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Constraints on shear wave attenuation in the Earth's inner core from an observation of PKJKP

A. Cao[1] and B. Romanowicz[2]

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[1] Based on the high quality broadband data from Gräfenberg array in Germany, we recently detected a reliable PKJKP phase, for which four kinds of evidence (travel time, slowness, back-azimuth, and comparison with a pseudo-liquid inner core model) were simultaneously provided. Also, for the first time, a clear waveform of PKJKP was observed. This gives us an unprecedented opportunity to put constraints on the shear wave attenuation in the earth's inner core using body waves. In order to minimize the potential influence of dispersion and phase shift caused by mantle heterogeneity, we adopt an envelope modeling approach. Our results show that the estimated Q_β from the shear phase PKJKP is significantly larger ($\sim$315 $\pm$ 150) than that from normal mode observations. Because PKJKP samples the deep inner core, this indicates an increase of Q_β with depth in the inner core, in agreement with what is generally observed for Q_α. **Citation:** Cao, A., and B. Romanowicz (2009), Constraints on shear wave attenuation in the Earth's inner core from an observation of PKJKP, *Geophys. Res. Lett.*, *36*, L09301, doi:10.1029/2009GL038342.

1. Introduction

[2] Constraining shear attenuation in the inner core may provide significant insights into the solidification processes at the earth's center. Even before the first indirect evidence of the solidity of the inner core was documented from seismic normal mode observations [*Dziewonski and Gilbert*, 1971], the study of Q_α from short-period body wave observations had suggested that Q_α is extremely low near the Inner Core Boundary (ICB) and increases with depth [*Sacks*, 1969]. This is consistent with the possible existence of a mushy zone with partial melting at the top of the inner core [*Doornbos*, 1974; *Loper and Fearn*, 1983].

[3] Since then, studies of Q_α based on both short-period and broadband data have presented evidence in support of this model [e.g., *Souriau and Roudil*, 1995; *Li and Cormier*, 2002] and revealed more complex attenuation structure in the inner core [*Souriau and Romanowicz*, 1996; *Cao and Romanowicz*, 2004; *Cormier and Li*, 2002]. In particular, Q_α is very large in the outer core, decreases just below the Inner Core Boundary (ICB) and then increases again with depth. Both scattering related with iron crystal texturing and diffusion related to liquid inclusions can account for the Q_α increase with depth [*Cormier and Li*, 2002; *Singh et al.*, 2000].

[1]Department of Earth Science, Rice University, Houston, Texas, USA.
[2]Berkeley Seismological Lab, University of California, Berkeley, California, USA.

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[4] While significant progress has been made in the study of Q_α in the inner core using body wave observations, the shear wave quality factor, Q_β, has mostly been constrained from normal mode measurements (for a review see *Romanowicz and Mitchell* [2007]), with the current consensus settling for relatively low Q_β of 85–110 [*Dziewonski and Anderson*, 1981; *Widmer et al.*, 1991; *Andrews et al.*, 2006]. Several years ago, we presented a clear observation of PKJKP based on long period (0.06 to 0.1 Hz) stacks at the GRF array [*Cao et al.*, 2005] (hereinafter referred to as Paper I) which suggested a larger Q_β, possibly as large as 300 [*Cao et al.*, 2005], however, this measurement was deemed uncertain because it was based on waveforms that had been stacked using the non-linear phase weighted stack approach [*Schimmel and Paulssen*, 1997]. Since then, *Wookey and Helffrich* [2008] have suggested a Q_β of $\sim$200 at the top 400 km and a Q_β of ∞ in the rest of the inner core, based on an observation of PKJKP at short periods ($\sim$0.5 Hz). In what follows, we revisit our 2005 observation, analyze it with consideration of the effect of noise in non-linear stacks, and confirm our previous measurement of $Q_\beta > 150$, with a best fitting value of $Q_\beta \sim 300$ averaged in the entire inner core.

2. Data, Method, and Results

[5] Figure 1a presents the raypaths through the earth of phases PKIKP and PKJKP. For the distance ranges considered, PKJKP samples the center of the inner core. Taking advantage of high quality broadband seismic array data, we previously presented (Paper I) a reliable PKJKP phase with a clear waveform (Figures 1b and 1c). Four kinds of constraints (arrival time, slowness, back-azimuth, and comparison with a quasi-liquid inner core model) were provided jointly to support our PKJKP observation. This observation was made on the Gräfenberg Array (GRF), the first digital broadband seismic array in the world (with an aperture of $\sim$100 km $\times$ 50 km), which has provided continuous high quality records at all 13 stations since 1980. The event considered occurred in the Santa Cruz Islands in the western Pacific (Mw = 7.3, depth = 76 km, 02/06/1999) and turned out to be particularly suitable for the detection of PKJKP[*Cao et al.*, 2005]: (1) the source duration is less than 9 seconds; (2) the expected PKJKP is emitted from the top of the lobe of the P-wave radiation pattern; (3) the potential interfering phases identified in previous studies [*Okal and Cansi*, 1998; *Julian et al.*, 1972], are at least 17 seconds away from the predicted PKJKP arrival time (with respect to the PREM model). The observation of PKJKP has been described in Paper I, and in the associated supporting online material, and we only briefly summarize it here.

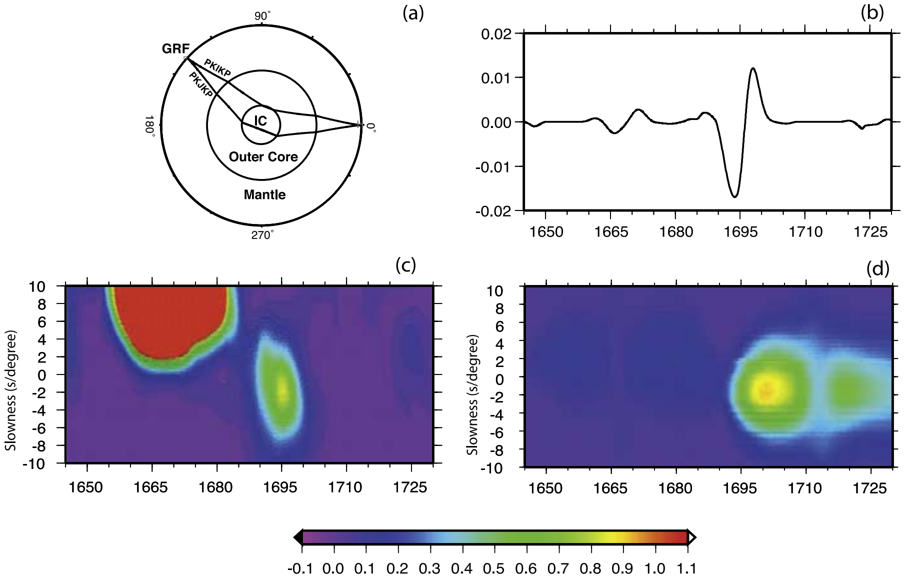

Figure 1. (a) Ray paths of PKJKP and PKIKP. The event epicenter and GRF seismic array are indicated by a star and a square, respectively. (b) Stacked waveform of PKJKP corresponding to the energy maximum in Figure 1c. (c) Observed vespagram for PKJKP in the slowness and travel time domain. The energy level is amplified 40 times. The slowness of the energy maximum is ~ -1.6 s/deg, close to the PREM prediction of -1.43 s/deg. The arrival time is also compatible with PREM (1695 sec for the maximum energy, compared to a prediction of 1690 sec for the high frequency onset of the pulse). (d) Synthetic differential vespagram. Both PKJKP and pPKJKP are visible after the interfering mantle phases have been removed. The estimated slownesses are both -1.4 s/deg, which are the same as the predictions based on PREM [*Dziewonski and Anderson*, 1981].

[6] We first aligned seismograms with respect to the origin time of the event after making an array-sided travel time correction, carried out by PKIKP + PKiKP waveform cross-correlation with respect to a reference station in the array. The seismograms were band-pass filtered in the frequency band 0.06–0.1 Hz, normalized with respect to the first arrival (PKIKP + PKiKP), and stacked (Figures 1b and 1c) using the Phase Weighted Stack (PWS) technique [*Schimmel and Paulssen*, 1997]. In order to rule out the possibility for the observed PKJKP phase to be misidentified and mistaken for an outer core, mantle, or crust phase, we further considered synthetic vespagrams that allowed us to uniquely identify PKJKP in the time and slowness window considered. The Direct Solution Method (DSM) was used to compute highly accurate and complete synthetic seismograms [*Takeuchi et al.*, 1996].

[7] It is impossible to detect PKJKP in an individual synthetic trace because PKJKP is so weak that it is deeply hidden behind unidentifiable mantle, outer core, and (or) crust phases. In order to clearly isolate PKJKP, we introduced a pseudo-liquid inner core model (Paper I), in which the shear wave velocity in the inner core is 8% less than that in the reference model PREM [*Dziewonski and Anderson*, 1981]. We computed synthetic seismograms for both solid and pseudo-liquid inner cores based on the same geometry for the event and the seismic array, and calculated differential seismograms. Because the S velocity in the inner core is sufficiently lower than that in PREM, the shear wave energy moves out of the window of study in the model with "pseudo-liquid" inner core. At the same time, because the shear velocity reduction, relative to PREM, is small, the energy in the compressional phases in this window is not artificially enhanced in the pseudo-liquid inner core. Therefore, the P energy cancels out in the window of study when the differential seismogram is computed, and we are confident that the only significant energy left is that of PKJKP (Figure 1c).

3. Constraints on Q_β in the Inner Core

[8] The observed and synthetic PKJKP waveforms could be used to constrain the shear wave attenuation in the inner core directly by waveform modeling. However, heterogeneity in the mantle can give rise to distortion and phase shift of the waveform. Thus we choose to model the envelope function of the stacked waveform rather than the stacked waveform itself. In general, the envelope function can characterize the amplitude and arrival time of the energy maximum better than the waveform.

[9] On the other hand, the synthetic vespagrams for the pseudo-liquid and the solid inner core models [*Cao et al.*, 2005, Figure 4] indicate that we cannot directly use the synthetic envelope function to constrain the shear wave attenuation in the inner core. In the time window of interest, several strong mantle phases are present in the synthetic vespagrams, although with quite different slownesses compared to PKJKP. However, these mantle phases are present in both the synthetics for the solid inner core and for the pseudo-liquid inner core models. By computing the difference between the two synthetics, the synthetic PKJKP (only present in the solid inner core model for the time window of interest) emerges. Mantle phases are thus removed in the differential seismograms, as well as in the differential vespagram, and their contribution will not bias the synthetic PKJKP amplitude. On the other hand, because these mantle phases are not present in the observed vespagram, most

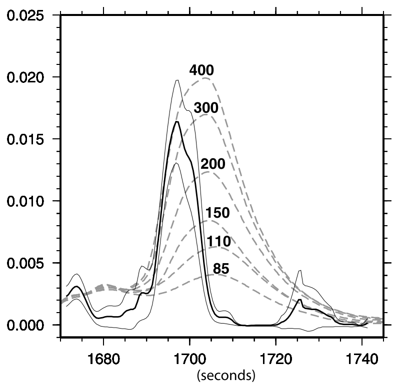

Figure 2. Observed PKJKP envelope (with its uncertainty) and synthetic envelope function modeling. The solid black line denotes the mean of envelopes calculated using the subsets of the observed records. The two thinner dashed lines indicate the range of the standard deviation, and those thicker dashed lines denote synthetic PKJKP with respect to different shear wave quality factors assumed in the inner core.

likely due to seismic scattering caused by mantle heterogeneities and Moho topography, we can directly compare the observed envelope of PKJKP, with the one obtained from the synthetic differential seismogram.

[10] In order to estimate the standard deviation of the observed PKJKP envelope, we use the Jackknife method [*Shao and Tu*, 1995], repeating the envelope calculation with subsets of stations of the GRF array. During this process, one or two stations are removed each time, from different subarrays. There is a total of ~60 such subsets. Clear PKJKP waveforms can be seen in all subsets after stacking. In principle, the envelope should not change with respect to any phase shift of the waveform. We use this criterion to further examine the stability of the stacked PKJKP waveforms. Two envelopes are computed for every stacked PKJKP waveform, the second one for the Hilbert transform of the waveform (90° phase shift). In most cases the two envelopes are very similar (amplitude variation less than 20%). The final envelope mean and its standard deviation (Figure 2) are estimated based on these stable envelopes.

[11] We process the synthetic differential seismograms, obtained for different assumed values of Q_β in the inner core, in the same way as the observed seismogram. Taking into account the standard deviation of the observed PKJKP envelope, the estimated Q_β in the inner core is in the range of ~220 to ~400. When we assume that Q_β is ~315, the envelope amplitudes of the observed PKJKP and the synthetic PKJKP are comparable.

[12] The envelope function of the observed PKJKP is narrower than that of the synthetic PKJKP (Figure 2). This is likely due, as we show below, to the background noise in the GRF seismic array. The presence of incoherent noise can make the waveform narrower after non-linear stacking [*Schimmel and Paulssen*, 1997]. In order to obtain further quantitative understanding, we conduct background noise experiments (Figure S1).[1] Realistic seismic noise is taken from time windows of 200 to 400 seconds before the first arrivals in the individual observed traces. This kind of noise is weaker than the real background noise (including interfering phases) near the arrival of PKJKP, and so we consider different "Levels" of background noise (Levels 0, 1, 2 in Figure S1). Level 0 means no seismic noise is added to the synthetic PKJKP traces; Level 1 means the original strength of seismic noise is added; and Level 2 means the strength of seismic noise is amplified twice before being added. Envelope functions of the synthetic PKJKP are computed from differential seismograms with the noise added in the individual traces.

[13] Our results show that the lower the original amplitude, the more influenced it is by background noise after stacking. For example, in the case of the background noise Level 2 (Figure 3), the envelope for Q_β = 85 in PREM [*Dziewonski and Anderson*, 1981] is more than 10 times smaller than that without noise (Figure 2), whereas the envelope for Q_β = 300 is only slightly affected by noise (~6.0 percent) (Figure S1). Our experiments demonstrate that the presence of background noise would make the PKJKP amplitude smaller in a realistic situation. This implies that Q_β in the inner core based on the envelope function modeling (Figure 3) is likely underestimated. In spite of this, we can still see that the envelope for the observed shear body wave PKJKP is significantly larger (>3.5 times) than that for the upper bound of the estimate of Q_β (<150) from normal mode observations [*Widmer et al.*, 1991] (Figure 3). If we take into account the uncertainty in the amplitude spectrum within the range of our study (Figure 2), the very conservative lower bound of our Q_β estimate is on the order of ~165. Comparison of Figures 2 and 3 also shows that the effect of noise is to make the envelope significantly narrower, and closer in width to that of the observation.

[14] As pointed out in Paper I, the envelope function modeling also suggests that the observed PKJKP is about 9.0 seconds faster than the synthetic PKJKP. This implies

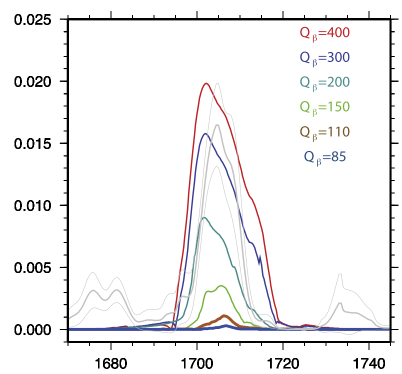

Figure 3. Comparison of the synthetic and observed envelopes after stacking. The background noise Level 2 is considered. The color lines are the synthetic envelopes for different assumed values of Q_β in the inner core, in which Q_β = 85 [*Dziewonski and Anderson*, 1981] and Q_β = 110 [*Widmer et al.*, 1991] are the estimates based on normal mode observations. The grey solid and dashed lines denote the observed envelope and its corresponding standard deviation range (shifted 9 s backwards).

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL038342.

that the constrained shear wave velocity in the inner core is ~1.5% faster than that for the PREM model (Figure 2). If we allow for the shear wave velocity to increase slightly faster towards the center of the inner core, and for up to 1 sec uncertainty due to possible mislocation errors, the measured shear velocity is compatible with that in PREM model.

[15] Finally, in the synthetic differential seismogram, pPKJKP is ~2.2 times weaker than PKJKP [*Cao et al.*, 2005, Figure 3]. The experiment (Figure S1) indicates that the amplitude ratio of PKJKP to pPKJKP may be as large as ~4.8 in the presence of noise. Therefore, it is not surprising that we do not observe pPKJKP for this event (e.g., Paper I).

4. Discussion

[16] It is clear that PKJKP and related shear phases of the inner core are very difficult to observe. First of all, a high quality broadband seismic array is necessary: due to strong shear wave attenuation in the inner core and poor phase conversion coefficients at the ICB, PKJKP is very weak. Most favorable conditions to detect PKJKP are at relatively low frequencies and after stacking [*Deuss et al.*, 2000; *Cao et al.*, 2005]. Second, a good combination of epicentral distance and event depth is necessary, so that potential interfering phases are far enough away from the elusive PKJKP. Third, the balance between the event magnitude and duration is important. A strong event (Mw > 7.0) but with a short source time history (less than 10 seconds) is desirable, to avoid interference of PKJKP and pPKJKP with other phases. Fourth, the broadband seismic array should have an ideal aperture. If it is too small, the slowness resolution is very poor; if it is too large, the number of potential interfering phases increases significantly, as well as the potentially strong effect of anisotropy in shear. Fifth, the identification of PKJKP should be conducted in a broad range of slowness (e.g., −10.0 to 0.0 s/deg) [*Julian et al.*, 1972; *Deuss et al.*, 2000; *Cao et al.*, 2005]. This is because the stacking usually introduces "spurious phases" when the background noise (including interfering phases) is large relative to the target phase [*Schimmel and Paulssen*, 1997]. Before claiming a stacked phase is PKJKP in a very narrow slowness range (e.g., ~0.5 s/deg), one should attempt to identify all other "blobs" in a much broader range. Finally, the joint provision of arrival time, slowness, back-azimuth, and comparison with a 'liquid' inner core model is indispensable. Especially, any lack of at least three pieces of diagnostic evidence could result in the misidentification of PKJKP.

[17] Large events usually have large rupture lengths and strong directivity. This may result in significant error for the direct estimation of Q_β in the inner core using the absolute envelope modeling of PKJKP. In order to control the influence of the directivity of the rupture as well as the uncertainty in the moment tensor, we normalized observed seismograms and synthetic seismograms with respect to the first waveform (PKIKP+PKiKP). The difference of take-off angles between PKJKP and PKIKP (or PKiKP) is only about 8 degrees. Therefore, we expect the directivity of the rupture to affect PKJKP and PKIKP in almost the same way.

[18] Due to the potentially strong shear wave anisotropy (or heterogeneity) in the inner core, we need to use a relatively small broadband array (aperture is from 100 to 200 km). If the broadband array is too large, the PKJKP signals recorded in the individual stations would not be coherent any longer because they sample the inner core with significantly different ray paths.

5. Conclusion

[19] We obtain a significantly higher value for Q_β in the inner core than that inferred from normal mode measurements [*Dziewonski and Anderson*, 1981; *Widmer et al.*, 1991]. Normal modes, which are sensitive to the shear wave structure in the inner core, mainly sample the shallow portion of the inner core, whereas PKJKP (and pPKJKP) samples deep into the center of the inner core (Figure 1a). Thus, we infer that Q_β most likely increases with depth in the inner core, just as Q_α does [*Souriau and Roudil*, 1995]. The potential Q_β anisotropy and Q_β frequency-dependency may also contribute to the difference, but a quantitative estimate of their influence is not possible right now.

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A. Cao, Department of Earth Science, Rice University, Houston, TX 77001, USA. (aimin.cao@rice.edu)

B. Romanowicz, Berkeley Seismological Lab, University of California, 215 McCone Hall, Berkeley, CA 94720, USA. (barbara@seismo.berkeley.edu)