On the observation of high frequency PKiKP and its coda in Australia

G. Poupinet a, b, *, B.L.N. Kennett a

a RSES, Australian National University, ACT, 0200 Canberra, Australia
b LGIT, Université Joseph Fourier and CNRS, BP53, 38041 Grenoble, France

Received 26 November 2003; received in revised form 8 April 2004; accepted 14 May 2004

Abstract

The seismic phase PKiKP, reflected from the inner core, and its coda give information on the short scale heterogeneities at and below the inner core boundary (ICB) of the Earth. We have collected PKiKP recorded at short distances (<45°) at broadband stations in Australia and at the Warramunga seismic array (WRA). Despite potential complications from a dual-passage through D″, PKiKP is frequently observed on single traces in the frequency band 1–5 Hz. PKiKP usually has a sharp onset, but sometimes its waveforms have multiple pulses separated by times of the order of 1 s. At WRA, the coda of PKiKP initially decays very rapidly after the main pulse. Thereafter, its amplitude is nearly constant and more than three times smaller than PKiKP with duration longer than 200 s. Our observations differ from those of [Nature 404 (2000) 273–275], at rather greater distances, who found that the coda is larger than PKiKP and increases slowly. We suggest that the PKiKP coda is generated near the inner core boundary by complex reverberation effects, rather than scattering through the volume of the inner core.

© 2004 Elsevier B.V. All rights reserved.

Keywords: Seismic phase; Heterogeneities; PKiKP; Inner core

1. Introduction

The inner core of the Earth (IC) has been the object of a number of recent studies. The inner core structure departs from spherical symmetry and may rotate with respect to the mantle (see Tromp, 2001 for a review). The fact that PKPnor travels faster in the polar directions than in the equatorial directions (Poupinet et al., 1983) is explained by P-anisotropy inside the inner core (Morelli et al., 1986). Song and Richards (1996) measured a temporal change in PKPnor–PKPnor differential times from which they postulated that the inner core is rotating by 1.1° per year with respect to the mantle. A debate on the size of the inner core rotation continues (Souriau, 1998; Poupinet et al., 2000) because the measurements are affected by the precision of the event locations. Several studies have relied on small scale PKP travel time gradients caused by heterogeneities inside the inner core. A temporal shift in the pattern of the small-scale heterogeneities on or near the ICB would be the best technique to prove that the inner core is rotating (Creager, 1997; Vidale et al., 2000). However, it is extremely difficult to prove that a travel time anomaly originates in the inner core (Bréger et al., 2000).

Small-scale heterogeneities are also important to understand the mechanism of formation of the inner
core (Vidale and Earle, 2000; Garcia and Souriau, 2000; Tromp, 2001). Vidale and Earle (2000) studied 12 earthquakes recorded during the 1970s on the large aperture seismic array (LASA) in the distance range from 50 to 70°. They found that the onset of PKiKP is not detected, but that stacking distinct events with suitable velocity filtering reveals a slow increase in amplitude after the theoretical time of PKiKP with a maximum achieved 60–70 s after PKiKP. Vidale and Earle (2000) interpreted this amplitude rise as the coda of PKiKP. The slow rise and slow decrease of the coda of PKiKP is the main argument in favor of strong scattering within the outer 300 km of the inner core; a model of textural anisotropy with about 1.2% velocity variation on a scale of 2 km has been suggested to explain this amplitude pattern. Heterogeneities of this size would imply the presence of lenses of melt in the inner core or short scale variations in the orientation or strength of anisotropy in the outer part of the inner core. Generally, the outer part of the inner core is thought to be less anisotropic than the deeper inner core (Garcia and Souriau, 2000). Tromp (2001) finds it difficult to imagine that the inner core is so heterogeneous because it has slowly crystallized in a homogeneous fluid outer core for several billion years.

Koper et al. (2003) have assembled a worldwide data set of PKiKP and PcP using beamforming and a cross-correlation algorithm, including some data from the Alice Springs (ASAR) and Warramunga (WRA) arrays in Australia; their differential PKiKP-PcP travel-times constrain the thickness of the core to vary by less than 3.5 km.

With broadband sensors at the upgraded Warramunga array, we found a number of examples of clear high-frequency PKiKP on single channels for comparatively close events and this encouraged us to look for examples of PKiKP at the portable broadband stations which have been deployed across Australia (see, e.g., Kennett, 2003). For intermediate and deep events with body wave magnitude above 6, we have found many examples of PKiKP arrivals with substantial energy above 1 Hz (Fig. 1) on records recorded over a broad area of the continent. Clear observations have been made at both sites on the Precambrian shield and in the Palaeozoic fold belts in the east of Australia for a number of events in the New Britain and Vanuatu arcs. The portable stations were only in place for about 5 months in each location so that only rarely are there more than one or two suitable events in the time period, but nevertheless examples of high frequency PKiKP are found for almost all sites.

In Fig. 2 we illustrate record sections for both high frequency PcP and PKiKP for an event in the Vanuatu subduction zone at a depth of 144 km recorded across the stations of the SC deployment of the Skippy experiment in the Northern Territory of Australia. High frequency PKiKP energy in the 1–5 Hz band can be tracked over a distance of nearly 8°, with comparable coherence to PcP which is about a factor of 4 larger than that of PKiKP. The variability of waveform is comparable for the two core phases, reflecting the conditions at the temporary stations. Clearly there needs to be a very rapid change in seismic properties at the inner core boundary for the region sampled by these observations and the others indicated in Fig. 1 for the consistent return of high frequency energy. In this case both PcP and PKiKP are clear at high frequencies, but often there is little high frequency PcP or ScP from events with clear PKiKP.

The permanent Warramunga array lies within the SC deployment and is now equipped with 24 vertical component broad-band sensors, which provides a powerful tool for the analysis of PKiKP. Koper et al. (2004) report observations of high frequency PKiKP...
on data from the Alice Springs Array (ASAR), which also lies within the area covered by the SC array. The Warramunga array was being upgraded for much of the time window studied by Koper et al. (2004) and so only a limited amount of data was available to them.

3. PKiKP data on the Warramunga array

The Warramunga array (WRA) was installed in the Northern Territory of Australia in 1965, with a L-shaped configuration of 20 short-period stations (the blue arm [WB] at approximate azimuth of 8° and the red arm [WR] nearly due east), installed into shallow boreholes drilled into granite. The station spacing is typically about 2.5 km. The GDSN station WRAB lies approximately 500 m from the junction of the two arms. WRA records a large number of earthquakes at short distances from the nearby earthquake belts, since it has very low noise levels in the 1–5 Hz frequency band and consequently high sensitivity to small signals. Buchbinder et al. (1973) presented several examples of PKiKP recorded at WRA. An extensive set of PKiKP phases recorded at sub-critical distance at WRA was extracted by Souriau and Souriau (1989); they showed that PKiKP for short-period sensors is usually hidden in the coda of P, ScS or SS, and that PKiKP could not be observed on single channels but was easily detected by beamforming.

In 1999 the sensors and the recording electronics were upgraded within the framework of the Comprehensive Test Ban Treaty with four new stations near the junction of the arms [WC]. The array currently comprises 24 broadband vertical seismometers and one three-component station (Guralp CMG ESP), with high dynamic range achieved by 24 bit A/D conversion at the sensor (Nanometrics Callisto) with 40 Hz sampling and digital telemetry to the central recording laboratory. We collected records for $M > 6.5$ earthquakes at distances less than 45° from the continuous array data for WRA which is archived to CD on site.

To extract PKiKP from the P-coda at WRA, a simple band-pass filter with a lower corner at 2.0 Hz is very efficient and stacking is not required. The events...
Fig. 2. Record section of high-frequency PKiKP, band pass 1–5 Hz, recorded at portable broadband stations in the Northern Territory of Australia [SC] from event C in Vanuatu at a depth of 144 km [22 August 1994, −11.53 S, 166.54 E].

used in the subsequent analysis are listed in Table 1 and their locations and ray paths are plotted in Fig. 3. The reflection on the inner core lies at the midpoint between source and station. Many clean PKiKP phases are observed on individual traces; a few examples are shown in Fig. 4 where the traces are band-pass filtered between 2.0 and 7.0 Hz. The traces are presented in order of adjacent stations, so that the variation in \( \frac{dT}{d\Delta} \) is obvious for the main two legs of the array. For event 4 which is located near Bali, the WB-leg is oriented perpendicular to the wave-front; all WB-sensors record PKiKP at the same time; the WR-leg shows a

<table>
<thead>
<tr>
<th>n</th>
<th>Date</th>
<th>Hour</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth</th>
<th>Magnitude</th>
<th>Distance</th>
<th>PKiKP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18-12-2000</td>
<td>01:19:21.6</td>
<td>−21.18</td>
<td>−179.12</td>
<td>628</td>
<td>6.7</td>
<td>43.48</td>
<td>942.89</td>
</tr>
<tr>
<td>2</td>
<td>21-12-2000</td>
<td>01:01:27.7</td>
<td>−5.71</td>
<td>151.12</td>
<td>33</td>
<td>6.6</td>
<td>21.59</td>
<td>994.57</td>
</tr>
<tr>
<td>3</td>
<td>09-01-2001</td>
<td>16:49:24.0</td>
<td>−14.93</td>
<td>167.17</td>
<td>103</td>
<td>7.1</td>
<td>31.68</td>
<td>991.73</td>
</tr>
<tr>
<td>4</td>
<td>16-02-2001</td>
<td>09:10:20.0</td>
<td>−5.91</td>
<td>130.20</td>
<td>33</td>
<td>7.0</td>
<td>20.78</td>
<td>994.18</td>
</tr>
<tr>
<td>5</td>
<td>31-10-2001</td>
<td>10:34:53.7</td>
<td>−14.65</td>
<td>153.27</td>
<td>34</td>
<td>6.7</td>
<td>23.79</td>
<td>995.52</td>
</tr>
<tr>
<td>6</td>
<td>26-04-2002</td>
<td>16:06:07.0</td>
<td>13.09</td>
<td>174.00</td>
<td>69</td>
<td>6.9</td>
<td>78.24</td>
<td>1035.9</td>
</tr>
<tr>
<td>7</td>
<td>21-12-2000</td>
<td>01:19:21.6</td>
<td>−21.18</td>
<td>−179.12</td>
<td>628</td>
<td>6.7</td>
<td>43.48</td>
<td>942.89</td>
</tr>
<tr>
<td>8</td>
<td>08-10-2001</td>
<td>09:10:20.0</td>
<td>−5.91</td>
<td>130.20</td>
<td>33</td>
<td>7.0</td>
<td>20.78</td>
<td>994.18</td>
</tr>
<tr>
<td>9</td>
<td>16-06-2003</td>
<td>22:08:02.1</td>
<td>55.49</td>
<td>160.00</td>
<td>174</td>
<td>6.9</td>
<td>78.24</td>
<td>1035.9</td>
</tr>
</tbody>
</table>
small offset between sensors. PKiKP is quite sharp, but has much smaller amplitude than P, by a factor of about 10,000 and than PcP, about a factor of a 100. Sometimes, it is even possible to pick PKiKP even though PcP is hardly visible.

In the 2–7 Hz band, phases reflected from the core mantle boundary often show noticeable waveform variations across the Warramunga array, yet PKiKP does not usually show such a degree of complexity; as can be seen from Fig. 4 most traces are well correlated. However, the PKiKP waveforms vary from one event to the other and are often composed of several well separated pulses, even though the P wave is simple. The time separation between the multiple onsets is of the order of 1–2 s, which is too small to be associated with depth phases or near source conversion from S to P. Such multiple onsets have also been seen at the portable stations, e.g., for event B at the SB stations (Fig. 1). The arrivals of PKiKP are mostly 0.5–3 s late compared to the times predicted for model ak135 (Kennett et al., 1995), and there do not appear to be any significant precursor complexities associated with a “mush” surrounding the ICB. The relative simplicity of the PKiKP arrivals compared with PcP and ScP is intriguing, since all have relatively steep paths at these short epicentral distances and thus would be expected to have comparable interaction with crust and mantle structure in the vicinity of the array. We note that the reflection and transmission points at the core-mantle boundary will be separated and PKiKP has to pass twice through D″. The high frequency behaviour of PcP, ScP suggests rather complex interactions in reflection at the CMB which will be the object of further study.

Fig. 5 shows the individual traces for the stations at WRA for event 4 filtered in three consecutive fre-
Fig. 4. Examples of PKiKP recorded on individual traces of the Warramunga seismic array for eight events. The data have been filtered between 2.0 and 7.0 Hz. There is no need to stack traces to observe clear reflections from the inner core boundary.
Fig. 5. PKiKP for event 4 at the WRA array in the three frequency bands 5.0–6.5, 3.5–5.0, 2.0–3.5 Hz. Two onsets are detected with a time interval of 1 s. The arrival time of PKiKP appears different for the two extreme frequency bands.

The complexity of the high frequency observations for PKiKP suggests that the sharp transition from the outer to the inner core may be accompanied by laterally varying layering with alternating lower and higher impedance.

4. The coda of PKiKP

The onset of PKiKP is followed by a long and complex coda, up to 200 s long, whose amplitude for events with epicentral distance less than 40° can reach about one-third of the initial pulse. The apparent slowness through the coda is close to that for PKiKP itself, which suggests an origin at depth rather than in the immediate vicinity of the array.

In Fig. 6 we display stacks of the records for the whole array for event 3 with a slowness appropriate to PKiKP for the full timespan from P to SKiKP. We show a number of different styles of stack which emphasise different aspects of the seismograms. The upper trace (WEV) is a stack of the envelopes of the records.
The cross-over between ScS and PKiKP occurs around 30°. ScS frequently displays a complex wave train reflecting the heterogeneity of D' (Lay et al., 1998 for a review), but has little expression on the vertical component. For events in the Fiji-Tonga region whose distance is of the order of 40° to WRA, ScS occurs within the coda of PKiKP and could cause some contamination despite its polarization and generally lower frequency. We therefore concentrate on the properties of the PKiKP coda at shorter distance.

For event 4 (521 km depth) we display the interval between PKiKP and pPKiKP in Fig. 7. The upper panel shows the stack records using the PKiKP slowness for band-passed records (2.0–6.0 Hz) which are shown in the lower panel. The stack records follow the same configuration as in Fig. 5, with the envelope stack, linear stack and the phase weighted stack accompanied by the measure of phase coherency. The amplitude of PKiKP on the envelope stack and the linear or phase weighted stacks is very large compared to any pulse following between this phase and the expected pPKiKP arrival time for this deep event. A distinct coda can be seen on many stations, although a few are somewhat noisy in this high frequency band. The detailed behaviour of the coda is revealed by looking in detail at the envelope stacks and extracting the background associated with prior phases. Four examples of such PKiKP envelope stacks are shown in Fig. 8 for events 1, 3, 4 and 9. We extrapolate the decreasing amplitude of the envelope stack of the segment ahead of PKiKP until we hit the intrinsic noise
Fig. 7. (a) Stacks of the WRA data for event 4 for PKiKP and its coda, with band pass filtering between 2.0 and 6.0 Hz. The stack traces are in the same style as in Fig. 5. (b) The filtered traces used in the stack. The amplitude of PKiKP is very large compared to any arrival in the following 100 s, but there are some bursts of relatively coherent energy.
threshold for the 3.0–7.0 Hz band dictated by the ambient noise at the array. The actual PKiKP coda is then represented by the difference between the stacked envelopes and the estimated decaying component from the coda of prior phases. For all the records we have for events with $M > 6.5$, PKiKP is followed by an observable coda in the frequency range 3 Hz to 6 Hz. At lower frequencies, the coda of previous phases—essentially P and S—dominates the noise and is larger than the PKiKP coda contribution. In the examples shown, the end of the PKiKP coda cannot be measured precisely but the duration seems to exceed 200 s. Interestingly, after a long interval with an almost constant level close to the noise threshold, the amplitude of the seismogram increases significantly from 1700 to 2000 s, as illustrated for two events in Fig. 9. This increase in amplitude occurs as a precursor to PKKP most likely generated by scattering near the core-mantle boundary (Chang and Cleary, 1981; Earle and Shearer, 1997; Earle, 2002). The duration of the increased amplitude is more than 100 s and declines before the onset of PKKP. Scattering from the central inner core would occur earlier than 1700 s and its absence limits the degree of heterogeneity inside the inner core.

The PKiKP coda at WRA for these events at distances less than 45°, with reflection points at the inner-core boundary (ICB) near the equator, differs in all frequency bands from that seen for events at LASA by Vidale and Earle (2000) at distances from 55 to 70° with mostly polar sampling of the ICB. In the observation of Vidale and Earle, the PKiKP coda is large compared to the onset of PKiKP with an amplitude increasing slowly during the first 60 s and then
Fig. 9. For travel times of the order of 1700s, an increase in the amplitude of the stacked signal is frequently observed, this corresponds to the arrival of precursors to PKKP as already observed by Earle and Shearer (1997) at larger distances.
decreasing very slowly afterwards. In our examples, the coda is usually smaller than PKiKP and remains at a nearly constant level for more than 200 s. Even for event 9 at large distance 74°, the amplitude of the PKiKP coda is of the same order as the amplitude of PKiKP. The large difference in coda behaviour needs to be understood. All the events of Vidale and Earle (2000) are at a distance beyond 55° and the coda from earlier phases should be smaller than for our events in the distance range 20–45°. The best frequency range for separating PKiKP from the P coda is higher than 2 Hz at WRA, working directly with raw data and with minimal processing. In contrast for Vidale and Earle (2000) the separation frequency is at 1 Hz for the LASA results that have been subjected to velocity filtering and a stack of multiple events; their processing is sophisticated but the relation to the visual traces is somewhat lost at the end of the processing.

The character of the PKiKP coda for events at distances less than 45° revealed in this analysis using the broad-band sensors of the updated Warramunga array is similar to that summarised by Koper et al. (2004) from a search through array data in the period from 1995 to 2000, which included data prior to 1998 from the older version of WRA with short-period seismometers. The peak amplitude, as in Fig. 8, lies at the onset of PKiKP with a relatively sharp drop over an interval of 10–20 s and then a relatively slow decay over an interval of 200 s.

We have searched for secondary arrivals within the coda of PKiKP by stacking techniques. Weak secondary pulses are observed in many cases, but their times and amplitudes vary considerably from event to event. Although the presence of interfaces inside the inner core cannot be excluded by the present analysis—we have some indications of clear reflections at 10 and 20 s after PKiKP—the absence of systematic results leads us to think that if there is an interface below the surface of the inner core, it does not appear as a constant depth reflector. However, we should note that to avoid contamination from the large

![Fig. 10. Isochrones for reflection from the ICB for an epicentral distance of 40°, in an equal area projection of the hemisphere centred on the geometrical reflection for PKiKP, the tone changes for each 10 s interval. GC denotes the great-circle direction between source and receiver.](image-url)
P and S coda at low frequency, we stack high frequency signals that are likely to be attenuated inside the inner core.

The extended PKiKP coda undoubtedly bears the imprint of heterogeneity encountered in the crust and upper mantle. How much of this signal is associated with the inner core? We can gain some measure of insight by stacking the WRA data for a broad range of different slownesses and making comparisons with PcP. The duration of the high-frequency PcP coda calculated in a similar way to that illustrated in Fig. 8, is around 60–80 s, which is substantially shorter than that for PKiKP. This is a similar duration to the PKiKP coda when stacked at the slowness for horizontally propagating S waves (25 s per degree), for which the coda envelope level is about one-third of that for the PKiKP slowness (0.75 s per degree).

We therefore have a good case for the long duration of the PKiKP coda having a direct association with the reflection of the PKiKP phase from the inner core boundary. Fig. 10 shows the isochrons for reflection from the inner core boundary as an equal area projection of the hemisphere centred on the geometrical reflection point for PKiKP at an epicentral distance of 30°, which we see to be extended transverse to the great-circle path between source and receiver. Along the great circle direction the maximum delay in asymmetric reflection would be about 120 s, and increases somewhat for reflection points transverse to the geometrical path. The domain of reflection times is slightly larger for shorter epicentral distances. Reflection from localized scatterers at the ICB can therefore account for a fair part of the duration of the PKiKP, but when we take account of the expected amplitudes including geometric spreading and scattering potential we would expect a steady diminution of amplitude rather than the constant level which is observed. We need therefore to have some class of structure close to the inner core boundary that can sustain the coda through some class of reverberation.

5. Discussion

Our observations imply that the inner core boundary is a more complex interface than envisioned in some previous studies. For instance, Cummins and Johnson (1988) have modeled PKiKP and PKP short period waveforms for various transition zones at the ICB. We need to explain the sharpness of the onset of most PKiKP phases and their high frequency content, as well as the appearance of multiple onsets separated by about 1 s. However, the low frequency content of PKiKP should be also kept in mind (Doombos, 1983; for a recent study on attenuation, see Cornier and Li, 2002). For instance for event 4, PKiKP recorded at NNA, Peru, is markedly lower frequency than the PKiKP phase at WRA; even though both waves propagate in the same azimuth from the source to the ICB, because PKiKP loses its high frequency after entering the ICB. The coda of PKiKP remains a high frequency wave train and rings with a nearly constant amplitude for at least 200 s.

There are some similarities with the long duration of high frequency coda sometimes associated with Pdiff, which itself is a rather low frequency phase (Bolt et al., 1968; Wright and Muirhead, 1969; Husebye and Madariaga, 1970; Bataille et al., 1990; Bataille and Lund, 1996; Tono and Yomogida, 1996, 1997). Bataille and Lund (1996) and Tono and Yomogida (1996, 1997) explained this coda by multiple scattering at the CMB. It is probable that both the coda of PKiKP and Pdiff are the result of similar physical processes related to a major interface. The ‘ringing’ of the PKiKP coda would appear to be related to some class of layered structure and lateral heterogeneities would contribute to the complexity and the variation in shape of the PKiKP waveforms depending on the reflection point at the ICB. Some kind of energy channeling has to be introduced to create such a long resonance near the ICB. The high frequency character of this coda excludes it originating deep in the inner core where attenuation is high. The nature of the PKiKP coda is likely to arise from multiple scattering at the ICB associated with reverberation in some class of structure with lowered wavespeed.

This mechanism for generating the PKiKP coda can be called inner core boundary scattering (ICBS) and differs from the inner core scattering (ICS) invoked by Vidale and Earle (2000). ICBS only gives information near the interface itself (the inner core boundary) and not on the bulk properties of the inner core. The main conclusion of Vidale and Earle (2000) which was that the observation of the coda implies the presence of strong heterogeneities within the inner core (may-be melt pockets) would not be valid if the coda...
is generated by ICBS. Further observations of PKiKP
coda in other locations are necessary before proper
modeling of this complex physical mechanism can
be attempted. The deployment of several small arrays
similar to Warramunga in the framework of the Com-
prehensive Nuclear Test Ban Treaty should provide a
wealth of new PKiKP data in the near future.

The PKiKP wave is transmitted twice through the
structure at the core-mantle boundary, which is known
to be complex and laterally heterogeneous. However,
the preservation of high frequencies implies that this
transmission is efficient, even though it could add
complexity to the transmitted waveform. In the lim-
ited sample of high-frequency core reflections we have
found at WRA the reflected pulse is simpler than the
onset of PKiKP. However, as noted above the reflec-
tion and transmission points are not the same, even
though they will be relatively close for short distance
observations. More observations are needed to resolve
the contribution of core-mantle boundary structure to
the character of PKiKP, but it does not appear to be
large.

6. Conclusions

(a) For large magnitude earthquakes ($M > 6.5$)
recorded on the portable broadband stations and at
the Warramunga array, PKiKP is often observed
at subcritical distances as clear onsets on single
traces with frequencies higher than 1 Hz, despite
double passage through the complex structure of
$D''$. At WRA the best separation frequency be-
tween PKiKP and the coda of prior phases is 2 Hz,
and simple filtering, without stacking suffices to
enhance PKiKP.

(b) The PKiKP waveform is usually a sharp arrival but
multiple onsets are frequently observed in the first
few seconds, from a range of source locations. At
WRA, the arrival time of the first onset is close to
that predicted from ak135 but is usually slightly
late.

(c) At WRA the amplitude of PKiKP is usually larger
than that of the PKiKP coda. The high frequency
PKiKP coda remains at a near constant level for
a duration of about 200 s after the PKiKP arrival
time. Unlike the examples shown by Vidale and
Earle (2000) for somewhat larger epicentral dis-
tance, the PKiKP coda at WRA does not increase
slowly as a function of elapsed time. If the coda
of PKiKP is generally as high frequency as ob-
served at WRA, the use of the correlation of event
doublets to detect a temporal variation in the coda
related to an inner core rotation may be problem-
atic. The two sources would need to be perfectly
similar even at high frequency.

(d) The stacks of the traces at WRA for the interval
following PKiKP do not detect any consistent re-
flectors at depth within the inner core, but do re-
veal an increase in amplitude at much later times
corresponding to precursors to PKKP.

(e) The long duration and complexity of the PKiKP
coda at WRA suggests the presence of inner core
boundary scattering with some class of reverber-
ate process. From these limited observations it is
difficult to propose a suitable physical model
that is consistent with both the variability of
the waveform of PKiKP and its complex coda.
However, it is possible that variations in material
anisotropy as the inner core surface freezes or
percolation of fluid could contribute to zones of
lowered wavespeed.

Acknowledgements

GP thanks the Research School of Earth Sciences,
Australian National University, for allowing him to
spend a sabbatical period in Canberra and CNRS for
supporting him. Program “Intérieur de la Terre” from
CNRS-INSU contributed to this project. We acknowl-
edge the help of Armando Arcidiacono for the War-
ramunga data and of Craig Bugden. We thank Nick
Rawlinson, Keith Koper and John Vidale for their
help.

References

the core-mantle boundary evidenced from scattered waves: a

seismic waves by core-mantle boundary and the P-diffracted

110$^\circ$ is structure in core or upper mantle responsible. Geophys.
J. R. Astron. Soc. 39, 523-537.


