D″. A path that crosses this region in 45° to the other two great circle paths shows evidence for a negative P velocity contrast. One explanation to reconcile observations in both regions is a phase transition from perovskite to post-perovskite with a fraction of 12% preferred crystal alignment in the post-perovskite phase. Depending on the travel direction of the waves with respect to the flow direction in the lower mantle, positive or negative velocity jumps can be expected. Other anisotropic models are considered but cannot fully explain the range of observations we find in the data.

1. Introduction

The lowermost Earth's mantle (the D″ region Bullen, 1949) exhibits a large number of variable seismic structures. These structures range from small-scale scatterers near the core–mantle boundary (CMB) to several hundred kilometres above the CMB (e.g. Hedlin et al., 1997; Thomas et al., 1999; Vidale and Hedlin, 1998), and ultra-low velocity zone (ulvz, e.g., Garnero et al., 1998; Rost and Revenaugh, 2003) to large-scale reflectors in regions of possible palaeo-subduction (Lay and Helmberger, 1983; Wysession et al., 1998 for a review). Recently, large-scale reflectors have also been found in regions where tomographic inversions (e.g., Grand, 2002; Kárason and van der Hilst, 2001; Masters et al., 2000) find large low-velocity regions (e.g. Lay et al., 2006; Ohta et al., 2008). In several regions of the Earth seismic anisotropy in the lowermost mantle has been reported (e.g., Kendall and Silver, 1998; Lay et al., 1998; Rokosky et al., 2006; Wookey et al., 2005a). Especially in regions of fast seismic velocity (e.g. Grand, 2002) a case of vertical transverse isotropy (VTI) or tilted TI can explain the data (Garnero et al., 2004; Maupin et al., 2005; Ritsema and Van Heijst, 2000; Thomas et al., 2007; Wookey and Kendall, 2008). Regions with slow seismic velocities seem to exhibit a more complex anisotropic scenario (see, e.g., Pulliam and Sen, 1998; Kendall and Silver, 1998; Lay et al., 1998).

Waves that reflect off structures in the D″ region, such as PdP and SdS (e.g., Weber, 1993) have been used to determine the presence and extent of seismic structures in the lowest few hundred kilometres of the mantle (e.g., Kendall and Shearer, 1994; Lay and Helmberger, 1983; Weber, 1993; Wysession et al., 1998). These reflected waves arrive with a travel time and slowness between P (S) and PcP (ScS) and through the use of array seismology they can be distinguished from other arrivals (e.g., Thomas et al., 2004a, b; Weber, 1993; Weber and Davis, 1990). Recently more than one reflection has been observed in the time window between P (S) and PcP (ScS) (Hutko et al., 2006, 2008; Kawai et al., 2007; Kito et al., 2007; Lay et al., 2006; Thomas et al., 2004a, b; van der Hilst et al., 2007) indicating a more complex structure in both fast and slow velocity regions.

Several hypotheses have been advanced in recent years to explain the reflectors and anisotropy in D″, for example, subducted oceanic lithosphere and a slab graveyard at the core–mantle boundary (CMB) (e.g. Kendall, 2000) can explain seismic reflections a few hundred kilometres above the CMB as well as observations of seismic anisotropy in D″ when assuming sheared melt inclusions (Kendall and Silver, 1998). A different way to explain the reflection in D″ was proposed by Lay et al. (2004) where they invoke chemical layering at

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the base of the mantle. Another scenario for explaining two reflectors in D″ is the model of Tan et al. (2002) where a new upwelling is generated below a subducted slab near the CMB but this model cannot explain anisotropy without invoking other mechanisms to account for it, such as sheared melt inclusions within the slab.

The recently discovered phase transition of perovskite to post perovskite (e.g. Murakami et al., 2004; Oganov and Ono, 2004; Tsuchiya et al., 2004) offers another hypothesis that can explain several seismic structures in D″. The phase transition generates a density increase (Murakami et al., 2004) but may only exhibit a small shear velocity jump (Murakami et al., 2007). Wookey et al. (2005b) used ab initio calculations to show that a small negative P-wave contrast and a positive S-wave contrast would be generated for a phase transition in $MgSiO_3$. It is also possible that the post-perovskite phase transforms back to the perovskite phase closer to the D″ region (Hernlund et al., 2005), thereby providing a mechanism to explain the two reflectors found in D″ in some fast velocity regions in the lowermost mantle (Hutko et al., 2006; Thomas et al., 2004a, b; van der Hilst et al., 2007). Recent results indicate that the post-perovskite phase is able to generate seismic anisotropy in the D″ region (e.g. Merkel et al., 2006; Oganov et al., 2005; Stackhouse and Brodholt, 2007; Yamazaki and Karato, 2007). Phase transitions to a post-perovskite phase in other minerals or in mid-ocean ridge basalts (MORB) might explain additional reflectors in D″ (Ohta et al., 2008) such as reported by Lay et al. (2006). Recently, however, Catalli et al. (2009) reported that in pyrolitic material, the phase transition to post-perovskite would take place over a large depth range, therefore not being able to produce short period P-wave reflections. Ammann et al. (2010) propose that strong crystallographic texture could be responsible for generating sharp reflectors consistent with seismic observations.

Distinguishing between the different hypotheses requires using as much information of the arriving seismic waves as possible. Waveforms and polarities of the reflections from structures in D″ provide a tool for constraining different scenarios. Here we use the polarities of reflected waves in D″ to test the hypothesis of post-perovskite anisotropy in D″ as mechanism for generating reflectors in P and S-waves.

2. Observations

Events located in South America recorded in North America have their reflection points in the D″ region beneath Central America (Fig. 1b), a region characterised by fast seismic velocities (e.g. Kárason and van der Hilst, 2001). The epicentral distances of the source–receiver combinations used for detecting reflections off structures in the D″ region are between 65 and 80°. In previous studies, Kito et al. (2007) and Hutko et al. (2008) used these event-receiver combinations and found small negative PdP waves, i.e. reflections from the top of D″. These studies and Thomas et al. (2004b) also detected positive S-wave reflections from the same region. Kito et al. (2007) and Hutko et al. (2008) used the model by Wookey et al. (2005b) that predicts small negative P-wave jumps and positive S-wave jumps for a post-perovskite phase transition in MgSiO3 and concluded that this phase transition can explain their observations. A similar scenario of positive S-wave velocity jumps and small negative P-wave velocity jumps has been detected by Chaloner et al. (2009) beneath Southeast Asia.

For a second test region we use events from the Northwest Pacific recorded in Germany with their reflection points beneath Eurasia (Fig. 1a), where tomographic models indicate fast seismic velocities in P and S-wave models (e.g. Grand, 2002; Kárason and van der Hilst, 2001). The selection criteria are the same as for the South America–North America path and the depth of the events lies between 50 and 660 km. This path has been investigated before (e.g. Thomas and Weber, 1997; Weber, 1993) and showed evidence for P- and S-wave reflections from D″ structures. For a near-perpendicular crossing path sampling the same region we use events from Hindu Kush recorded at Canadian stations. Such a path has been used by Thomas et al. (2002) and Wookey and Kendall (2008) where they found reflections from D″ as well as anisotropy in both source–receiver combinations. Due to the limited number of deep Hindu Kush events and stations in Canada in a suitable epicentral distance the data quality and quantity for this direction is poorer than for the Kurile to Germany path.

We use vespagrams (see e.g. Rost and Thomas, 2002) to analyse the polarities of the seismic waves. Three examples for P-wave reflections are shown for the path Kuriles–Germany (Fig. 2a–c). In each vespagram the P and PcP waves are visible as well as PdP waves

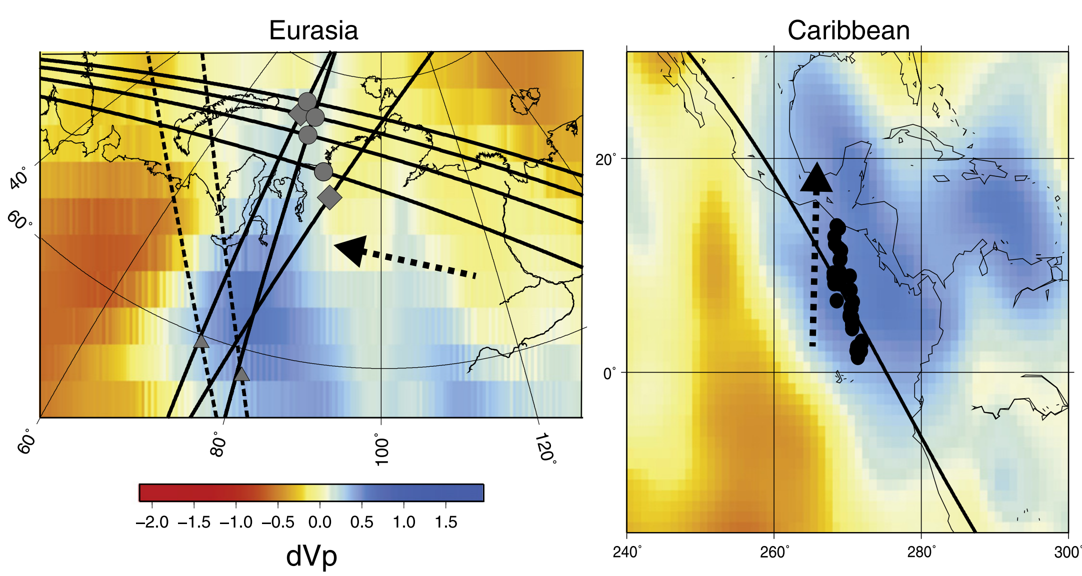

Fig. 1. a) The region imaged with sources in the Kuriles and Japan recorded in Germany (reflection points in the lowermost mantle shown as grey circles) and for the perpendicular raypath sources in the Hindu–Kush region and receivers in Canada (reflection points as grey diamonds). Additionally shown are source receiver combinations for which the great circle path crosses the region in other orientations (thick and thin dashed lines) with reflection points in the lowermost mantle shown as grey triangles. b) Earthquakes in South America recorded at stations in North America with reflection points in the lowermost mantle as black circles. The PcP and PdP reflection points for both regions lie in a fast velocity region for the model of Kárason and van der Hilst (2001). Dashed arrows show the paleosubduction direction 100 Ma ago of the Kula and Farallon plates, respectively.