Global Elastic Response Simulation

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We pursue accurate numerical techniques to obtain theoretical seismic waves for realistic three dimensional (3-D) Earth models using Spectral-Element Method. We have tried to solve forward problem, that is, to calculate synthetic seismic waveform for fully 3-D Earth model. We introduce a heterogeneous region at Earth's core-mantle boundary by combining a small, strongly anomalous region to a large, weakly anomalous region. We calculate synthetic seismograms for this model and found that Sdiff phase, which is diffracted S-wave at core-mantle boundary, is followed by a significant postcursor. This is consistent with the anomalous Sdiff waveforms which sample beneath Hawaii. We use antipodal seismic observations to review the Earth's Core based on our synthetic seismograms. Our results imply that there may be anomalous structure at the Earth's inner core-outer core boundary.

Keywords: Synthetic seismograms, 3-D velocity structure of the Earth, Spectral Element Method

1. Evidence of a thick and localized ultra low shear velocity zone inside the Pacific slow region at the base of the mantle [5]

Prominent postcursors to S/Sdiff waves with delays as large as 26 s are observed in Northern America for Papua New Guinea events. These waves sample the northern side of the Pacific large low shear velocity province revealed by global shear velocity (Vs) tomographic models. The emergence of the postcursors strongly depends on the epicenter-to-station azimuth, indicating that the waveforms are, in general, strongly affected by 3-dimensional (3D) heterogeneities. We limit our focus to an azimuthal range around 60° where the records show a relatively small azimuthal variation, suggesting a relatively small 3D effect there. In this azimuthal range we attempt 2D structural modeling along the great circle plane towards stations in southern US.

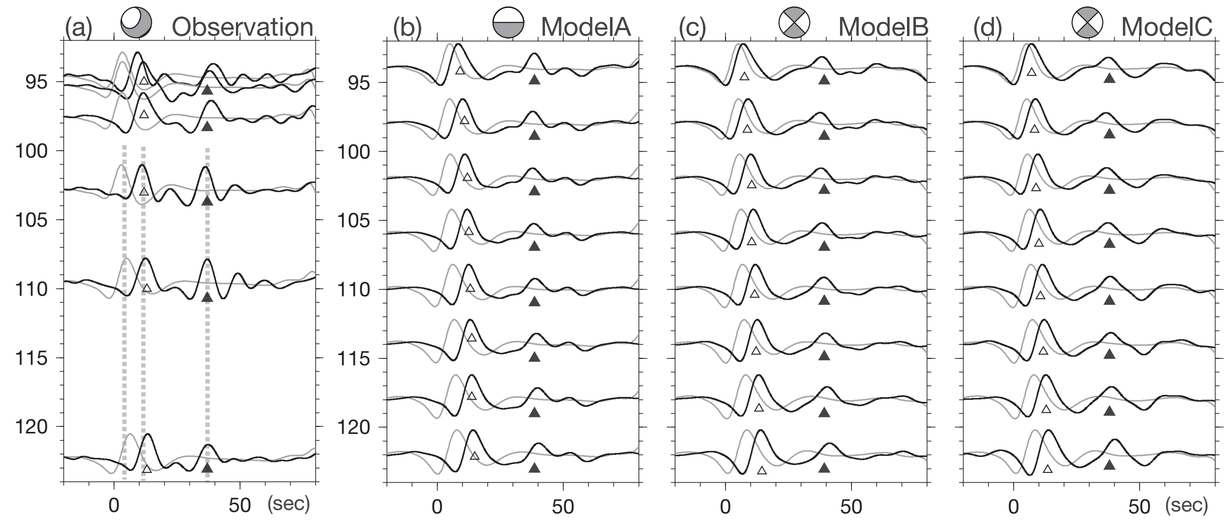

Fig. 1 (a)S/Sdiff waveforms of event 20030612 recorded at station azimuths between 60° and 63° are aligned in the order of distance and shown by solid lines [5]. The PREM synthetics are shown by grey lines. The main Sdiff phase and postcursor is indicated by open and solid reversed triangle. Three vertical grey dashed lines show a constant slowness of 8.3 s/deg fitted to the observed main Sdiff phase, postcursor and the synthetic Sdiff predicted by PREM. Each trace is normalized by its maximum amplitude. Records are bandpass filtered between 0.03 and 0.125 Hz. (b-d) Synthetic waveforms calculated by SEM for ModelA, Model B and Model C [5] . They are filtered and normalized in the same way as for the observed waveforms. Model parameters are given in Table 1. Configuration of LWAR and SSAR of the three models are shown in Fig. 2 (b-d).

Figure 1a shows observed Sdiff waveforms obtained at the station azimuth between 60° and 63°. They are aligned in order of epicentral distance. The arrivals of the main Sdiff phase (open reversed triangles) and the postcurcors (reversed solid triangles) are both characterized by a slowness of about 8.3s/deg, which is in an agreement with the slowness of Sdiff for PREM. This agreement indicates that the main Sdiff and the postcursor are both core-diffracted waves that depart from the same location on the CMB where the structure is similar to PREM. Therefore, the 26 sec delay of the postcursor relative to the main Sdiff phase has to be attributed to the effect of an anomalous body located between the source and the entering point of Sdiff ray path to the CMB, which is at an approximate distance of 50° from the source.

First, we perform 2D ray-tracing to examine whether a single anomalous body placed on the CMB can generate two Sdiff ray paths, with a travel time difference of 26 sec. Although diffracted waves cannot be handled by ray theory, we assume that Sdiff is generated when the ray enters the CMB tangentially. We demonstrate eventually that this is a good approximation by showing results of waveform modeling. We examined 270 different models, which are parameterized by the location of the source-side border of the anomalous body and the 1D Vs profile within it. 1D Vs profiles are expressed by the height, the Vs gradient at the top of the slow anomaly region and the Vs reduction inside the region. The height is changed from 151 km to 551 km above the CMB. The Vs reductions at the base of the mantle examined are 3, 6 and 9% with respect to PREM. The sidewalls of the anomalous body are kept perpendicular to the CMB to limit the number of parameters. Figure 2a shows one

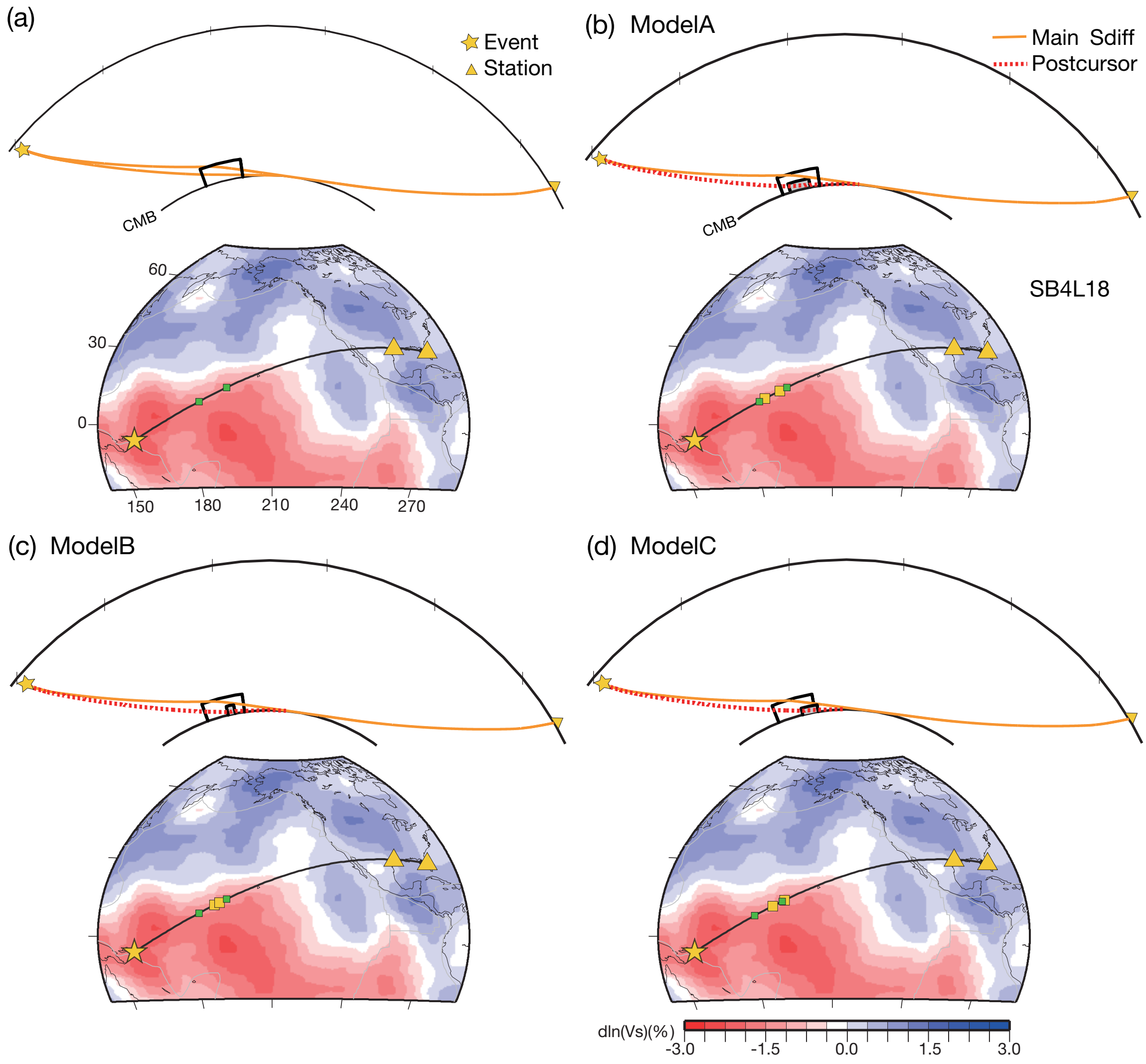

Fig. 2 Top Panel: A cross-section of a model with one slow anomaly region, which generates two Sdiff ray paths. The two Sdiff paths are shown by orange lines. The travel time difference of the two paths is only 0.7 seconds. The anomaly region is 351 km high and has 6% Vs reduction at the base of the mantle. Vs linearly decreases from 351 km to 251 km above the CMB below which it is constant down to the CMB. The two side walls are located at 30° and 42° from the source. Bottom panels: The location of the slow anomaly region is plotted on the Vs tomographic maps of SB4L18 [6]. The locations of the side walls are indicated by green diamonds. (b-d) Models with two types of slow anomaly regions, which generate two Sdiff ray paths, whose arrival times are approximately 26 seconds apart. The locations of the side walls of LWAR and SSAR are shown by green and yellow diamonds respectively on the tomography maps.

of the models, which provides two Sdiff ray-paths by placing a slow anomalous body on the CMB. One Sdiff ray enters the anomalous body from its top and the other enters from its side. However, the travel time difference of the two paths is only 0.7 seconds, which are two orders of magnitude smaller than the observed arrival time difference of 26 seconds. The largest arrival time difference between the two paths among the models examined is 2.2 seconds, which is far less compared to the observation. By tilting the side walls, the time difference increases only 0.5 seconds or so.

In order to obtain models that provide the observed travel time difference of 26 seconds, we combine a small, strongly anomalous region (hereafter called SSAR), to a large, weakly anomalous region (hereafter called LWAR). We conducted 2D ray tracing for thousands of models by systematically changing the Vs profile and the locations of the source-side walls of LWAR and SSAR. Figure 2 (b-d) are three of the successful models. Model parameters are given in Table 1. The path of the main Sdiff enters LWAR from its top and does not sample SSAR. The path of the secondary arrival enters SSAR from its source-side wall, samples SSAR horizontally and exits from its station-side wall.

Figure 1 (b-d) show synthetic waveforms calculated for models shown in Fig. 2 (b-d). Waveforms are calculated by Spectral Element Method (SEM) at periods down to 5 seconds [1][2]. The method can handle strong 3D heterogeneity and is well adapted to the spherical geometry of the CMB. It is an adequate method to investigate the diffracted waves, which interact with the strong heterogeneities near the CMB [3]. The synthetic waveforms for all the three models have two Sdiff arrivals of the same polarity, which are approximately 26 seconds apart. The slowness values are those as expected from PREM, at least beyond the distance of 100°. These features are consistent with the observations.

The observed waveforms cannot be explained by placing one anomaly region on the CMB, in which the Vs profile is given as a function of depth. A laterally localized region with extremely low Vs, with more than 25% Vs reduction (SSAR) should exist inside or at the edge of the larger slow anomaly region with less than several percents of Vs reduction (LWAR). Such an internal structure is required to generate two Sdiff arrivals that are approximately 26 s apart. The localized SSAR should be more than 100 km high in thickness in order to generate the secondary arrival. The data we have analyzed sample the northern edge of the Pacific large low shear velocity province (LLSVP). LWAR obtained in this study constitutes a part of the Pacific LLSVP. The analyses of the limited data show that SSAR can be placed either at the edge or inside of the LWAR. Further investigations are required to determine the absolute locations of SSAR and LWAR.

2. Antipodal Observations of Earth's Core

We use antipodal seismic observations to review the Earth's Core, where the seismic energy broadly samples the Inner Core and lowermost Outer Core. The data set contains several station-event pairs (Δ>179°), including Algeria-Tonga, Brazil-Indonesia, and China-Chile. The seismic waves that travel the Earth's Inner Core are categorized as PKIKP, which penetrates the center of the Earth, and PKIIKP, which reflects once at the Inner Core –Outer Core boundary. We model global seismic wave propagation generated by the earthquake by using a spectral-element method (SEM) [1]. The spectral-element

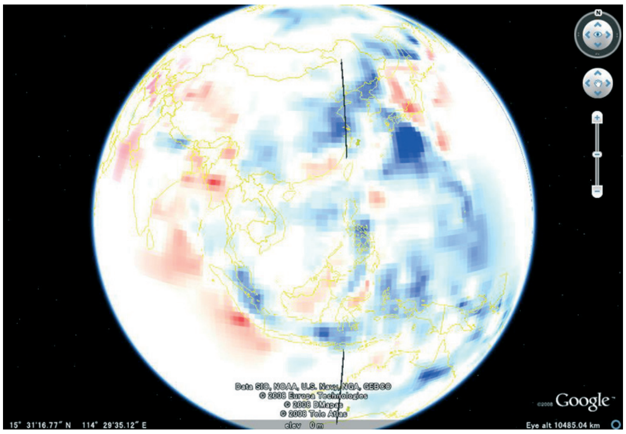

Fig. 3 P-wave seismic velocity model of GAP-P1. The region at depth 600 km is shown in blue if the P-wave velocity is faster than the average and shown in red if the P-wave velocity is slower than the average. This figure is created at: http://www.jamstec.go.jp/pacific21/google_earth/

Parameters of the models examined by SEM.

Model	LWAR			SSAR		
	Height Mid-height	dVs/Vs	Wall locations	Height	dVs/Vs*1	Wall locations
ModelA	351 251(km)	-6 (%)	30°42°	171	-18, -48, -18	32.5°39°
ModelB	351 251	-6	30°42°	171	-60	36.7°39°
ModelC	351 301	-6	28°40°	131	-25, -52	36°41°

Table 1 Parameters of the models examined by SEM. Synthetic waveforms are shown in Fig. 1. *Height*: Height of the slow anomaly region above the CMB. Vs starts to decrease linearly with respect to depth from this height. *Mid-height*: Height at which the Vs gradient with respect to depth changes. Vs decrease linearly from Height to Mid-height. Below Mid-height Vs is kept constant down to the CMB. *dVs/Vs*: Vs reduction at the CMB with respect to PREM. *1 In ModelA, the anomaly *dVs/Vs* of SSAR laterally changes from -18% at the both side edges to -48% at the center. In ModelC, the anomaly of SSAR changes laterally from -25% at the source-side edge to -52% at the station side edge.

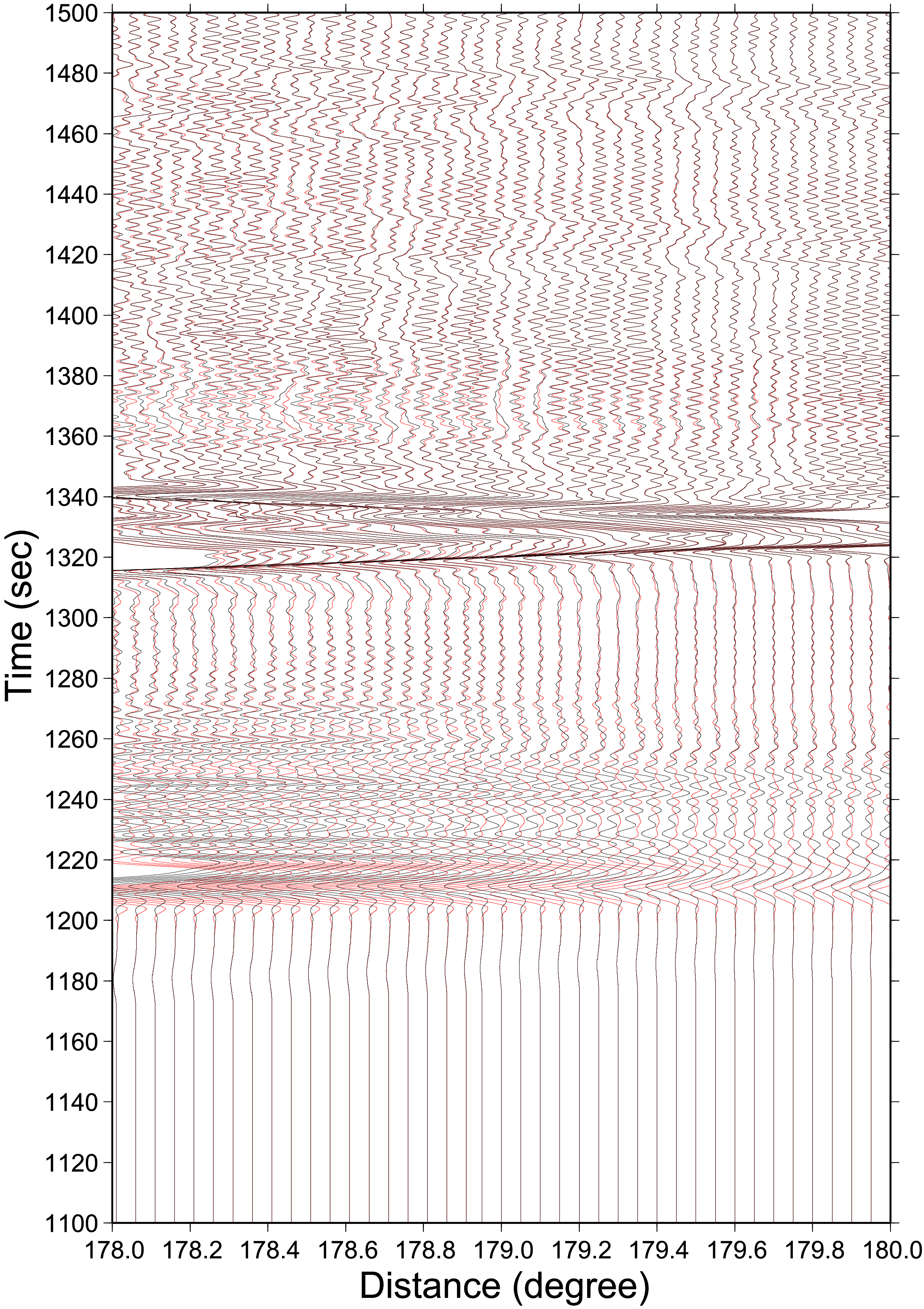

Fig. 4 Comparison of vertical component synthetic seismograms computed at Algeria station for Tonga earthquake with epicentral distance from 178 to 180 degrees. Red traces are the synthetic seismograms computed for standard Inner Core and Outer Core structure. Red traces are synthetic seismogram computed for modified Inner Core structure with the P-wave velocity reduced by 2% from PREM model below depth 1020 km.

method can take into account three-dimensional variations inside the Earth, such as P-wave velocity, S-wave velocity and density, attenuation, anisotropy, ellipticity, topography and bathymetry, and crustal thickness. [1] We use P-wave velocity model GAP-P1 of the mantle[4] (Fig. 3), model CRUST2.0 of the crust, and topography and bathymetry model ETOPO5. The only factor which is not taken into account in this realistic three-dimensional model is the effect of the seismic wave propagation in the ocean layer. Following the previous work [2], the simulations are performed on 1014 processors, which require 127 nodes of Earth Simulator 2 (ES2). We use a mesh with a total of 13.5 billion global integration grid points, which corresponds to an approximate grid spacing of 2.0 km along the Earth's surface and should enable us to get synthetics seismograms accurate up to 3.5 seconds. The inner core and outer core structure used in the first experiment is the same as that of PREM. The result shows that the general features of observed seismograms are reproduced well by the synthetics but those waves, such as PKIIKP are not modeled well. Then for the second experiment, we have reduced the P-wave velocity by 2% inside the Inner Core from the PREM model. Figure 4 shows comparison of the synthetics computed for the original PREM model and reduced P-wave velocity model. The figure demonstrates that PKIIKP waves, which arrive at around 1240 sec, show significant amplification and suggests there may exist lower P-wave velocity layer inside the Inner core.

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全地球弾性応答シミュレーション

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スペクトル要素法により現実的な 3 次元地球モデルに対する理論地震波形記録を計算した。今年度は、地球の核マントル境界で回折する S 波である Sdiff 波に見られる顕著な後続波を説明することを考えた。観測される Sdiff 波の性質から、核マントル境界に局在する地震波速度異常を考え、そのモデルに対する理論地震波形を計算した。得られた理論地震波形には観測波形に見られる Sdiff 波の後続波が現れており、用いたモデルが定性的に観測を説明できることを示している。Sdiff 波の後続波の振幅を定量的に説明するためには、さらにモデルを改良する必要があることが分かった。地震の対蹠点における地震波の観測を説明するために、理論地震波形を計算した。スペクトル要素法を対蹠点の理論地震波形計算に用いる利点は、地球の中心が特異点とならず安定して理論波形を計算出来る点にある。対蹠点で観測される地震波形には、地球の中心を通過してくる波や、内核－外核境界で回折や反射してくる波があり、内核－外核境界の性質を調べるために適している。最近の観測では、対蹠点の地震波形でこれまでの地球モデルでは説明できないものがあることが報告されている。ここでは、内核－外核境界に異常な地震波速度構造を導入すると、そのような地震波を説明できる可能性があることが分かった。

キーワード: 理論地震波形記録, 3 次元地球内部構造, スペクトル要素法