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Mantle discontinuities under southern Africa from precursors to $P'P'_{df}$

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Abstract. We investigate the reflection properties of upper-mantle discontinuities beneath southern Africa using precursors to the *df* branch of $PKPPKP$ ($P'P'$). The $P'P'$ *df* branch is weaker than the *ab* and *bc* branches, but it does not have the complication of a caustic and appears across a wider distance range. Stacks from hundreds of short-period seismograms recorded in California from the March 9, 1994 Tonga earthquake (M_W = 7.6) show an ~5% reflection (at 3.5 s dominate period) from 660–km depth indicating a sharp "660" under southern Africa. A 3.5 s period reflection from 410–km depth is also visible in these stacks, but only ~2% the strength of $P'P'_{df}$. This result contrasts with the observation of the "410" and the "660" reflecting comparable amounts of high-frequency energy under the Indian Ocean [*Benz and Vidale*, 1993a], indicating either a diffuse "410" boundary under southern Africa or global variations in the impedance change across the "410". A 1.5 s period reflection may indicate the existence of fine-scale heterogeneity near 320–km depth. Reflectivity synthetic seismograms also show that a previously claimed reflection from 785–km depth has the more likely explanation as $PcPPKP$.

Introduction

The precise nature of seismic mantle discontinuities and their effects on the Earth's dynamic behavior and petrological properties continues to be the subject of interest for many geoscientists, with many details remaining unresolved. The seismic discontinuity near 660–km depth (the "660") is now widely accepted to mark the γ spinel to perovskite + magnesiowüstite phase transition due to increasing pressure with depth in the Earth [*Bina*, 1991; *Ito and Takahashi*, 1989]. This boundary has been interpreted to be less than a few kilometers in thickness where it is best observed [*Benz and Vidale*, 1993a; *Sobel*, 1978; *Husebye et al.*, 1977; *Whitcomb and Anderson*, 1970].

The seismic discontinuity near 410–km depth (the "410") is generally attributed to the olivine $\alpha \rightarrow \beta$ phase transition [*Bina*, 1991; *Ringwood*, 1969]. The sharpness (width of the velocity transition) of the seismic boundary near 410–km depth is not well determined. In addition, mineral physics predictions about the spatial sharpness of the phase change near 410–km depth are variable [*Helffrich and Wood*, 1996; *Lees et al.*, 1983].

Underside high-frequency P–wave reflections from upper-mantle discontinuities that precede the $P'P'$ phase provide important constraints on the existence and physical properties of these boundaries. Figure 1 shows typical ray paths for $P'P'_{ab}$ and $P'P'_{df}$. $P'P'$ arrives about 40 minutes after the earthquake in a quiet interval on the seismogram.

Previous studies have concentrated on the large amplitude precursors to $P'P'$ in the vicinity of the *b* caustic, which appears between 65° and 80° depending on reflector depth [*Adams*, 1971; *Benz and Vidale*, 1993a; *Whitcomb and Anderson*, 1970]. The caustic complicates the comparison of the precursor amplitude with that of the surface–reflected $P'P'$ arrival.

The *df* branch, on the other hand, has no caustic, so we can estimate the high–frequency reflection coefficient of each discontinuity. Since $P'P'_{df}$ precursors have low signal–to–noise ratios in single station seismograms, array measurement is necessary to analyze these phases. Stacking enhances the signal–to–noise ratio of the arrivals, allowing slowness information to be recovered [*Benz and Vidale*, 1993a]. The increased availability of large–aperture–array data since 1990 has enhanced our ability to characterize the amplitude and sharpness of upper mantle discontinuities [*Benz and Vidale*, 1993b].

In this paper, we document the usefulness of $P'P'_{df}$ precursors for studying details of upper–mantle layering, discuss our observations in the context of other seismological and petrologic results, as well as provide a more likely explanation for an observed $P'P'_{df}$ precursor previously associated with an underside reflection from a depth of 785 km.

Observations

The March 9, 1994 Tonga earthquake struck 563 km below the Earth's surface. With a source duration of about ten seconds and moment magnitude of 7.6, it was a powerful and compact source of 1–10 s period waves. This event was recorded by the Northern and Southern California Seismic Networks, which together consist of more than 600 short–period vertical component seismometers, and have recorded continuously since the early 1990s. These seismometers record 100 samples per second, and despite their short–period instrumentation have in exceptional cases been used to study up to 20 s period waves [*Wald and Heaton*, 1991].

The $P'P'$ arrivals across California from this Tongan earthquake have already been the subject of one study [*Le Stunff et al.*, 1995]. That study identified precursors that were attributed to the *ab* branch of $P'P'$ reflecting from layering near 785– and 1200–km depths. The arrival attributed to layering near 785–km depth is clearly visible in our data, but is given the alternative explanation of $PcPPKP$ below in this paper. The signal from 1200–km depth had a frequency content below the sensitivity of the short–period

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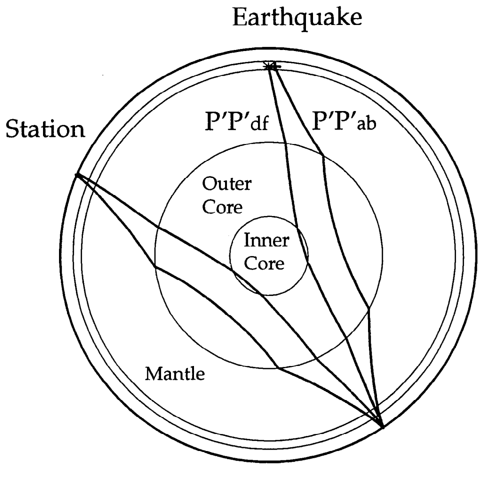

Figure 1. Ray paths of *ab* and *df* branches of $P'P'$.

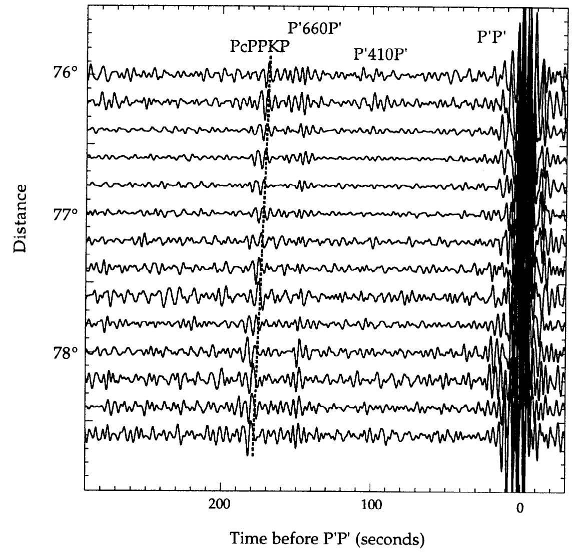

Figure 2. Seismic section of binned and stacked seismograms from the Northern and Southern California Seismic Networks. 394 seismograms were selected for lack of noise and coda from more than 600 available stations. Each bin of 0.2° had between 8 and 69 traces, whose sum is shown. No filtering has been done. Trace have been shifted so that the *df* branch of $P'P'$ is aligned at time zero. For all stacks in this paper, each trace was normalized to a peak $P'P'_{df}$ amplitude of one.

seismometers, so we do not discuss it further. The previous study also noticed the presence of the 660–km–depth precursor to the *df* branch of $P'P'$, but did not analyze its amplitude due to the use of non–linear stacking techniques, which are useful for detecting signals, but distort amplitude information.

For our analysis, we obtain over 600 seismograms of the Tongan earthquake from the Northern and Southern California Seismic Networks, which range in distance from 75° to 79°. Next, we visually select the seismograms with the clearest $P'P'_{df}$ main phase (least coda and lowest noise levels); those containing data spikes in the precursors time window are also removed.

A partially stacked record section is shown in Figure 2. Slant stacks of the same data were shown in *Le Stunff et al.* [1995]. The $PcPPKP$ and "660" arrivals are plainly visible 150 to 200 s ahead of the $P'P'_{df}$ arrival. Perhaps an increase in energy is visible 50 s behind the "660" reflection, where "410" arrival is expected, but it is not clear in this partial stack.

Calculated seismograms and traveltimes are shown in Figure 3. The reflectivity waveforms and the ray–traced times were computed with the velocity model *ak135* [*Kennett et al.*, 1995]. $P'P'_{df}$ is the largest phase in the section, with several smaller arrivals preceding it by up to 200 s. The biggest precursor is $PcPPKP$, as verified by the agreement between the ray–traced traveltime and the arrival seen in the seismograms between 85° and 100°. The $PcPPKP$ arrival extends across the entire section, but it diffracts around the core–mantle–boundary at distances closer than ~85° and becomes noticeably longer period at distances less than 70°.

The arrival time and moveout of $PcPPKP$ matches that of the phase observed 170 to 180 s prior to $P'P'$ in Figure 2. *Le Stunff et al.* [1995] interpreted this phase as a reflection from a depth of 785–km under southern African, which is also consistent with the data. We use Occam's Razor to support the interpretation as $PcPPKP$; this phase is predicted by standard earth models whereas a reflection from 785–km depth is not.

Next, we stack selected subsets of filtered seismograms to achieve the highest resolution of $P'P'$ precursors. Figure 4 shows stacks of $P'P'$ precursors in two pass bands. These are coherent stacks, summed along the $P'P'_{df}$ slowness, with an envelope function applied after stacking , as in *Vidale and Benz* [1992].

Figure 4a shows the tremendous dynamic range obtained from stacking hundreds of seismograms, a value of more than 200. The stacks have a dominate period of 3–4 s as a result of source spectrum of the earthquake, the low–pass filter and the high–frequency instrument response. The envelope function and the duration of the earthquake make the arrivals appear broader than 3.5 s. Precursors to the *df* branch of $P'P'$ are visible from 660– and 410–km depth. Both slowness and timing of these precursors match that expected from *ak135* [*Kennett et al.*, 1995]. The amplitude of the "410" and "660" reflections are respectively 2.2% and 5.0% that of the main $P'P'_{df}$ arrival. The $PcPPKP$ slowness is significantly different from $P'P'_{df}$, so it is less coherently stacked. Thus, $PcPPKP$ appears smaller in Figure 4a than in Figure 2. Note the absence of any other reflections more than 1% the amplitude of $P'P'$.

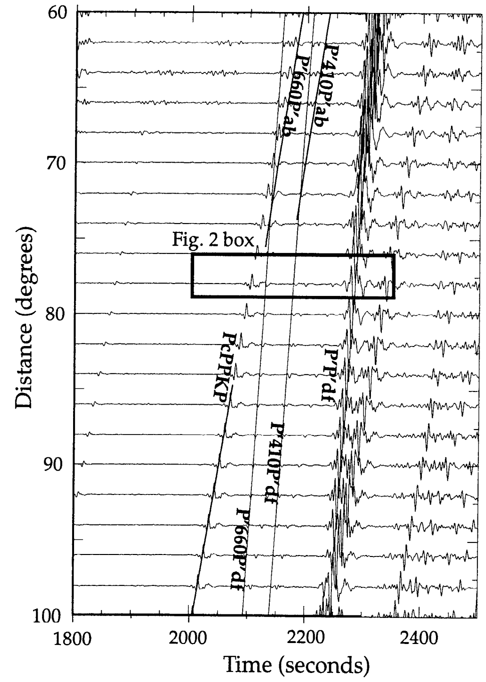

Figure 3. Calculated seismic section showing times and waveforms of $PcPPKP$ and $P'P'$. The waveforms are calculated by reflectivity and the traveltimes are computed using the *ak135* velocity model [*Kennett et al.*, 1995].

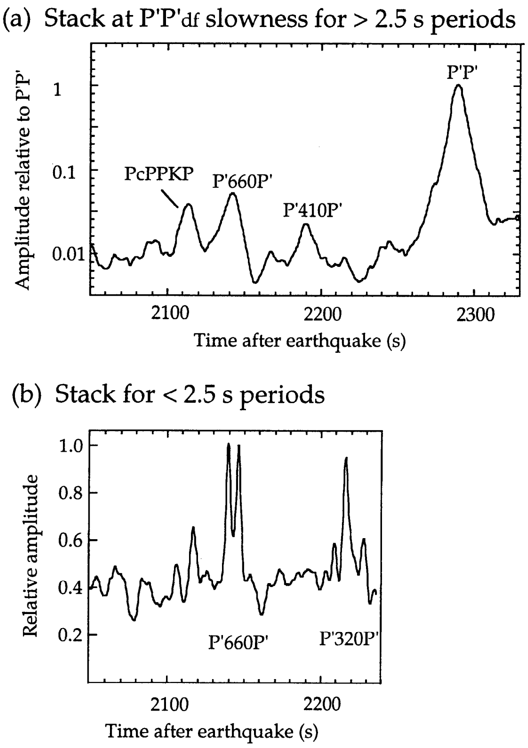

Figure 4. Envelope stacks at the slowness of $P'P'_{df}$. (a) Stack of the 394 best unfiltered traces, which shows energy near 3.5 s period. The arrival near 2110 s is a sidelobe of $PcPPKP$, which peaks at a different slowness. Note the logarithmic amplitude axis and the vast dynamic range in the stack. (b) Stack of the 100 best traces after high-pass filtering. This stack shows about 1.5 s period energy. Note that the amplitude scale is now linear, and the dynamic range limited.

Figure 4b shows a stack of 1.5 s period motions. Far fewer traces were included than in the Figure 4a stack because of lower signal–to–noise ratios. $P'P'$ itself stacks poorly at this frequency, probably due to upper–mantle attenuation and scattering at the Earth's surface. However, a clear reflection from 660–km depth is visible, as is energy that comes at the time of a reflection from near 320–km depth. Each phase that comes from the Tongan mainshock shows the extended earthquake duration [*Houston and Vidale*, 1994].

Discussion

Discontinuity sharpness

The amplitude of seismic energy reflecting from a small zero–thickness discontinuity depends on the angle of incidence and the impedance contrast across the boundary [*Aki and Richards*, 1980], where impedance is the product of velocity and density. For seismic waves reflecting from high gradient zones, the amplitude of reflected energy diminishes rapidly as the width of the zone exceeds a significant fraction of a wavelength [*Richards*, 1972]. Thus, upper–mantle discontinuity sharpness can be estimated by comparing the observed high–frequency reflection coefficient to the zero–thickness reflection coefficient, which is calculated from total impedance contrast across the boundary.

The 2.2% reflection observed for a depth of 410 km beneath southern Africa is ~50% smaller than the reflection predicted for a zero–thickness discontinuity using the $P'P'_{df}$ ray geometry and the *ak135* Earth model. We estimate the reduction in precursor amplitude due to a finite–thickness discontinuity using a simple model of vertically–incident P energy [*Richards*, 1972] and find the observed amplitude discrepancy can be accounted for by spreading the velocity transition near 410–km linearly across ~11 km. The 5.0% reflection from the "660" discontinuity is ~22% smaller than the predicted zero–thickness value, indicating an ~6 km velocity transition near 660 km. Using another reference earth model, PREM [*Dziewonski and Anderson*, 1981], we obtain similar thicknesses estimates of 9 km for the "410" and 6 km for the "660".

The "410" is likely even broader than 10 km under Africa, given that high resolution regional P–wave studies [*Walck*, 1984; *Melbourne and Helmberger*, 1997] find the velocity contrast across the "410" up to 65% greater than that of *ak135*. Our "410" thickness estimate is almost doubled if the *ak135* P–wave velocity and density contrast are scaled by this amount. Conversely, the "660" is likely sharper than 6–km, considering discontinuity models which predict zero–thickness reflection coefficients less than our observed values [*Walck*, 1984; *Estabrook and Kind*, 1996].

In summary, our estimates of discontinuity thickness range from 9 to 20 km for the "410" and 0 to 6 km for the "660" depending on the selected reference model. We caution that these sharpness predictions come from a single earthquake and several simplifying assumptions. The estimates do not account for degradation of the surface reflected $P'P'$ pulse from crustal reverberations, upper–mantle attenuation and scattering. Furthermore, travel–time anomalies accrued in the upper–mantle $P'P'$ legs may result in incoherent stacking of the "410" and "660" arrivals lowering their amplitudes. Focusing and defocusing from discontinuity topography can also cause variations in precursor amplitude. [*Davis et al.*, 1989] showed topography of only 10–km over a scale length of 1000–km can cause up to a factor of two variation in $P'P'$ precursor amplitude. Confidence in the discontinuity sharpness estimates will increase with better modeling and the addition of more data.

Other discontinuities

We infer a reflector near the depth of 320–km (Figure 4b), Reflectors at similar depths have been reported in different tectonic settings *Hales et al.* [1980]; *Revenaugh and Jordan* [1991]; *Revenaugh and Sipkin* [1994]. Our observation of a "320" is complicated by its absence in the lower frequency stack (Figure 4a). It is possible to obtain band–limited reflections from complicated velocity transitions, however, we will not further interpret this arrival here.

The absence of high–frequency "520" P reflections (Figure 4) and the existence of lower–frequency "520" S reflections [*Shearer*, 1996] is consistent with an olivine $\beta \rightarrow \gamma$ phase change occurring over a depth interval of 50 km [*Katsura and Ito*, 1989; *Akaogi et al.*, 1989] with an impedance contrast of 2.5–5% for P and 3–4.5% for S [*Rigden et al.*, 1991].

Global variability

A robust feature of the data is the difference between the "410" and "660" reflection amplitude, consistent with a sharper "660" than "410" given similar impedance contrasts. The absence of the "410" reflection in the higher pass–band stack (Figure 4b) also supports this interpretation. The $P'P'$ phases we present here reflect from an approximately 900–km by 300–km northeast–southwest trending swath centered near 11° S, 29° E beneath southern Africa. The characteristics of these precursors contrast with regional array observations of $P'P'_{ab}$ precursors which reflected beneath the Indian Ocean [*Benz and Vidale*, 1993a]. In that study, both the "410" and the "660" were equally effective reflectors of short–period P waves, indicating either a diffuse "410" boundary under southern Africa or global variations in the impedance change across the "410".

Previous $P'P'$ studies with smaller aperture arrays and global network data generally find that the "660" produces noticeable precursors while the "410" does only sometimes, [*Engdahl and Flinn*, 1969; *Adams*, 1971; *Husebye et al.*, 1977; *Nakanishi*, 1988; *Whitcomb and Anderson*, 1970; *Earle and Shearer*, 1997]. However, one study observed only a small fraction of events with "660" or "410" precursors, despite fine data [*Davis et al.*, 1989].

Studies using different methods have produced a variety of results. Short–period reflections and conversions tend to indicate sharp discontinuities [*Neele*, 1996; *Yamazaki and Hirahara*, 1994; *Vidale et al.*, 1995]. Using both short–period and broadband refracted P waves, *Melbourne and Helmberger* [1997] modeled the "410" under Colorado plateau as a sharp boundary over–lain by a gradient zone. Refraction data from nuclear tests in the former Soviet Union, on the other hand, has been used to argue for a "410" distributed across 35 km under the central Eurasian craton [*Priestley et al.*, 1994]. Broadband studies of transmitted S–to–P conversions suggest that the "660" may be accompanied by a distributed velocity increase, while the "410" is not [*Petersen et al.*, 1993].

Radial earth models also often exhibit an enhanced velocity gradient below the "660" [*Dziewonski and Anderson*, 1981; *Kennett et al.*, 1995; *Shearer*, 1996]. Such a gradient may indicate a gradual phase transition in the garnet component of mantle rock, while the sharper "660" would be the phase transition in spinel [e.g., *Faust and Knittle*, 1996]. Near the "410", only the olivine phase has a transformation, so there may not be a wide gradient nearby.

Mineral physics studies of the probable mantle phase transitions may provide an explanation for discrepancies in the results of seismic investigation into the details of the mantle discontinuities. Lateral variations in reflection amplitude and frequency content may be due to variations in mantle bulk composition or amount of H_2O present [*Helffrich and Wood*, 1996; *Stixrude*, 1997]. The reflection properties are expected to depend a little on temperature [*Helffrich and Bina*, 1994]. Finally, non–equilibrium phase transitions have been suggested as reasons for the apparent variation of the discontinuity thickness [*Solomatov and Stevenson*, 1994].

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