Global Elastic Response Simulation

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Seismic waves provide almost unique tool to investigate the internal structure of the Earth because electromagnetic waves do not pass through the Earth. Therefore it is necessary to compute seismic waves for realistic Earth models as accurate as possible. Here 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 (Vs) 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. We do not use ray theoretical approximation in computing synthetic waveforms, which enables us to treat rigorously the wave propagation effect due to lateral heterogeneity of the velocity structure. The 3D velocity model, we obtained, might help us to obtain very fine structure around subducting slabs and upwelling plumes and discuss their geodynamical implications. 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 calculate synthetic seismograms for anisotropic inner core model and compare with the observed seismograms to check reality of existing anisotropic inner core model.

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

1. Waveform Inversion for Fine Deep Structure

Inversion for detailed 3-D global Earth structure is important to constrain the dynamics of the Earth. There were a few studies to obtain Earth models by inverting seismic waveform data themselves rather than secondary data (such as phase data extracted from seismic waveform data). Such inversion method (called as waveform inversion) has a potential to improve the resolution of the Earth models because we can fully utilize the information included in the seismic waveform data. However, because of huge requirements of computational resources in simulating global elastic responses, rough approximations were employed in previous studies.

We applied our efficient computational method (Direct Solution Method; Takeuchi et al., 2000[1]) together with the Earth Simulator and conducted waveform inversion based on full 3-D simulations of global elastic responses. Preliminary model was obtained last year. This year we achieved the following two improvements. First we optimized memory allocation, which allow us to increase the number of model parameters from 3,610 to 5,054. Second we improved data weighting scheme to prevent errors in source parameters from degrading structure models. Applying these improvements, we succeeded in resolving fine deep structure. The results are expected to impose further constraints on up- and downwelling dynamics.

(1) Fine Structure of Upwellings

It is well known that two large low velocity provinces exist near the CMB (Core-Mantle Boundary) beneath Africa and the Pacific, which are assumed to be related to mantle upwellings. Figure 1 shows vertical sections of our model in these upwelling regions. The results clearly show the difference of two upwelling systems. The strong low velocity anomalies (indicated by orange or deep red; lower than –0.82 %) beneath the Pacific are restricted to approximately the lowermost 300–400 km, whereas those beneath Africa extend for about 1,300–1,400 km from the CMB. These results indicate variability of thermal and/or chemical structure in upwelling regions.

(2) Fine Structure of Stagnant Slabs Around Japan

Fukao et al. (2001)[2] showed that the slabs around Japan (from the South Kuril to the Izu-Bonin region) stagnate on the 670 discontinuity. Here we inspect their detailed structures. We choose four vertical sections around Japan and

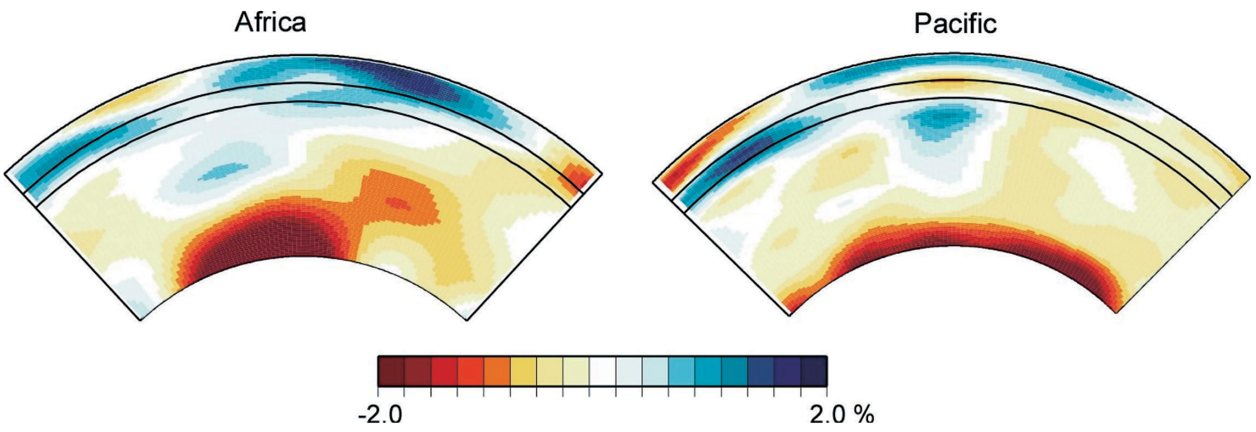

Fig. 1 Vertical sections of our model for the sections beneath Africa (left) and the Pacific (right). The color scale is saturated if the heterogeneity exceeds –2.0 % or 2.0 %.

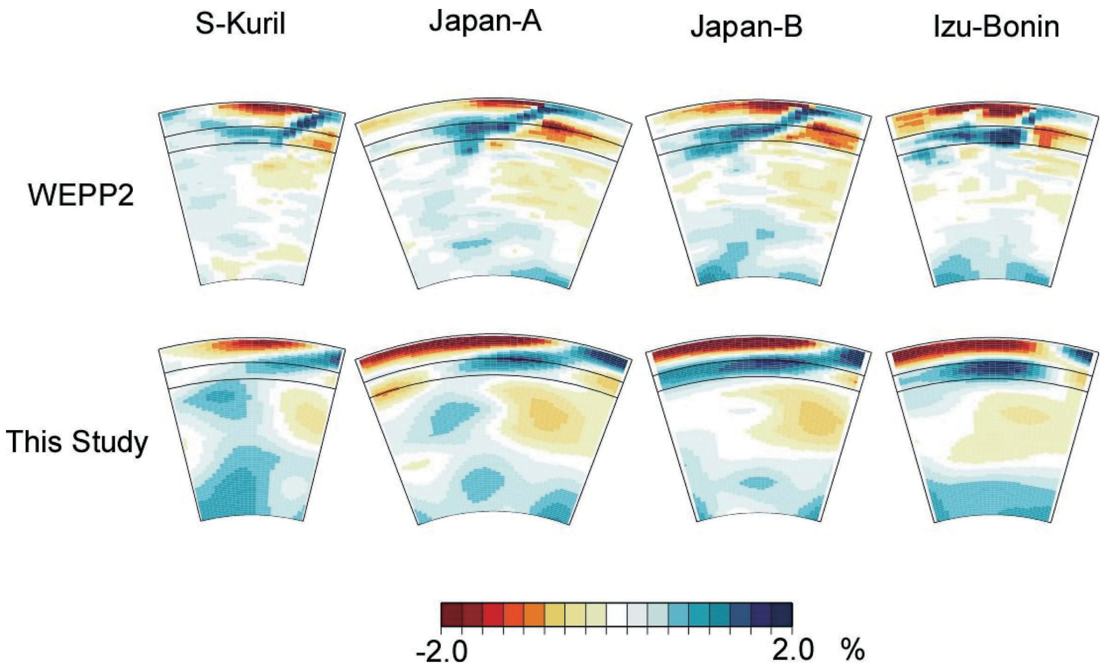

Fig. 2 The vertical sections of WEPP2 (upper) and our model (lower) for four sections around Japan. The color scale is saturated if the heterogeneity exceeds –2.0 % or 2.0 %.

compare the short wavelength P model, WEPP2 (presented in Fukao et al., 2001[2]), and the model obtained in this study. Figure 2 shows the result.

WEPP2 clearly shows the stagnant slabs on the 670 discontinuity, which appears to be a consistent feature among recent short wavelength P models. WEPP2 also shows further detailed features. If we focus on the depth of the strongest high velocity anomalies within the stagnant slabs, we see variations region by region. The highest velocity anomaly is in the shallower part of the transition zone for the S-Kuril and Japan-A section, whereas it is in the deeper part of the transition zone for the Izu-Bonin section. Although there should be debate on the reliability of such a detailed structure, it is notable that similar features can be observed in the model obtained by this study. Our model shows the high velocity anomalies in the transition zone in each section. Our model also shows the depth variations of the highest velocity anomalies: the depths for the S-Kuril and Japan-A sections seem to be shallower than that for the Izu-Bonin section. These depth variations were not commonly observed in previous global Earth models.

2. Implications to Earth's inner core anisotropy

The Earth has solid inner core inside the fluid core with the radius of about 1200 km. It is proposed that the inner core has anisotropic structure, which means that the seismic velocity is faster in one direction than the other, and used to infer inner core differential rotation. Because the Earth's magnetic field is originated by convective fluid motion inside the fluid core, the evolution of the inner core should have important effect to the evolution of the Earth's magnetic field.

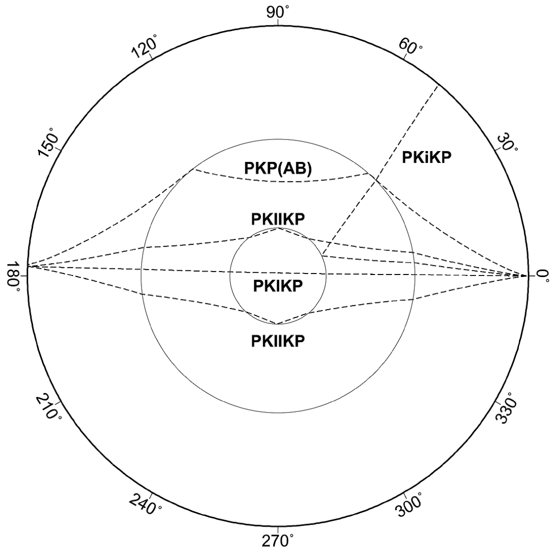

Fig. 3 Raypaths and its naming conventions of seismic waves, which travel inside the Earth's core.

Figure 3 illustrates definitions of typical seismic waves which travel through the Earth's core. The seismic wave, labeled as PKIKP, penetrates inside the inner core and its propagation time from the earthquake hypocenter to the seismic station (that is travel time) is used to infer the seismic velocity structure inside the inner core. Especially the dependence of PKIKP travel time to the direction is useful to estimate anisotropic structure of the inner core. We calculate synthetic seismograms for those PKIKP and PKP(AB) waves and evaluate the effect of inner core anisotropy to these waves. We calculate synthetic seismograms by using the Earth Simulator and Spectral-Element Method (SEM) for deep earthquake on April 8, 1999, at E. USSR-N.E. CHINA Border region (43.66N 130.47E depth 575.4km Mw7.1). 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]). When we construct global mesh in SEM computation, we put one small slice at the center of the Earth. Because of this, we do not have any singularity at the center of the Earth, which makes our synthetic seismograms very accurate and unique. We calculate synthetic seismograms for both isotropic inner core model and anisotropic inner core model and compare with the observed seismograms. Figure 4 summarizes comparisons of synthetics and observation. Travel time differences of (synthetics)-(observed) are overlaid

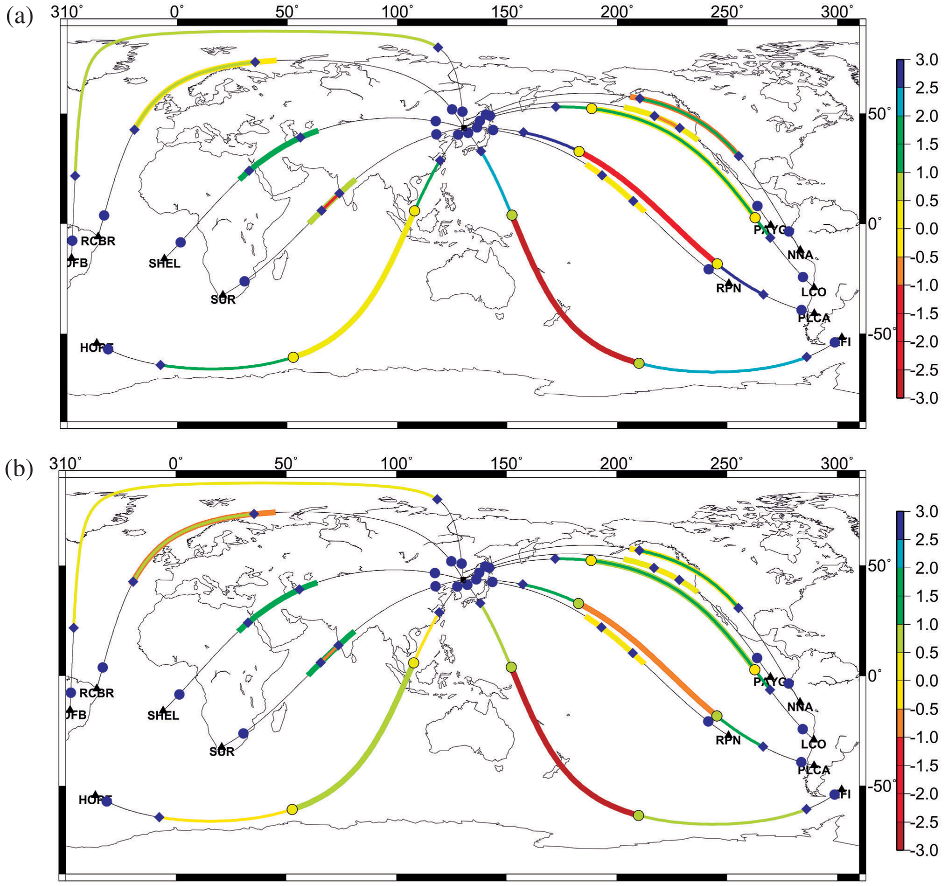

Fig. 4 Great circle paths to the broadband seismograph stations from the earthquake. Open circles show crossing points of Pdiff paths along the core mantle boundary (CMB). Red circles show crossing point at CMB for PKP(AB). Blue circles show crossing point at CMB for PKIKP. Blue squares show crossing point at ICB for PKIKP. Travel time differences of (synthetics)–(observed) are overlaid along the great circle paths with the color scale shown in the right of the figures. Comparison for isotropic inner core model (a) and anisotropic inner core model (b).

along the great circle paths with the color scale shown in the right of the figures. The results show:

(1) Travel time differences of PKIKP phases are decreased by introducing anisotropic inner core.
(2) For some stations, there still left significant differences in travel time differences for PKIKP.
(3) Observed Pdiff phases, which are diffracted wave along the core mantle boundary, are slower than the synthetics, which shows that we need to introduce slow velocity at CMB.

These results illustrate that the current inner core anisotropic model does improve the observation but it also should be modified to get much better agreement. They also demonstrate that there exist some anomalous structure along some portion of the core mantle boundary. This kind of anomalous structure should be incorporated in the Earth model to explain observed travel time anomaly of Pdiff waves.

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全地球弾性応答シミュレーション

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詳細な3次元不均質地球モデルのインバージョンは、地球のダイナミクスを理解する上で重要である。(地震波形データから抽出された)位相データではなく、波形データそのものを用いてインバージョンを行えば、地震波形データに含まれるすべての情報が活用できるので、解像度の改善が期待できる。膨大な計算時間を要することが問題であったが、我々は独自の効率的な計算手法(Direct Solution Method)と地球シミュレーターを活用することによりこれを解決した。予備的な解析は既に昨年度行われているが、本年度はメモリ使用量を節約し、モデルパラメータ数を1.4倍に増やすことに成功した。また、構造モデルが震源パラメータの推定誤差により乱されることを防ぐようなデータの重みづけ手法を導入した。この結果、上昇流域・下降流域それぞれに、特徴的な微細構造を検出することに成功した。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。また日本周辺の670km直上に滞留するスラブの内部構造に地域性があることを検出した。これらの結果は、上昇流・下降流のダイナミクスに新たな制約を与えると期待できる。

さらに今年度は、地球内部全体の3次元不均質構造モデルと内核異方性構造を考慮した理論地震記録を、スペクトル要素法により計算した。スペクトル要素法による理論波形計算では、地球を細かいブロックに分けて、さらに格子点に分割する。その際に地球の中心には小さなブロックを配置するので、地球の中心が特異点になることがない。そのために、PKIKP波のように地球の中心を通過する波も正確に計算することが出来る。ここでは、これまで地球シミュレータを用いて理論地震波形記録を計算してきたものと同じモデルパラメタにより、周期3.5秒の精度で理論地震波形記録を計算した。3D地球モデルはこれまでと同様にS20RTSを選んでいるが、今回の計算では、内核にIshi (2002)の異方性構造モデルを導入している。理論波形を計算した地震は、E. USSR-N.E. CHINA Border region (April 8, 1999 Mw7.1 43.66N 130.47E depth 575.4km)及びSALTA PROVINCE, ARGENTIN (March 21, 2005 Mw6.8 24.98S 63.47W depth 579.1km)である。観測点はそれぞれ、IRIS GSNの広帯域地震観測点を選び、Pdiff, PKP(DF), PKP(AB)について理論波形と観測波形の比較を実施した。計算した理論波形ではPKIKP、PKP(AB)ともに観測波形と良い一致が見られた。走時残差を観測点ごとに詳細に検討すると、異方性構造を入れたことにより、PKIKPの走時残差は減少する傾向にあり、導入したモデルは大局的には正しい内核の異方性構造を示していると考えられることが分かった。しかしながら、残差は1秒以上残っている観測点があり、異方性構造の程度を大きくするか、あるいは深さ依存性についての再検討が必要であることが分かった。また、特に南太平洋下のCMBを通過する波線経路を持つ観測点では、Pdiffの観測波形が明らかに理論波形よりも遅いことが分かり、CMBに不均質構造を導入する必要があることが明らかになった。

キーワード：理論地震波形記録, 地球内部3次元構造, Direct Solution Method, Spectral-Element Method