Global Elastic Response Simulation

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We calculate synthetic seismograms for realistic three dimensional (3-D) Earth models by using the precise numerical techniques and perform inversion to obtain 3-D seismic velocity model for Earth's mantle. We pursue accurate techniques to obtain theoretical seismic waves in two ways: one is Direct Solution Method and the other is Spectral-Element Method. Using these different methods, we have tried; (1) to solve inverse problem, that is, to perform waveform inversion for three dimensional (3-D) shear wave velocity structure inside the Earth and (2) to solve forward problem, that is, to calculate synthetic seismic waveform for fully 3-D Earth model. We have conducted waveform inversion for 3D shear wave velocity structure with much finer resolution than previously performed and checked reliability of low velocity anomalies obtained by waveform tomography performed in previous years. We use the Spectral-Element Method for the forward modeling calculation and calculate synthetic seismic waveform for a 3-D Earth model, which includes a 3-D velocity and density structure, a 3-D crustal model, ellipticity as well as topography and bathymetry. We confirmed the existence of the stagnant slab under the Japanese Islands. We also modeled seismic waves that travel along the core mantle boundary and characterized the location of low velocity regions.

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

1. Reliability of Low Velocity Anomalies Obtained by Waveform Tomography

In the last fiscal year, we inverted seismic waveform data for 3-D global SH velocity structure [1]. The inversion is characterized by fully utilizing the later phase information and rigorously computing the effect of lateral heterogeneities. The resultant model (SH18CE) is expected to have higher resolution especially for upwelling regions where the data sampling was previously poor. We detected the different natures of the two major upwelling systems: the strong low velocity anomalies beneath Africa extend for more than 1000 km from the core–mantle boundary (CMB), whereas those beneath the Pacific are restricted to 300–400 km from the CMB. We also conducted resolution tests and showed that resolution of the model is sufficient to resolve this feature. However, the accuracy of model is not yet estimated, and the purpose of the study in this fiscal year is to conduct accuracy tests to finally conclude the reliability of the focused feature.

In this study, we invert the data from different events from those used for obtaining SH18CE. In addition, we used events with different magnitude range (Mw is between 6.0 and 6.4 in this study and Mw is equal to or greater than 6.5 in the previous study). Figure 1 shows the distribution of

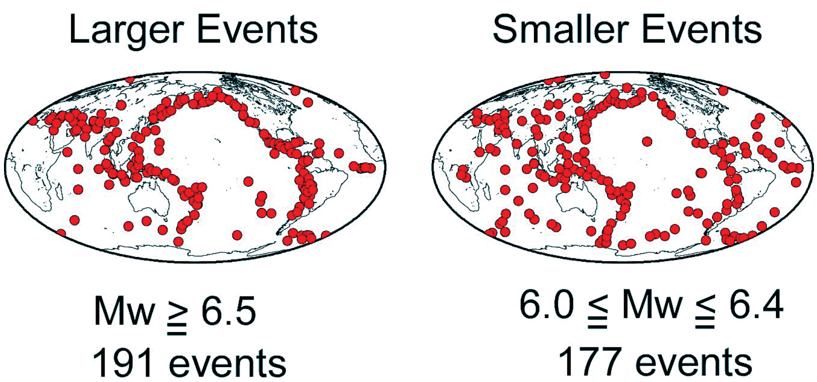

Fig. 1 The event distribution used in the previous study (left) and used in this study (right).

events used in this study and used in Takeuchi (2007) [1]. Larger number of ridge events is included in the new data set. The new data set is thus significantly different both in S/N and data sampling. If we could retrieve similar low velocity anomalies from the new data set, we can conclude that the model is sufficient accurate to conclude that the focused feature is reliable.

Figure 2 shows the comparison of SH18CE (left) and the model obtained in this study (right). As it is pointed out by Takeuchi (2007) [1], in the model SH18CE, the area of strong low velocity anomalies (colored in red or orange) beneath the Pacific is comparable with that beneath Africa at the CMB but is much smaller at the 2390 km depth. The similar feature is observed in the model obtained in this study. We can observe the strong low velocity anomalies (colored in orange) with similar size beneath the Pacific and Africa at the CMB, but strong anomalies beneath Africa is about three times larger than those beneath the Pacific at the 2390 km depth. The model obtained in this study, in general, has smaller absolute amplitude of the heterogeneities compared to SH18CE, which is presumably due to different size and different S/N of the data sets used. However, note that we can still discuss the relative amplitude of heterogeneities between two different regions. The coincidence between the models obtained by two independent data sets suggests the reliability of the focused feature.

In the recent paper by Takeuchi et al. (2008) [2], the extent of the low velocity region is independently elucidated by the analyses of the data from the array data. They analyzed the data from the Vietnam Broadband Seismograph Array, which provides unique opportunities to constrain the vertical extent of the low velocity region beneath (the western part of) the Pacific. It is because the direct S and sS waves from Tonga-Fiji deep events to this array bottom in the vicinity of the CMB. They found that only S and sS waves whose bottoming depth is within 400 km from the CMB have positive travel time anomalies. This result shows that the strong low velocity anomalies beneath the Pacific are confined within 400 km from the CMB, which supports the conclusion of this study.

2. Synthetic seismograms for stagnant slab model

We have shown that combination of Spectral-Element Method (SEM) and the Earth Simulator enables us to calculate synthetic seismograms for realistic three dimensional Earth model with the accuracy of up to 3.5 sec [3]. SEM

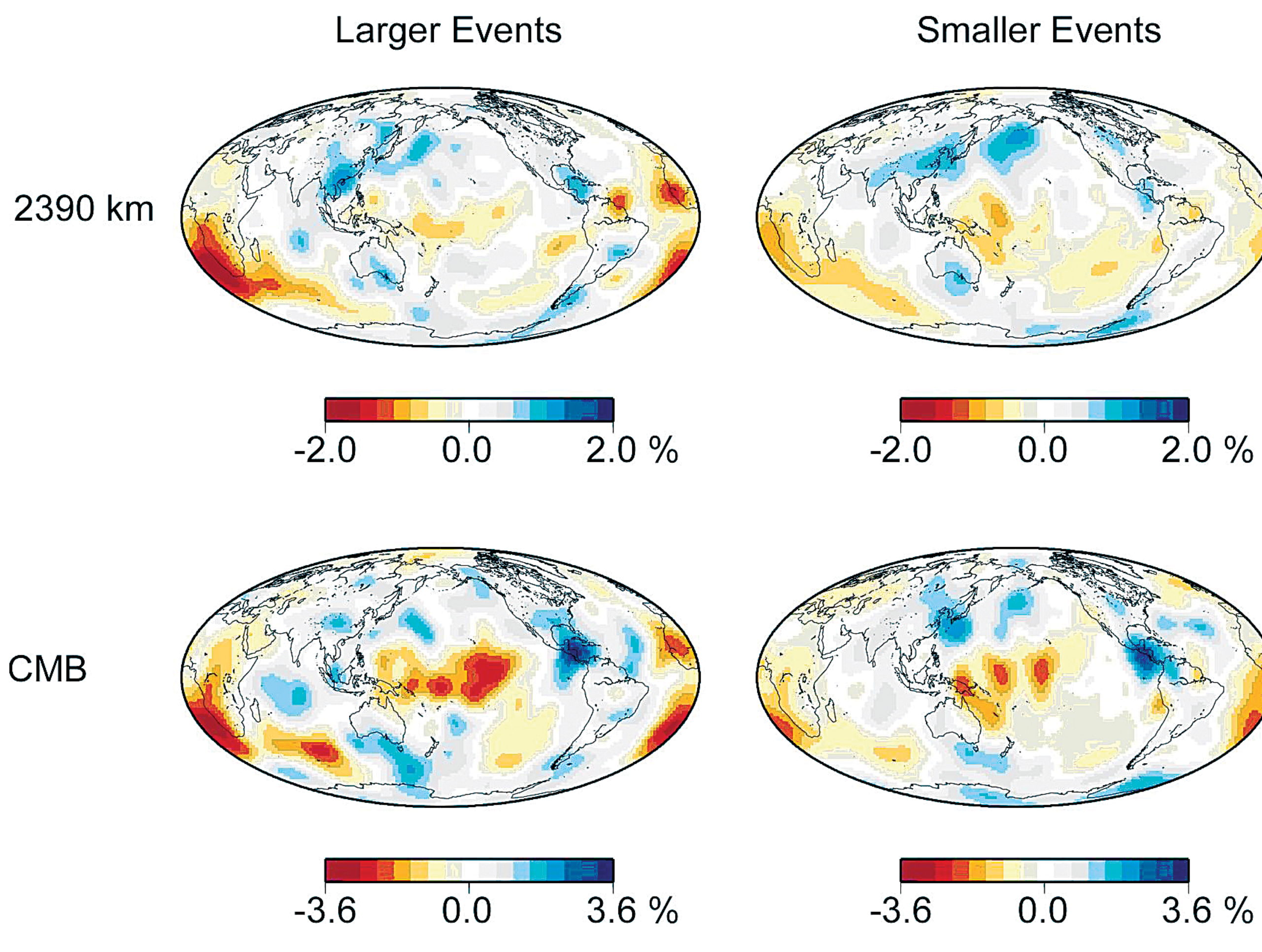

Fig. 2 The SH velocity models at 2390 km (top) and CMB (bottom) obtained in the previous study (left; SH18CE) and this study (right).

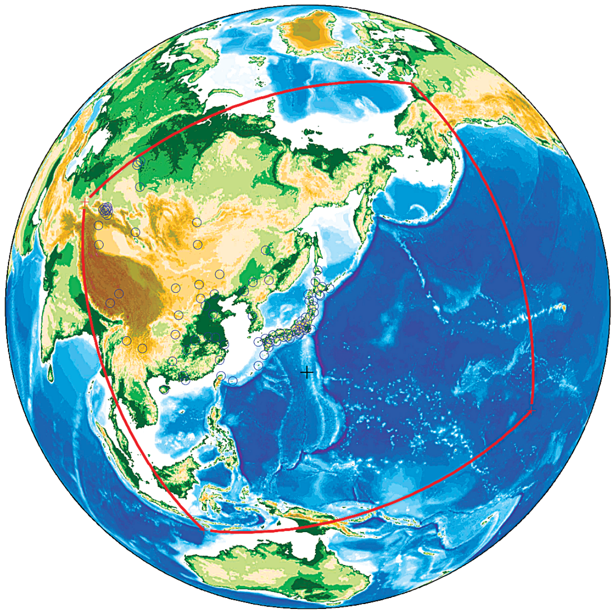

Fig. 3 Black plus sign represents epicenter of June 3, 2002 Bonin earthquake. Blue circles show locations of stations. Red curves show boundary of the one chunk at the surface of the Earth used in the computation.

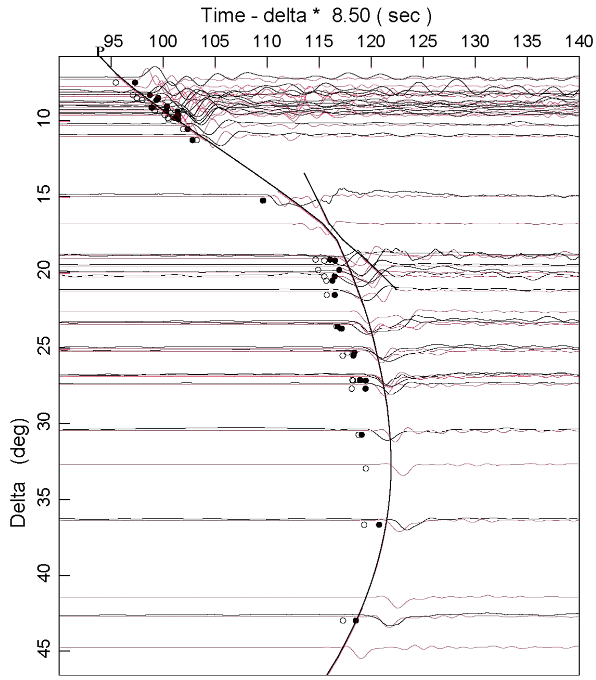

Fig. 4 Comparison of synthetic seismograms (red) and observed seismograms (black). Vertical component displacement seismograms for P-arrivals are shown. Observed traces are low-pass filtered at 4 sec. Solid curve in the figure shows theoretical travel time of Iasp91 model. Solid circles are observed arrival times of P-wave and open circles are theoretical ravel times by GAP-P1.

divides the Earth into 6 chunks and subdivides each chunk into slices. We may use only one chunk to have much finer mesh and calculate synthetic seismograms with accuracy of shorter period. Here we divide the one chunk to 64 × 64 = 4096 slices and allocate one CPU of the Earth Simulator to each slice, which requires 512 nodes of the Earth Simulator. This mesh enables us to calculate synthetic seismograms which are accurate up to 2 second. We use global P-wave velocity tomographic model of GAP-P1 [4]. S-wave velocity model is obtained with the scaling relation from P-model. We select the location of the chunk so that it includes Japanese Islands and calculate synthetic seismograms for deep June 3, 2002 Bonin Islands earthquake. Figure 3 shows location of epicenter and stations inside one chunk. We compare the synthetic seismograms with the observation for seismic stations in Eurasia. 3-D tomographic model has characteristics of significant stagnant slab under the Japanese Islands. Figure 4 shows that the effect of the stagnant slab is significant in the synthetic seismograms so that the arrival time of P-wave matches well with the observation for those stations in Eurasian continent. There are also stations where the agreement of the synthetics and the observations is not good, which suggests that the tomographic model needs further improvement.

3. Implications to heterogeneity at core mantle boundary

We calculate synthetic seismograms by using the Spectral-Element Method (SEM) for several deep earthquakes to compare travel times of diffracted wave along the Earth's core mantle boundary. We use 507 nodes of the ES and calculate synthetic seismograms which are accurate up to 3.5 seconds in global scale (Komatitsch et al., 2005[3]). Seismic wave, which travels along the core mantle boundary, is called P-diff wave and is observable for stations with the epicentral distances greater than about 100 degrees. We calculate synthetic seismograms of P-diff waves for 3-D mantle model and compare with the observed seismograms to get travel time differences between synthetics and observations. Because the SEM put explicit discontinuities at the core mantle boundary when constructing the mesh, SEM can reproduce those waves that travel along the discontinuity accurately. Figure 5 summarizes comparisons of synthetics and observation. Required corrections to the seismic velocity structure at the core mantle boundary based on the travel time differences of (synthetics)-(observed) are overlaid along the great circle paths with the color scale shown in the left of the figures. The results show:

(1) Raypaths along the South Pacific Ocean show red colors, which demonstrates that the seismic velocity at the core mantle boundary under these raypaths should be slow.

(2) Raypaths along the North Pacific Ocean show purple colors, which demonstrates that the seismic velocity at the core mantle boundary under these raypaths should be normal.

(3) Raypaths along the south of Indian Ocean show red colors, which demonstrates that the seismic velocity at the core mantle boundary under these raypaths should be slow.

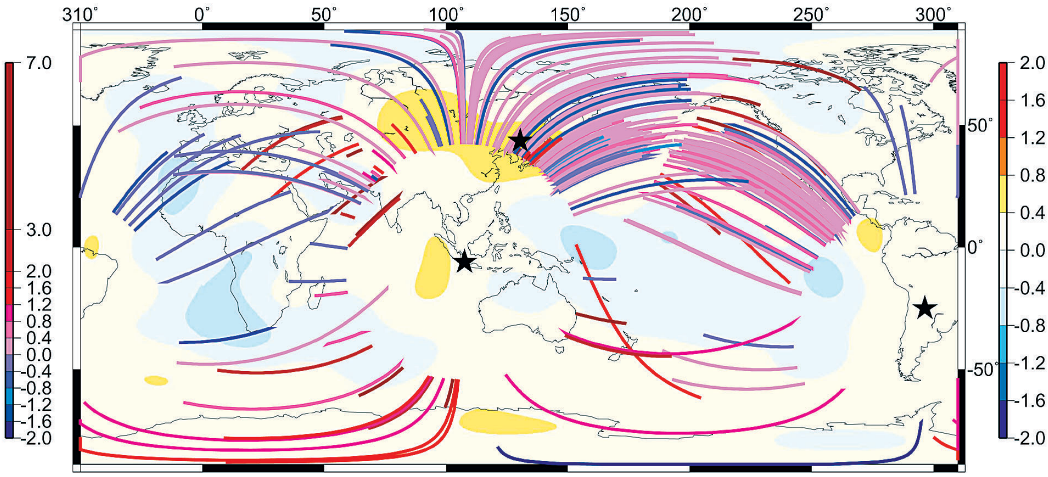

Fig. 5 Great circle paths to the broadband seismograph stations from the earthquake along the core mantle boundary. Stars indicate the epicenters of earthquakes used in this study. Required corrections to the seismic velocity at the core mantle velocity based on the travel time differences of (synthetics)-(observed) are overlaid along the great circle paths with the color scale shown in the left of the figure. Color bar in the right of the figure shows velocity scale of 3D mantle seismic velocity model at the core mantle boundary.

These results illustrate that the core mantle boundary structure below the South Pacific Ocean represents slow seismic velocity structure, which may coincide with the location of the root of the super plume.

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全地球弾性応答シミュレーション

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昨年度の研究では、波形インバージョンによる全マントルＳ波速度構造推定から、アフリカ及び太平洋の下の二大マントル上昇流域の低速度異常構造に明確な相違を検出した。アフリカの下にはＣＭＢから1000 km 以上にわたって顕著な低速度異常が広がっているのに対し、太平洋の下の顕著な低速度異常は、ＣＭＢから 300–400 kmの範囲に局在化していた。また、解像度テストを実施し、得られたモデルにこの描像を解像できるだけの解像度があることを確認した。本年度は、精度テストを実施し、得られた描像が信頼できるものであることを最終的に結論づけた。具体的には、昨年度に用いたデータセットとは独立なデータセットを用い、同様の特徴が再現できるかを検証した。マグニチュードや震源分布が有意に異なるイベントを用いてデータセットを作成し、データサンプリングやS/Nに相違を設け、データセット間の高い独立性を確保した。得られたモデルは、アフリカ及び太平洋の顕著な低速度異常の分布範囲に関して、昨年度のモデルと整合的であり、注目している描像の信頼性が確認された。

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、スペクトル要素法で全球を6個のブロックに分ける際の、一つのブロックのみを用いて、日本付近の地震に対して周期2秒の精度で地震波のP波とS波を計算した。計算した理論記録を観測記録と比較した結果、用いた3次元地球モデルの特徴である日本列島下に横たわるスラブの影響が理論波形には顕著であり、その結果の走時異常の観測結果を理論波形はよく説明できることが分かった。

さらに、地球内部の核・マントル境界を伝わる回折波であるPdiff波を計算し、観測波形との比較から、核・マントル境界の速度異常について検討した。その結果、南太平洋下の核・マントル境界は用いたモデルよりも遅い地震波速度構造を持つことが示唆されており、この地域に存在するとされるスーパープリュームと調和的であることが分かった。

キーワード: 理論地震波形記録, 地球内部3次元構造, Direct Solution法, スペクトル要素法