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The observation of inner core shear waves

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SUMMARY

Although the Earth's inner core has long been thought to be solid, there have not, as yet, been unequivocal observations of inner core shear waves. Here we present observations of the phases *pPKJKP* and *SKJKP* for the Flores Sea event of 1996 June 17. The observations support the value of approximately 3.6 km s^{-1} for the inner core shear wave velocity and open up new possibilities for exploring the anisotropic structure and the attenuation properties of the inner core. The analysis and validation of the observation is based on a new method that can be used in the search for and identification of inner core shear waves. In this method normal mode synthetics for a solid inner core are compared with those for a fluid inner core. It is only by such comparisons that it is possible to be certain that inner core shear waves, rather than interferences of other phases, are responsible for observed energy maxima in stacked seismic records.

Key words: inner core, *S* waves, seismic phase identification, synthetic seismograms.

1 INTRODUCTION

Since early in the last century, seismologists have believed that the Earth consists of a liquid core surrounded by a solid mantle and crust (Oldham 1906). The liquid core produces a shadow zone in which no waves are expected to arrive. When Lehmann (1936) observed waves in the core's shadow zone, she proposed the existence of an inner core with a somewhat larger *P*-wave velocity than the outer core. It has long been thought that the inner core is solid (Birch 1940; Bullen 1946) and that is has a sharp boundary (Engdahl *et al.* 1970). Seismological evidence for its solidity can be obtained in two different ways, namely from normal mode observations and from body wave observations.

It was demonstrated that free-oscillation overtone data require a solid inner core with a mean shear velocity close to 3.6 km s^{-1} (Dziewonski & Gilbert 1971, 1972; see Bullen 1975 for a discussion of earlier work). Additional evidence came from the fact that inner core anisotropy is needed to explain the anomalous splitting of modes sensitive to the inner core (Woodhouse *et al.* 1986; Tromp 1993). This anisotropy is also observed for *PKIKP* body waves that travel faster along polar paths than along equatorial paths (Morelli *et al.* 1986; see Song 1997 for a recent review).

Direct evidence for the solidity of the inner core could be obtained from body wave observations by observing phases that traverse the inner core as shear waves. Examples of these waves, the *J*-phases, are *PKJKP* and *SKJKP*, in which *J* denotes passage as an *S* wave through the inner core (see Fig. 1). It is important to try to identify inner core shear waves in order to place more precise constraints on the shear velocity, attenuation and anisotropy of the inner core, which represents a state of matter not yet adequately understood.

Many researchers have sought to identify such a phase and the debate on its observability continues. Bullen (1951) showed that the *J*-phases will have very low amplitudes because of the inefficient conversion from *P* to *S* at the inner core boundary: an inner core shear wave will be at least five times smaller than a similar inner core compressional wave. Doornbos (1974) concluded that it will probably be impossible to observe inner core shear waves because of the inefficient conversions and the high attenuation at short periods in the inner core.

Nevertheless, there have been several claims of inner core shear wave observations. Julian *et al.* (1972) reported observations of *PKJKP* in short-period data from the LASA seismic array. This observation has been disputed by Doornbos (1974); in addition, the inferred shear velocity ($\sim$2.95 km s^{-1}) is at variance with the value inferred from free-oscillation studies. Recently, we (Deuss *et al.* 1998) reported observations of long-period inner core shear waves consistent with an inner core shear velocity of 3.6 km s^{-1}; Okal & Cansi (1998) made similar claims at shorter periods.

In this paper we first explain how weak signals can be observed using a phase-weighted stacking method and we then present a new method to evaluate whether these signals do indeed have the characteristics of inner core shear waves. We present an observation of *J*-phases and show that only by the

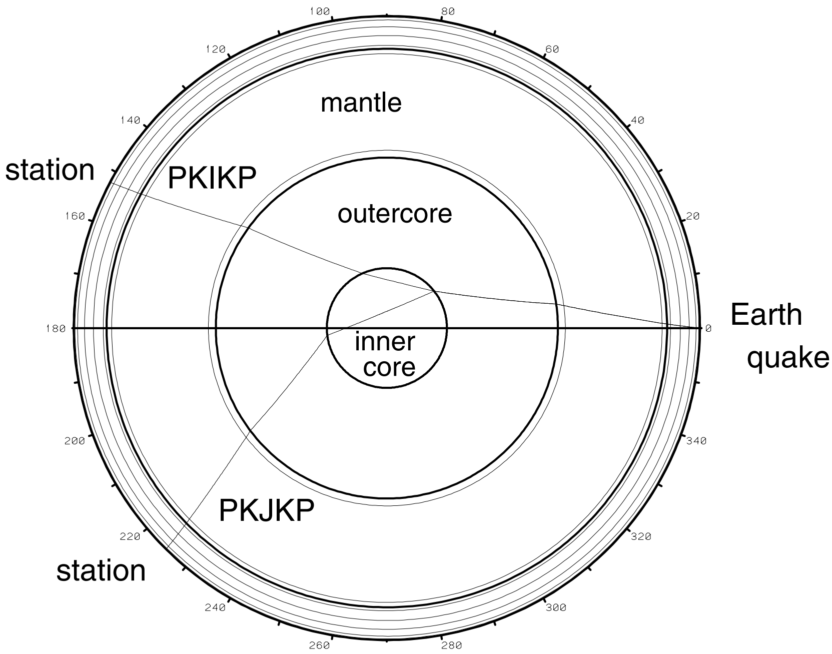


Figure 1. Ray paths of the inner core shear wave *PKJKP*, arriving from the major arc direction. For comparison, ray paths are also shown for the similar inner core compressional wave *PKIKP* that arrives from the minor arc direction and is easy to observe.

approach presented here can these observations be validated. Finally, we use our new method to investigate claims made by other researchers.

2 PHASE-WEIGHTED STACKS

Inner core shear waves have been shown to have a very low amplitude and consequently cannot be observed in an individual seismogram. In their attempt to observe *PKJKP*, Julian *et al.* (1972) made linear stacks of seismograms in the slowness time domain. We employ a new stacking method developed by Schimmel & Paulssen (1997) termed the *phase-weighted stack* (PWS), which has been shown to be more effective in unmasking weak arrivals than a linear stack. We briefly outline this method; a more detailed description and tests of its effectiveness can be found in Schimmel & Paulssen (1997).

The analytical signal or complex trace $S(t)$ can be constructed from the seismic trace $s(t)$ by taking its Hilbert transform $H(s(t))$ and writing

$$S(t)=s(t)+iH(s(t))=A(t)\exp[i\Phi(t)]\,, \quad (1)$$

where $A(t)$ is the envelope of $s(t)$ and $\Phi(t)$ is the instantaneous phase, which can be used as a measure of coherence. We seek to suppress incoherent noise by multiplying the linear stack $[\Sigma s_j(t)]/N$ with the phase stack $\{\Sigma_{k=1}^{N}\exp[i\Phi_k(t)]\}/N$, resulting in the phase-weighted stack

$$g(t)=\frac{1}{N}\sum_{j=1}^{N}s_j(t)\left|\frac{1}{N}\sum_{k=1}^{N}\exp[i\Phi_k(t)]\right|^{v}. \quad (2)$$

In this non-linear stacking method the linear stack is weighted by the phase stack with a power v. Setting $v=0$ results in the ordinary linear stack. We found it convenient to use $v=2$ in order to make the weighting not too severe.

We employ the method of slant stacking, in which records are stacked using a time delay $p\Delta$, where Δ is the epicentral distance, for a range of slownesses p in which the arrivals of interest are expected to occur. The stacks are used to generate contour diagrams in the τ–p domain, with $\tau=t-p\Delta$. *J*-phases arrive from the major arc direction with a small negative slowness $-2.1\ \mathrm{s}/^\circ\leq p\leq 0.0$ at a distance $90^\circ\leq\Delta\leq 180^\circ$. Ray theory for the reference model PREM predicts that the amplitudes will be maximum for $120^\circ\leq\Delta\leq 150^\circ$.

3 INTERPRETATION BY MODELLING OF SYNTHETIC SEISMOGRAMS

The first step in trying to observe inner core shear waves is computing phase-weighted stacks for real data in the time–slowness domain. This results in contour plots in which candidate *J*-phases appear as extrema at the expected slowness and arrival time. In order to verify that the stacks are similar to those expected for *J*-phases and that the extrema identified as *J*-arrivals cannot be accounted for by the interference of other phases, it is necessary to calculate stacks based on synthetic seismograms.

We compute synthetic seismograms by summing the Earth's normal modes (Gilbert 1971) up to a period of 6 s for the preliminary reference earth model (PREM, Dziewonski & Anderson 1981). This results in long-period seismograms containing all phases that arrive in a specific time window and therefore should be comparable to the corresponding observed seismograms. We convolve the seismograms with an appropriate source time function. It should be noted that normal mode synthetics are computed for an anelastic spherical earth, excluding the effects of inner core anisotropy and heterogeneity, and therefore a complete correspondence between normal mode synthetics and data cannot be expected.

The fact that there is good agreement between the data stacks and synthetic stacks for regions of the time–slowness domain corresponding to J-phases does not necessarily imply that these phases *are* J-phases; it is possible that other phases, travelling only in the mantle and the outer core, could interfere constructively in the stacks. Synthetic seismograms for the J-phases alone can be calculated by ray methods, and we compute ray theoretical seismograms using the WKBJ method (Chapman 1976). Correspondence between the observed and ray theoretic signals might suggest that the observations are J-phases. Again this could be a coincidence.

To validate further a possible identification of a J-arrival, we make a comparison between the data stack and synthetic stacks of normal mode seismograms obtained using models with and without a solid inner core. We shall refer to this as the fluid inner core (FIC) test. Parts of the signal that are present in the solid inner core stacks and not in the fluid inner core stacks can be attributed to inner core solidity. Mode catalogues (i) for PREM and (ii) for a model that is identical to PREM except that the shear velocity is set to zero in the inner core are calculated for periods to 6 s by the method of Woodhouse (1988). The shear velocity is set to zero and the P-wave speed and P-wave attenuation are kept unchanged. The *difference* between the synthetic seismograms obtained using these two mode catalogues makes it possible to identify clearly phases that are dependent on inner core solidity.

The essential rationale is that if a stacking method fails to give reliable results for synthetic data then there is no reason to rely on it when applied to real data. Of course, the synthetic seismograms used here are not an exact match to real data. Nevertheless, we show that using seismograms that are at least realistic ones (containing all phases for the PREM model) it is possible to obtain stacks having extrema that, while occurring at the appropriate τ–p values, cannot be identified with inner core phases. Whether or not inner core phases are identifiable in a given experiment depends on the source parameters, the station distribution, the frequency band used, etc.

4 APPLICATION TO DATA

We make use of data from two large, deep events (see Table 1). Recent expansions in the global digital seismic networks have led to large collections of broad-band seismograms for these events. We filter the data between 0.01 and 0.1 Hz. In general, J-phases are predicted to arrive with a slowness less than 2.1 s/° and the first J-phase, which is *PKJKP*, is predicted to arrive approximately 1600 s after the earthquake centroid time, depending on the depth of the event.

4.1 Flores Sea 1996 June 17

Fig. 2 shows the individual data traces for the Flores Sea event. As earthquakes typically generate S waves some five times larger in amplitude than P, it is worthwhile searching not only for *PKJKP* but also for *SKJKP*. It is clear that there are no

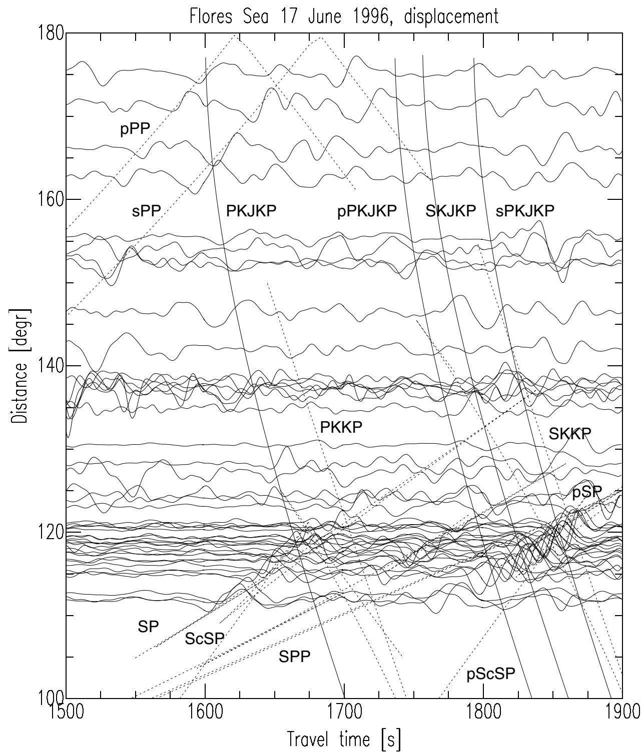


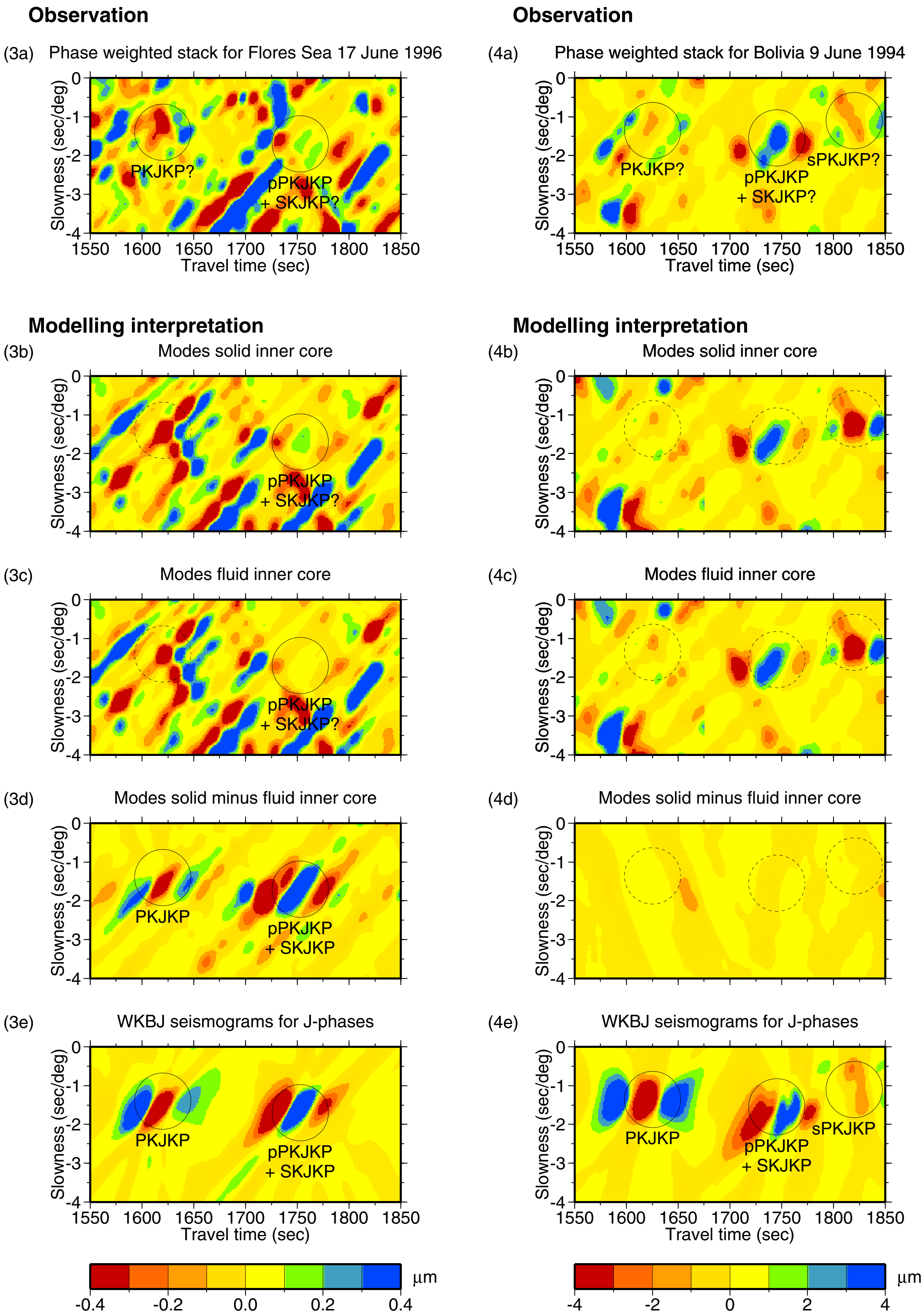
Figure 2. Data corresponding to the Flores Sea event. 47 vertical-component displacement seismograms from the IRIS/IDA and GEOSCOPE networks for the Flores Sea event of 1996 June 17, $M_W = 7.9$ at a depth of 584 km. Traveltime curves for *SKJKP*, *PKJKP*, *pPKJKP*, *sPKJKP* (solid lines) and *PKKP*, *SKKP*, *pPP*, *sPP*, *SP*, *pSP*, *SPP* (dotted lines) are plotted. None of the J-phases can clearly be identified in the original traces. A similar plot for the noise-free normal mode synthetics for a solid inner core does not show the J-phases either, indicating that the expected amplitudes are indeed very small.

arrivals identifiable as *PKJKP* or *SKJKP* in the data. A similar plot for the noise-free normal mode synthetics does not show the J-phases either, indicating that the expected amplitudes are indeed very small. The amplitudes predicted by PREM are below the level of other energy arriving at this time.

We calculate phase-weighted stacks for the Flores Sea event for the time window 1550 s $\leq \tau \leq$ 1850 s in which *PKJKP*, *pPKJKP* and *SKJKP* are predicted to arrive. We find clear extrema in the contour diagrams at the expected τ and p. Fig. 3(a) shows the contour plot in the slowness–time domain for the data from the Flores Sea event. There is a large arrival visible at the predicted slowness and time for *PKJKP* and a much smaller one for the interference between *pPKJKP* and *SKJKP*. We compute synthetic normal mode stacks for a solid inner core and a fluid inner core (Figs 3b and c), convolved with an appropriate source time function (Goes *et al.* 1997). The large arrival is still present in the stack for a fluid inner core, but the small green feature disappears in the fluid

Table 1. Event information for two recent large and deep earthquakes. The event parameters all come from the Harvard centroid moment tensor catalogue (Dziewonski *et al.* 1995, 1997).

Region	Date	Centroid time	Latitude	Longitude	Depth	Mw	Strike/dip/slip
Bolivia	1994 June 9	00:33:45.4	−13.20 N	−67.25 E	647 km	8.2	302/10/−60
Flores Sea	1996 June 17	11:22:33.7	−7.38 N	123.02 E	584 km	7.9	98/54/−52


Observation
(3a) Phase weighted stack for Flores Sea 17 June 1996
PKJKP?
pPKJKP + SKJKP?
Observation
(4a) Phase weighted stack for Bolivia 9 June 1994
PKJKP?
pPKJKP + SKJKP?
sPKJKP?
Modelling interpretation
(3b) Modes solid inner core
(3c) Modes fluid inner core
(3d) Modes solid minus fluid inner core
PKJKP
pPKJKP + SKJKP
(3e) WKBJ seismograms for J-phases
(4b) Modes solid inner core
(4c) Modes fluid inner core
(4d) Modes solid minus fluid inner core
(4e) WKBJ seismograms for J-phases
sPKJKP
Slowness (sec/deg)
Travel time (sec)
µm
-0.4 -0.2 0.0 0.2 0.4
-4 -2 0 2 4

inner core stack. This arrival can thus be attributed to J-phases (*SKJKP*+*pPKJKP*) as it appears in the synthetic stack only for the case in which a solid inner core is present.

It is desirable to verify that the features circled in Figs 3(a) and (b) are at the time and slowness expected for the J-arrival. In order to do this we need to be able to isolate the J-phase contribution to the seismograms. This can be done in two ways—(i) by calculating ray theoretic (WKBJ) synthetic seismograms for the J-phases alone, and (ii) by calculating the *difference* between the modal synthetic seismograms for models with and without a solid inner core. Fig. 3(d) shows the stack obtained using the differential synthetic seismograms, and Fig. 3(e) shows that obtained using the WKBJ seismograms. It is clear that both approaches give a strong feature at the location of the candidate J-phase arrival in Figs 3(a)–(c). All contour plots are on the same scale. The higher amplitudes in Figs 3(d)–(e) result from the high coherence, in the non-linear stack, of the synthetic seismograms containing only the J-arrivals. Note that in Figs 3(d) and (e) *PKJKP* is also strongly evident, but in the stacks for complete seismograms (*cf*. Figs 3b and c) this phase is largely masked by other arrivals.

4.2 Bolivia 1994 June 9

The largest arrivals for candidate J-phases are observed in phase-weighted stacks for the Bolivia event. Fig. 4(a) shows the data stack for this event. Features that could be due to inner core shear waves are indicated. Again we compute synthetic stacks for a solid inner core (Fig. 4b), and there is good agreement between the data and synthetic stacks. All the synthetics are convolved with a source time function for the Bolivia event (Lundgren & Giardini 1995). Again we show stacks for differential synthetic seismograms (Fig. 4d) and for WKBJ synthetic seismograms (Fig. 4e).

We then computed isolated ray theoretical J-phases using WKBJ seismograms (Fig. 4e); the observations in the real data appear to be explained by *PKJKP* and an interference of *pPKJKP* and *SKJKP*. One is thus tempted to conclude that this is indeed an observation of inner core shear waves. However, if we apply the FIC test and compute normal mode stacks for a fluid inner core (Fig. 4c) we find that the large features, tentatively identified as candidate J-phases, are still present in the stacks for a fluid inner core. Therefore, these cannot be J-phases and the observations for the Bolivia event are not validated by synthetic modelling. Also, the J-phases do not appear in the difference between the solid and fluid inner core seismograms (Fig. 4d). We have to conclude that the large arrivals at the slowness and arrival times for J-phases must have been caused by aliasing of mantle or outer core phases with different slownesses.

5 DISCUSSION OF THE OBSERVATION

Our observation for the Flores Sea event is in close agreement with the arrival time predicted by the PREM model.

Doornbos (1974) argued that *PKJKP* will be too small to be observed owing to the inefficiency of the conversions from P to S (and vice versa) at the inner core boundary and attenuation at high frequencies (e.g. 1 Hz). Theoretically, attenuation can be described as a filter in the frequency domain (Aki & Richards 1980),

$$A(\omega)=A_0(\omega)\exp\left[\frac{-\omega t^*}{2}\right]=A_0(\omega)\exp\left[\frac{-\pi t^*}{T}\right], \tag{3}$$

where A is the amplitude, ω is the angular frequency, T is the period and t^* is given by

$$t^*=\int Q^{-1}\,dt\,, \tag{4}$$

where the integral is with respect to traveltime along the ray path. The value t^* is dependent on the distance, but for PREM, having inner core $Q_\mu=85$, t^* values in the range 8.0–9.0 s are obtained for *PKJKP*. Some authors suggest a higher value for inner core Q_μ. For example, if $Q_\mu=125$, t^* has values of 5.5–6.5 s. Fig. 5 shows the frequency response of the attenuation filter. It is clear that for frequencies less than 0.01 Hz there is almost no influence of inner core attenuation. Using $t^*=8.5$ and 6.0 we find that the amplitude is reduced to one-tenth for periods of 11 and 8 s, respectively. Thus, amplitudes will be severely reduced for frequencies above 0.1 Hz.

We agree with Doornbos (1974) that at high frequencies it will indeed be impossible to observe J-phases. We therefore performed our search and modelling on low-frequency data between 0.1 and 0.01 Hz for which the influence of attenuation is not too severe.

The relative difference in amplitude between the J-phase observation and the surrounding signal is very similar for both the data and synthetic normal mode stacks. This suggests that the shear wave attenuation of PREM is close to the attenuation of our observation.

6 OTHER CLAIMS

Our finding rules out the inner core S-wave velocity of 2.95 km s^{-1} inferred by Julian *et al.* (1972) from short-period observations. Okal & Cansi (1998) have claimed an observation of *PKJKP* at intermediate periods (2–10 s) by progressive multichannel correlation (PMCC) for eight stations of the

Figure 3. Phase-weighted stacks for the Flores Sea event of 1996 June 17. (a) Data stack in displacement for 47 stations. (b) Normal mode stacks for solid inner core. (c) Normal mode stacks for fluid inner core. (d) Normal mode stacks for solid minus fluid inner core. (e) WKBJ seismograms for J-phases only (*PKJKP*, *pPKJKP*, *SKJKP* and *sPKJKP* arrive in this time window). All seismograms, synthetics and data, are deconvolved for instrument responses to displacement and filtered between 10 and 100 s. Normal mode and WKBJ synthetics are convolved with the source time function. The horizontal axis represents traveltime for the reference distance $\Delta=152°$. Black circles indicate the arrival times of maximum energy (centroid time) and ray parameter of the J-phases as indicated by PREM. It is clear that the feature for *pPKJKP* and *SKJKP* is present in the data and solid inner core stacks, while it disappears in the fluid inner core stack.

Figure 4. Phase-weighted stacks for the Bolivia earthquake of 1994 June 9. Similar to Fig. 3 but for a reference distance $\Delta=154°$ and 34 stations. Black circles again indicate J-phases. Although there are clear arrivals visible in the data for candidate J-phases, these cannot be confirmed by synthetic modelling. (In a, b and c amplitudes are amplified by a factor of 3 for times less than 1675 s to enhance visibility.)

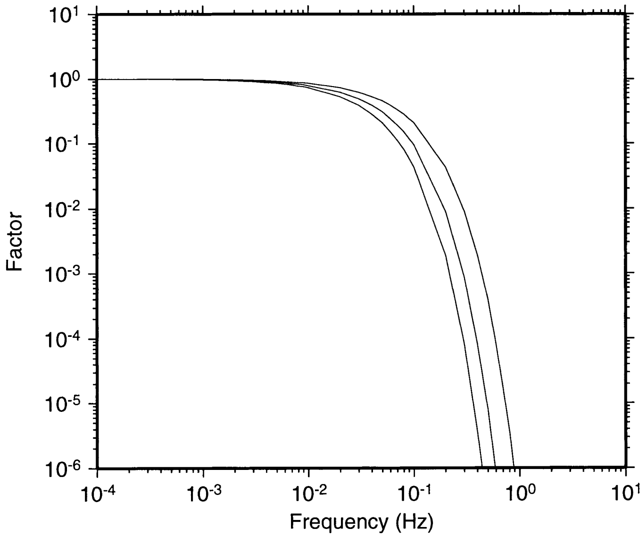


Figure 5. Attenuation filter for $t^*=5$, 7.5 and 10 s; factor$=\exp(-\omega t^*/2)$.

French short-period network. For the Flores Sea event this array has a width of only 6.5°, which is rather small to obtain good slowness resolution for an event with a source time duration of 20 s.

The PMCC method is a way to analyse array data for slowness and amplitude as a function of both frequency and arrival time. An observation is claimed when there is a signal detected at the predicted arrival time and slowness; it is in that sense very similar to our method. The next step is then to investigate the frequency content of the observed signal. A lower frequency content is caused by more attenuation; in this way Okal & Cansi (1998) separated *PKKPdf* ($t^* \approx 0.8$ s) from *PKJKP* ($t^* \approx 8.0-9.0$ s). However, the observation is in the frequency range 0.1–0.5 Hz, which is rather high for observing a much attenuated phase such as *PKJKP*, and the difference in frequency content is only qualitative and not quantitative.

Although we have not reproduced the analysis technique of Okal & Cansi (1998), we have performed normal mode modelling using their station distribution (see Fig. 6). These calculations, carried out at frequencies of 0.01–0.1 Hz, show a relatively strong feature at the slowness and time reported by Okal & Cansi (1998) (hereafter OC), but calculations using a fluid inner core also show the same feature, totally unchanged. The difference between the solid and fluid inner cores contains a very small signal, that has to be enhanced 15 times compared to the solid or fluid core stacks to make it visible. It must be concluded from this FIC test, therefore, that the large feature is not associated with inner core shear waves.

The calculation shows that *PKJKP* is masked by much larger signals. We suggest that the large arrival is caused by the interference of mantle waves, a similar phenomenon to that found in the Bolivia stacks (see above). For example, *SP* arrives at $T=1665$ s for $\Delta=116°$ with $t^*=5.5$ s and might explain both the arrival time and lower frequency content of the misidentified *PKJKP* arrival. We have also performed the same computations at a frequency of 0.15 Hz, which is the

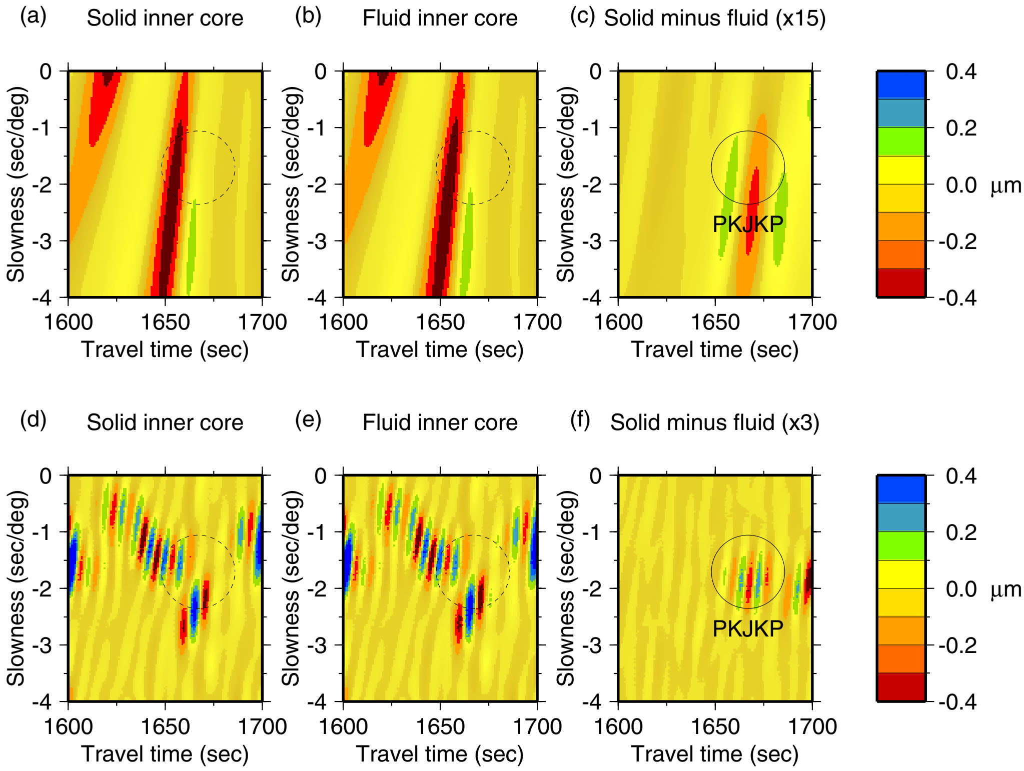


Figure 6. Phase-weighted stacks of synthetic normal mode seismograms for the station distribution of Okal & Cansi (1998) for the Flores Sea event. Similar to Figs 3 and 4. (a), (b) and (c) are in the same frequency range of 0.1–0.01 Hz as our observations; (d), (e) and (f) are at 0.15 Hz, which is the lower range of Okal & Cansi's (1998) frequency spectrum. In both computations there is little difference between the solid and liquid inner core; difference signals on the right have been enhanced by factors of 15 and 3 respectively.

lower part of OC's frequency range (see Fig. 6, lower panels). These calculations show that using the station distribution, etc., of OC, the synthetic stacks are dominated by non-inner core waves. This result does not constitute a complete simulation of the OC experiment, but would lead us to conclude that such a simulation is needed to validate completely their identification of inner core arrivals.

7 CONCLUSIONS

While there have been a number of identifications of inner core shear phases claimed, the weakness of the phases and the interference or potential interference of other phases leads to the possibility of misidentification. Here we have presented a stringent test of the hypothesis that a given extremum in a stack can be identified as an inner core shear phase, and have presented data that pass the test. There is reason to believe that previous claims would not pass such a test. Thus we claim the first fully validated identification of inner core shear phases.

This is a long-period observation (20–30 s). Attenuation in the inner core is expected to lead to J-phase amplitudes strongly diminishing with increasing frequency. Given a t^* of the order of 10 s, a value that finds some support in the data analysed here, the amplitude decay would be proportional to $10^{-13.6/T}$, where T is the period. We are thus in agreement with Doornbos (1974) that identification of J-phases at short periods is likely to be impossible.

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