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GEOPHYSICS

New Concept of the Earth's Outer/Inner Core Boundary

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1. Seismological studies of the past few years (see, for example, [1, 4, 5, 8, 9]) demonstrate that the structure of the Earth's inner core is much more complex than was accepted in standard models (PREM, IASPEI91, and others). In these models, the outer/inner core boundary (ICB) is sharp with jumps in density and primary/shear wave velocity.

In this paper, we present the results of measurement of different parameters of subcritical short-period PKiKP waves reflected from the ICB and give a model explanation of the peculiarities. The main conclusion is in the fact that the ICB is a region with structure, and we suggest its main elements.

2. We used the data of digital seismic stations, which recorded five seismic events in Central Asia in a wide range of epicentral distances from 3° to 95°. Four events are underground nuclear explosions at Lobnor site (China), whereas the fifth event is a deep earthquake in Pamir. The source parameters of the seismic events are given in Table 1.

The PKiKP waves are relatively weak signals masked by the seismic coda generated by wave propagation through all the overlying shells of the Earth (crust, mantle, and outer core). The amplitude of PKiKP waves at epicentral distances of about 30° is approximately 1000 times smaller than the amplitude of P waves. For seismic events with magnitude 6.0, it is equal to a few nanometers. Bandpass filtering and different modifications of frequency–wavenumber (*f–k*) analysis are used to detect such waves. Figure 1 shows the plot record section of seismograms (duration 50 s) with PKiKP waveforms. Filtering in the 1–5 Hz band allows us to detect with confidence in-phase arrivals of waves at distances up to 30°–35°. A more complex processing procedure is required at greater distances due to the influence of shear waves and partly Lg waves. Records of low-aperture seismic arrays were used at these distances, which allow us to carry out *f–k* analysis and separate high-velocity PKiKP waves from low-velocity noise. Additional parameters, such as the azimuth to the source and slowness (inverse apparent velocity) measured at seismic arrays, increase the reliability of identification of PKiKP waves. For example, the *f–k* analysis of P, PcP, and PKiKP waves after the August 17, 1995, explosion recorded at Station Fines yielded the azimuth of 93.6°, 94.1°, and 108.4°, respec-

Table 1. Parameters of the sources of seismic events

Date	Time in source, h : min : s	N	E	Depth, km	m_b
		degrees			
Nov 7, 1994	03:26:0.18	41.573	88.720	0.59	6.0
May 15, 1995	04:06:0.20	41.5508	88.7505	0.65	6.1
Aug 17, 1995	01:00:0.14	41.5407	88.7531	0.59	6.0
June 8, 1996	02:56:0.06	41.5799	88.6902	0.53	5.9
Mar 21, 1998	18:22:28.4	36.433	70.133	228	5.9

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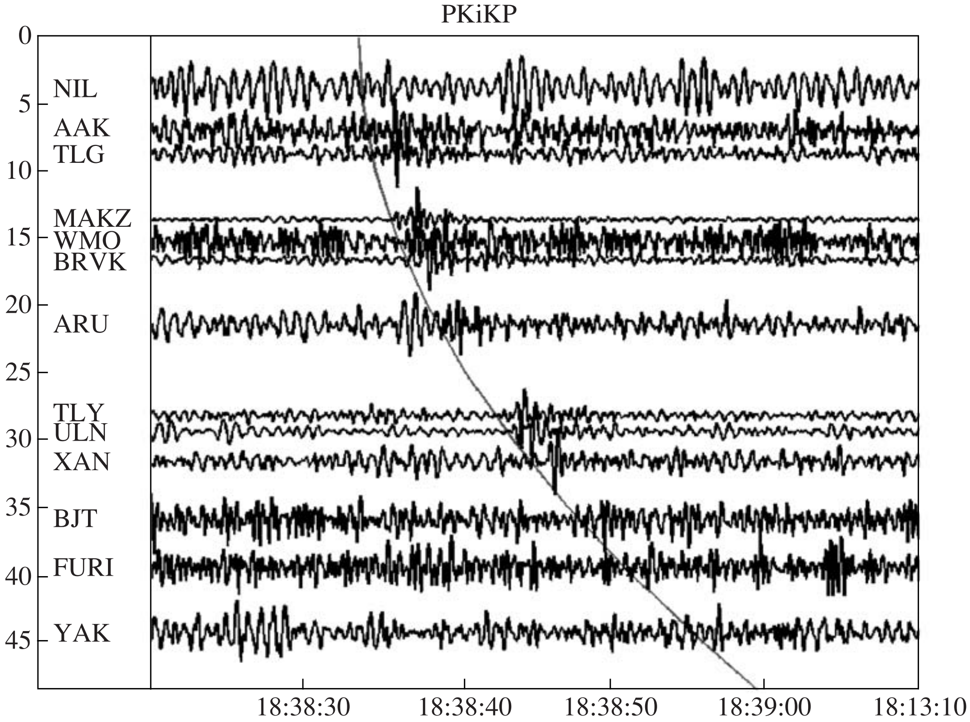

Fig. 1. Plot record section for the March 21, 1998, earthquake with records of the PKiKP waveforms. The epicentral distance (in degrees) and time of day on March 21, 1998, are shown along the *Y* and *X* axes, respectively. The PKiKP traveltime is shown, and seismic station codes are given for each trace.

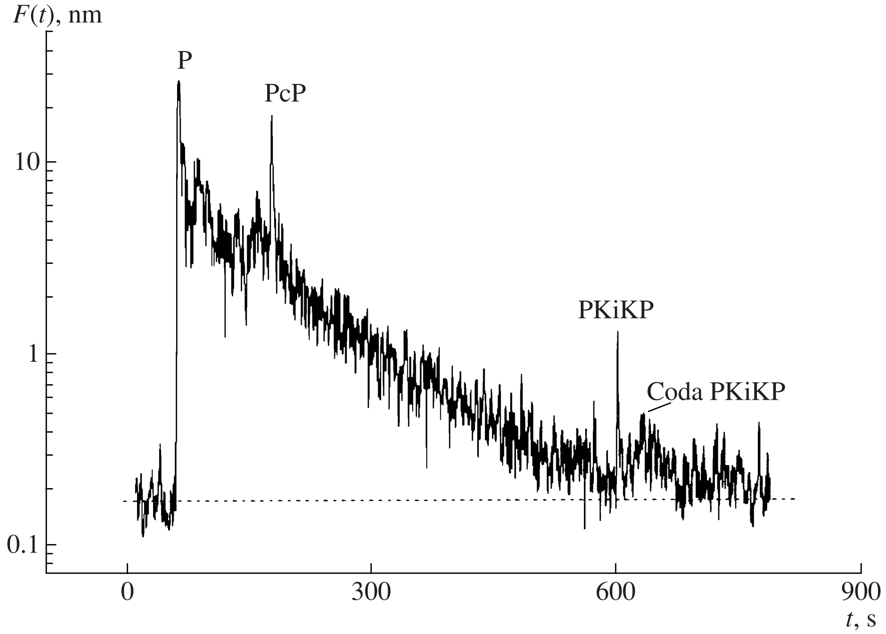

Fig. 2. Coda decay curve for the explosion of June 8, 1996, recorded at Fines (frequency band 2–4 Hz). The epicentral distance is 41.8°. The dashed line shows the noise level before the first arrival.

tively. The correlated values of azimuths of three waves allow us to state that they are related to one source of seismic oscillations.

Finally, to investigate the character of the time variation of the total amplitude at groups of stations (or groups of explosions recorded at one station), we calculated the decay curve $F(t)$ based on the formula

$$F^2(t) = \max_{\mathbf{k}}\left\{(2\tau)^{-1}\int_{t-\tau}^{t+\tau}\left[n^{-1}\sum_{i=1}^{n} f(t'-\mathbf{k}\mathbf{r}_i)\right]^2 dt'\right\},$$

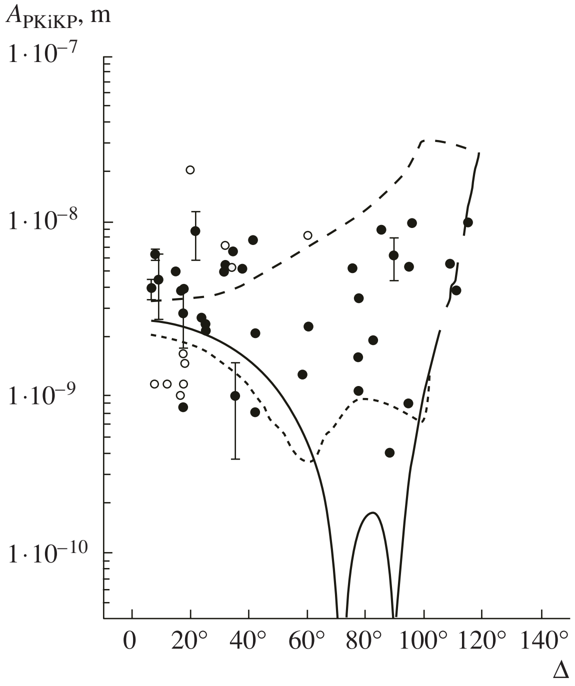

Fig. 3. Amplitude of the PKiKP wave vs. the epicentral distance. Black circles denote measurements for seismic events from Table 1. Black circles with vertical ticks and open circles are data from [4]. The solid curve shows the dependence of amplitude on distance according to the PREM model; the dashed line, modification of the PREM model including the thin high-velocity layer at the basement of the outer core; and the dotted line, modification of the PREM model including the high-velocity layer at the top of the inner core.

where $f(t - \mathbf{k}\mathbf{r}_i)$ is the seismogram at seismic recorder i of the group, n is the number of the seismic recorder in the group, $\mathbf{k}$ is the wave vector, $\mathbf{r}_i$ is the radius-vector of the observation point, and 2τ is the length of the time window. Figure 2 shows an example of a decay curve in the frequency band 2–4 Hz. It is seen that PKiKP arrival is followed by growth in amplitude in the form of an arch (coda). Such a peculiarity was not noted for the PcP wave.

Table 2. Normalized spectral ratio of PcP and PKiKP waves

Frequency, Hz	$\frac{S_{\mathrm{PKiKP}}}{S_{\mathrm{PcP}}}$
0.7	0.5
1.0	0.56
1.5	0.72
1.8	1.0
2.1	0.94
2.4	0.74
2.5	0.65

3. Figure 3 shows the measurements of the maximal amplitude of the PKiKP wave of seismic events. They are related to the reflection points in the Northern Hemisphere of the inner core.

The projections of reflection points at the Earth's surface are located in Central and Southeast Asia, near the North Pole, and in the northeastern Russian Platform. It follows from Fig. 3 that in the range of epicentral distances 70°–90°, the measured amplitudes are more than one order of magnitude higher than the amplitudes predicted for the PREM model. For the sake of better correlation between the predicted and measured amplitudes, it is enough to assume that the velocity of shear waves in the uppermost part of the inner core is smaller than 2 km/s, which contradicts the data on free oscillations of the inner core [3]. In addition, other characteristics of PKiKP waves do not allow us to accept the above interpretation.

Table 2 presents for a number of frequencies the spectral $\frac{S(f)_{\mathrm{PKiKP}}}{S(f)_{\mathrm{PcP}}}$ ratio for PcP and PKiKP waves, which were recorded at ZRN (Zerenda) in Kazakhstan at a distance of 17.2° at a signal/noise ratio greater than 3. One can see that the PKiKP wave has a relatively greater high-frequency composition compared to the PcP wave. We think that this fact is related to the structural peculiarities of the outer/inner core transition region. Had such peculiarities not existed, the spectra of PcP and PKiKP waves should be close, because propagation of the PKiKP wave in the homogeneous outer core with a high Q-factor ($Q \approx 10\,000$) cannot lead to any significant variations in the spectral composition of the PKiKP wave compared to the PcP wave. However, we cannot exclude the possibility that the spectral ratio is influenced by the inhomogeneities in the lower mantle and, especially, in zone D'', where PcP and PKiKP waves are divided by 650–700 km. This distance exceeds the size of the first Fresnel zone (70–80 km).

Statistically more representative material was obtained from the measurements of the visible period of PKiKP and PcP waves given in Table 3. These data also point to a greater high-frequency composition of PKiKP waves.

Table 3 also presents the number of measurements n, t-statistics, and probability (P) of the error for the accepted hypothesis that mean periods differ strongly.

A statistical test based on the Student criterion for all explosions demonstrates a significant difference between the mean periods with a probability of error ranging from 0.005 to 0.007.

One of the simplest models for explanation of the greater high-frequency composition of PKiKP waves is a thin layer of high-velocity either at the basement of the outer core or at the top of the inner core [2, 4]. Figure 3 shows the variation of amplitude with distance for these models by dashed and dotted lines. They are

Table 3. Mean periods T and their errors σ

Date	PcP			PKiKP			t	P
	T, s	σ, s	n	T, s	σ, s	n		
Nov 7, 1994	0.67	0.083	13	0.54	0.133	14	3.0996	0.005
May 15, 1995	0.66	0.089	5	0.52	0.079	10	2.9914	0.010
Aug 17, 1995	0.68	0.177	16	0.57	0.125	12	1.8723	0.073
June 8, 1996	0.69	0.13	13	0.53	0.15	9	2.7354	0.012

apparently the two bounds to describe the experimental data. Such models have the right to exist because the investigation of dynamic scenarios of the growth of the inner core accompanied by freezing of light fractions assume the formation of plates (thickness ~10 km), which have a smaller density than the enclosing medium. Later, they can float up and dissolve at a distance not greater than 200 km from the ICB [6, 7].

The PKiKP wave coda shown in Fig. 2 indicates that the upper part of the inner core includes inhomogeneities, where the coda is formed and scattered. The coda (up to 200 s long) consists of high-velocity waves and has a frequency between 2 and 4 Hz. A model of Born scattering was suggested to explain the arch-type coda in [9]. Such a model is characterized by the high-frequency composition of scattered waves as compared to the parent wave. Indeed, the dominating frequency of the PKiKP wave is 1.7–1.9 Hz, while the coda is observed at frequencies of 2–4 Hz. A similar result was observed in [5] for the reflection points at the surface of the core projected mainly to the regions of Southeast Asia. According to [8] (reflection points are projected to Oceania), the coda recorded as individual high-velocity pulses is related to reverberation in a thin layer.

The experimental data considered here allow us to conclude that the outer/inner core boundary is a region with structure, whose main elements are represented by relatively thin plates located either at the top of the inner core or at the basement of the liquid core. The existence of such a structure explains the character of variation of amplitude with distance, the relatively high-frequency composition of the PKiKP wave, and the formation of the coda in the form of individual pulses. The inner core near the boundary also includes inhomogeneities (their nature is not yet clear), where PKiKP waves are scattered and the arch-type coda is formed.

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REFERENCES

1. V. V. Adushkin and V. M. Ovchinnikov, Dokl. Earth Sci. **397**, 883 (2004) [Dokl. Akad. Nauk **397**, 815 (2004)].
2. V. V. Adushkin, A. A. An, V. M. Ovchinnikov, and D. N. Krasnoshchekov Dokl. Earth Sci. **354**, 595 (1997) [Dokl. Akad. Nauk **354**, 382 (1997)].
3. A. M. Dziewonski and F. Gilbert, Nature **234**, 465 (1971).
4. D. N. Krasnoshchekov, P. B. Kaazik, and V. M. Ovtchinnikov, Nature **435**, 483 (2005).
5. K. D. Koper, J. M. Franks, and M. Dombrovskaya, Earth Planet. Sci. Lett. **228**, 227 (2004).
6. P. L. McFadden and R. T. Merril, Phys. Earth Planet. Inter. **43**, 22 (1986).
7. H. K. Moffart and D. E. Loper, Geophys. J. Int. **117**, 394 (1994).
8. G. Poupinet, and B. L. N. Kennet, Phys. Earth Planet. Inter. **146**, 497 (2004).
9. J. E. Vidale and P. S. Earle, Nature **404**, 273 (2000).