EXPRESS LETTER

Reconciling \( PP \) and \( PP' \) precursor observations of a complex 660 km seismic discontinuity

Elizabeth A. Day* and Arwen Deuss

Department of Earth Sciences, Bullard Laboratories, University of Cambridge, Cambridge CB3 0EZ, United Kingdom. E-mail: eaday@mit.edu

Accepted 2013 March 25. Received 2013 March 22; in original form 2013 January 30

SUMMARY

High frequency precursors to \( PP' \) almost invariably observe a narrow 660 km discontinuity, whereas \( PP \) precursor studies at long periods struggle to detect a reflection from the ‘660’ despite its apparent sharpness to \( PP' \). To investigate these contradictory observations we compare \( PP \) and \( PP' \) precursors in the same region. Using short period \( PP' \) precursors we observe a sharp 660 km discontinuity, which appears to vary in depth substantially. The apparent topography on the ‘660’ is too large to originate solely from thermal variations, regardless of its cause, therefore indicating chemical variations at the base of the mantle transition zone. Long period \( PP' \) precursors show no ‘660’ as they are sensitive to a larger area and thus average out the apparent topography, in agreement with long period \( PP \) precursors. Instead, we see some evidence in both long period data types for a reflection from 720 km depth, which is likely to correspond to a phase change in the garnet system.

Key words: Mantle processes; Composition of the mantle; Body waves.

1 INTRODUCTION

The 660 km seismic discontinuity (the ‘660’) at the base of the mantle transition zone (MTZ) marks the boundary between the upper and lower mantle. The seismic signature of the ‘660’ is attributed to the post-spinel phase transition in olivine, in which ringwoodite transforms into perovskite and periclase (Ita & Stixrude 1992). The nature of the 660 km seismic discontinuity governs the behaviour of the mantle as a whole, with its properties as a chemical and mechanical boundary controlling mantle convection and the fate of subducting slabs (Schubert et al. 2001).

Observations of the 660 km seismic discontinuity in precursors to body waves have painted a complex and sometimes even contradictory picture. Despite the common observations of \( P'660P' \) at short periods (Benz & Vidale 1993; LeStunff et al. 1995), longer period \( P660P \) signals are rarely seen (Estabrook & Kind 1996; Shearer & Flanagan 1999). Studies that do record a \( P660P \) signal detect an intermittent and complicated discontinuity (Deuss et al. 2006; Thomas & Billen 2009; Schmerr & Thomas 2011). Observed \( P'660P' \) signals, on the other hand, indicate that the ‘660’ is sharp and narrow, with a thickness of less than 4 km (Xu et al. 2003). \( S660S \) is commonly detected, even in regions where \( P660P \) is not observed, which has been attributed to the different sensitivities of \( PP \) and \( SS \) waves to the post-spinel and majorite garnet phase transitions (Deuss et al. 2006; Houser & Williams 2010).

Here, we explore the complex and potentially contradictory observations of the ‘660’ in compressional body waves by directly comparing \( PP' \) and long period \( PP \) precursor observations in the same region under South East Africa. We investigate the topography of the 660 km discontinuity and the frequency dependence of the seismic signals to reconcile the \( PP \) and \( PP' \) observations.

2 DATA AND METHODS

Surface reflected body waves such as \( PP \) and \( PP' \) are preceded by smaller amplitude arrivals, known as precursors. These arrivals have been reflected at discontinuities below the Earth’s surface and are therefore sensitive to the impedance change at the discontinuity. \( P'P\)d\( f \) (also known as \( PKIKPKIKP \) and hereafter as \( PP' \)) is a seismic phase which traverses the entire Earth before reflecting off the Earth’s surface, as illustrated in Fig. 1. \( PP' \) precursors are referred to as \( P'dP' \), where ‘\( d \)’ denotes the depth of the interface at which they have been reflected. \( PP' \) precursors have a relatively high frequency content (∼1 Hz) and approach discontinuities with a steep angle of incidence, making them sensitive to sharp transitions and small scale structure. \( PP \) travels only in the mantle and its precursors are referred to as \( PdP \). \( PP \) precursors are studied at lower frequencies of ∼0.05 Hz and arrive with a less steep angle of incidence.

\( PP' \) precursors are small amplitude arrivals which are not visible on individual seismograms. To allow the weak precursor signals to rise above the background noise level, traces are stacked in bins with common precursor bounce points. We apply linear and power two and four phase weighted stacking techniques (Schimmel & Paulsen...
Incoherent noise is suppressed, while the coherent signals of the main arrival and its precursors are enhanced. We use earthquakes in the Fiji/Tonga region detected at the Northern and Southern Californian Seismic Networks. The events have magnitudes larger than $M_w 6.8$ (with source parameters taken from the CMT catalogue, http://www.globalcmt.org), are deeper than 150 km, and arrive at an epicentral distance of greater than $75^\circ$.

The vertical component broad-band data are filtered in a range of bands between 0.5 and 75 s. Each trace is normalized on the $P'$ amplitude and visually inspected for a signal to noise ratio greater than two.

The depths of apparent reflectors observed in the stacks are calculated from the measured traveltime difference between $P'$ and its precursor, using the reference model AK135 (Kennett et al. 1995) and $P$ wave 3-D mantle model MIT-P08 (Li et al. 2008), which includes CRUST2.0 (Bassin et al. 2000). $PP$ precursor data were processed as described in Deuss et al. (2006) and filtered between 8 and 75 s.

3 RESULTS

Five events have been identified for which we were able to make observations of $P'660P'$ arrivals (see Table 1). The vespagram and slowness stack for a typical event (071504C) are shown in Fig. 2. The main $PP$ signal and its $P'660P'$ precursor are both clearly visible with amplitudes above the noise level in the slowness stack (Fig. 2a) and can also be identified in the vespagram at the expected slowness and arrival time (Fig. 2b); there is no clear arrival visible for $P'410P'$. $PP'$ at 1 Hz has a relatively short wavelength of 10 km at the base of the MTZ, confirming that the impedance contrast of the ‘660’ reflector is less than 4 km wide.

3.1 Apparent topography on the ‘660’

We measured the arrival times of each $P'660P'$ precursor with respect to the main $PP$ arrival in linear slowness stacks. To ensure the measured arrivals are robust we calculated 95 per cent confidence intervals using bootstrap resampling (Efron & Tibshirani 1991) and compared these robust arrivals to phase weighted stacks. We define the arrival time of $PP'$ as the first robust, large amplitude arrival which is also detected in phase weighted stacks at an appropriate time and slowness; $P'dP'$ arrivals must meet the same criteria and are also generally similar in character to the $PP'$ arrival. The measured arrival times are converted to reflector depths for each of the five events, correcting for mantle and crustal structure using MIT-P08 (Li et al. 2008). We find significant variations in the apparent depth of the ‘660’ reflector of up to 34 km, over distances of just a few hundred kilometres laterally (Fig. 3).
are solely caused by unaccounted for crustal structure, despite the potential complexity of the crust under Africa.

For variations in upper mantle structure to account for the $P'660P'$ – $PP$ traveltime anomalies we observe would require highly laterally localized mantle heterogeneities of ±2.25 per cent $V_p$ for the entire top 660 km of the upper mantle. These are larger than the anomalies observed by Bastow et al. (2008) under the Mid-Ethiopian Rift (MER), a substantially more anomalous region of the upper mantle than this section of the East African Rift, which is thousands of kilometres away from the MER.

3.2 Frequency dependence of precursor observations

The frequency dependence of the $PP$ precursor signal was investigated by filtering the $PP'$ data in frequency bands 1 s wide every 0.5 s from 0.5 to 7.5 s (i.e. the microseismic noise band). The Fresnel zone of $P'660P'$ increases with increasing period (Neel et al. 1997), which will allow us to place constraints on the length scales of variations around the ‘660’. We find that the $P'660P'$ signal dies out at a period of around 5.5 s (Fig. 4a), which corresponds to a Fresnel zone with a diameter of ~5°. The size of the Fresnel zones of the $P'660P'$ reflections then encompasses the whole area of the apparent topography observed on the ‘660’ shown in Fig. 3. Stacking over such a large area makes the $PdP'$ signals more vulnerable to averaging out apparent topography leading to the ‘660’ becoming undetectable at longer period.

Fig. 4(b) compares the $PP'$ precursor observations with $PP$ precursor stacks for the same region. The long period $PP$ stack shows a clear, robust reflection from the 410 km discontinuity, but there is no arrival from the ‘660’. Also shown is the $PP$ precursor stack at long periods of 8-75s, the same frequency band as used for the $PP$ precursors. At these periods the Fresnel zone of $P'660P'$ is 15° and similar to the $P660P$ Fresnel zone. We again see no robust signal at a time and slowness that we could attribute to $P'660P'$. Thus, the apparent contradiction between the $P660P$ and $P'660P'$ observations can be reconciled as being due to frequency effects, with the 660 km discontinuity not being observable at long periods in either data type. We therefore would not expect to see a reflection from the ‘660’ if the Fresnel zone enclosed substantial ‘660’ topography, as we have observed at shorter periods in this region.

Looking in more detail, it appears that the short period $PP$ is sensitive to an impedance change around 660 km depth while longer period $PP$ also reflects from a transition beginning at a depth of 720 km. The long period $PP$ precursor stack under South Eastern Africa shows non-robust $P660P$ and $P720P$ signals, which appear to line up with the both the short and long period $P'660P'$ and long period $P'720P'$ signals, respectively. Although the long period $PP$ stack does not show robust signals in linear stacks from reflections at 660 or 720 km depth (Fig. 4b), phase weighted vespagrams show coherent energy with an appropriate time and slowness (Fig. 4c), therefore we feel confident that the energy corresponds to real structures in the MTZ.

4 DISCUSSION

4.1 Possible causes of apparent topography on the ‘660’

Substantial variations in the depth of the ‘660’ have been observed before. Global $SS$ precursor studies have found over 35 km of variation in the depth of the ‘660’ (Flanagan & Shearer 1998; Schmerr & Garnero 2007), however, these variations occur over much larger
distances than we observe and are correlated with expected temperature fluctuations. Hetényi et al. (2009) and Cornwell et al. (2011) detected variations in the depth of the ‘660’ at comparable length scales to those observed here using receiver functions.

The two likely explanations of the substantial variation in $P'660P'$ time (i.e. variation in apparent ‘660’ depth), are depth variations of the post-spinel phase change or velocity heterogeneities along the wave paths or near the 660 km discontinuity. If the apparent topography on the ‘660’ is caused by the post-spinel phase transition alone, a variation in depth of 34 km would require a difference in temperature of up to 700K (Bina & Helffrich 1994), which is unrealistically high. In this case it seems likely that the apparent topography on the ‘660’ is caused not only by thermal variations, but also variations in chemical composition.

Alternatively, we may assume that the apparent topography is actually caused by velocity heterogeneities at some point along the different paths of $P'P'$ and $P'660P'$. As P410P is almost invariably seen in all regions this would indicate that the P410P reflection is unaffected by the same destructive interference or defocussing effect which eliminates the P660P signal. Therefore if the apparent topography we see is caused by mantle heterogeneities along the ‘660’ to surface path we can limit these velocity heterogeneities to around the base of the MTZ. These heterogeneities would cause local perturbations to the velocity structure near the discontinuity, or change the gradient of the phase transition resulting in variations in reflection depth. Again, the variations are too large to be due to thermal effects alone.

4.2 410 km discontinuity

A reflection from the 410 km discontinuity is clearly visible in the long period $PP$ stacks shown in Fig. 4(b), which, as discussed earlier, limits any substantial velocity heterogeneities to the base of the MTZ. However, the ‘410’ is not visible in either the long or short period $PP$ stacks. Any long period $P'410P'$ signal is masked by the large, slightly delayed SKKSdf arrival, as seen on the vespagram in Fig. 4(c) and the stack in Fig. 4(b). The lack of a $P'410P'$ signal at periods of up to 7 s (Fig. 4a) is most likely due to the discontinuity being too wide to be detected by such short period waves (i.e. the majority of the impedance change associated with the discontinuity must take place over greater than ~15 km), as has been seen in previous global $PP$ studies (Xu et al. 2003).

4.3 Multiple reflectors at the base of the transition zone

Additional phase transformations in the non-olivine components of the mantle are the likely cause of multiple reflections around the ‘660’, which are visible in the long period $PP$ and $PP'$ linear and phase weighted stacks shown in Fig. 4. Up to 40 per cent of the upper mantle is made of pyroxenes, and at pressures and temperatures close to those around 660 km depth majorite garnet is expected to transform into calcium pervoskite (Hirose 2002). P720P signals have previously been attributed to phase changes in the garnet system of the mantle assemblage (Deuss et al. 2006), as have signals in $SS$ precursors (Houser & Williams 2010) and receiver function studies (Simmons & Gurrola 2000; Andrews & Deuss 2008). The non-robust nature of the P660P and long period $P'660P'$ in linear stacks under South Eastern Africa, shown in Fig. 4(b), is likely to reflect the apparent topography that caused the $P'660P'$ signal to become incoherent at periods greater than 5.5 s. A reflection from around 720 km depth in long period $PP'$ stacks, seen non-robustly
in linear stacks but with coherent energy in phase weighted stacks (see Fig. 4c), is most likely due to the majorite to perovskite phase change.

5 CONCLUSIONS

Using short period $PP$ precursors we observe variation in the apparent depth of the 660 km seismic discontinuity of up to 34 km over 200 km laterally under South East Africa. This apparent topography on the ‘660’ makes it difficult to observe a reflection from the ‘660’ in long period data types, as their correspondingly larger Fresnel zone makes them sensitive to a larger region which encompasses the variation in ‘660’ depth. The apparent topography on the ‘660’ is not necessarily caused by the post-spinel phase change varying in depth, but may alternatively result from substantial velocity heterogeneities around the base of the MTZ. The variation in ‘660’ depth we observe is too large to originate solely from thermal variations and therefore must be indicative of some variations in chemistry. In addition, we see some evidence for a reflection from a depth of 720 km in long period $PP$ precursor data, which is likely to correspond to a reflection from an additional phase change, such as majorite to perovskite.

ACKNOWLEDGEMENTS

EAD is supported by a NERC studentship (NE/F007175/1). AD is supported by the European Research Council (ERC) under the European Community’s Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement number 204995. Data has been provided by the Southern and Northern Californian Data Centers and the IRIS Data Management Center. Ray tracing has been carried out using the TauP toolkit (Crotwell et al. 1999). Figures have been created using Generic Mapping Tools (Wessel & Smith 1998). We thank Christine Houser and Nick Schmerr for thoughtful reviews.

REFERENCES