Global Elastic Response Simulation

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The targets of this project are; (1) to solve inverse problem, that is, to perform waveform inversion for 3-D shear wave velocity (Vs) structure inside the Earth using the Direct Solution Method and (2) to solve forward problem, that is, to calculate synthetic seismic waveform for fully 3-D Earth model. In this report we describe results obtained through the forward problem calculation. 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 snapshots of seismic wave propagation for 2002 Denali earthquake and have found that some of the later arrivals of seismic waves, which appeared in the synthetic seismograms, are really observed in the actual seismograms. We have found that these waves are originated from the heterogeneous crustal structure and should become useful to reveal complex crustal structure beneath mountain ranges. We also have started to calculate synthetic seismograms for earthquakes with magnitude larger than 6.5 using fully 3D Earth model and distribute these synthetic seismograms through our web site. These synthetics should be used as reference seismograms to study 3D structure of the Earth.

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

1. Introduction

We use the spectral-element method (SEM) developed by Komatitsch and Tromp (2002) to simulate global seismic wave propagation throughout a 3-D Earth model, which includes a 3-D seismic velocity and density structure, a 3-D crustal model, ellipticity as well as topography and bathymetry. The SEM first divides the Earth into six chunks. Each of the six chunks is divided into slices. Each slice is allocated to one CPU of the Earth Simulator. Communication between each CPU is done by MPI. We could use 507 nodes (4056 CPUs) of the Earth Simulator by using the SEM last year. Using 507 nodes (4056 CPUs), we can subdivide six chunks into 4056 slices (4056 = 6 × 26 × 26). Each slice is then subdivided into 48 elements in one direction. Because each element has 5 Gauss-Lobatto Legendre integration points, then the average grid spacing at the surface of the Earth is about 2.0 km. The number of grid points in total amounts to about 13.8 billion. Using this mesh, it is expected that we can calculate synthetic seismograms accurate up to 3.5 sec all over the globe. However, we could not use 507 nodes in the first half of the last year, because large number of nodes is allocated mainly to climate modeling research. Therefore we use 243 nodes for our calculation throughout the year.

2. Propagation of seismic wave in the 3D Earth model

We calculate synthetic seismograms for fully 3-D Earth model using the SEM code and 243 nodes of the ES for November 3, 2002 Alaska earthquake (Mw 7.9, depth 15.0 km) and create movie file that shows seismic wave propagation at the surface of the globe. Figure 1 illustrates an example of the snapshot prepared to create this movie file. While

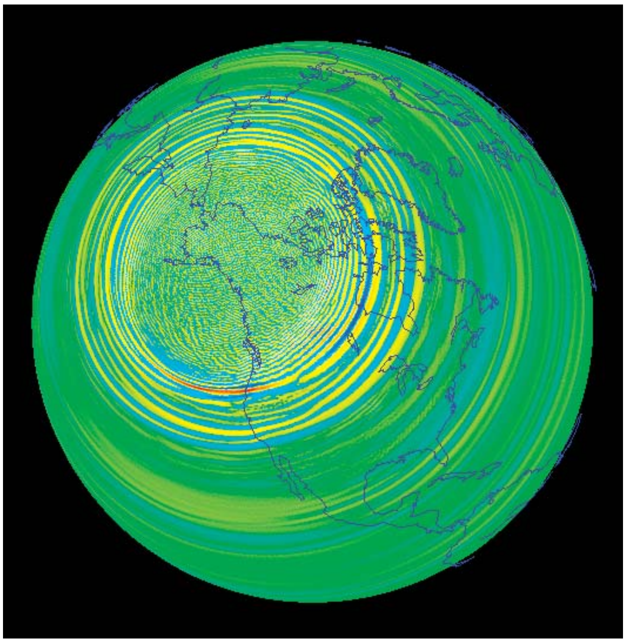

Fig. 1 Snapshot of the propagation of seismic waves in the Earth during the November 3, 2002 Denali fault earthquake simulated in Tsuboi et al (2003). Note that large amplification in the western coast of the United States due to the source directivity is modeled in the simulation.

creating this movie file, we have found that there are anomalous waves which seem to be originated from the heterogeneous structure inside the Earth. We have made another close-up figure of the snapshot to make these waves appear more clearly.

Figure 2 (Ji et al., 2005) shows a snapshot at 1200 sec after the earthquake initiation, when the body waves, such as the direct P and S waves, have already passed the North America plate. Figure 2 shows the motion of Rayleigh waves and, in particular, the high amplitude and long wavelength wave packet near the Gulf California is the long period fundamental mode Rayleigh wave (T>40 sec). Another high amplitude but shorter wavelength wave packet is so called continental Airy phase. The shapes of their wavefronts indicate that they propagate roughly along the great circle path from the epicenter. However, we found two anomalous wave packets (dashed boxes, Fig. 2), which seem to propagate along off-great-circle paths. The blue box highlights a wave packet whose peaks are along a line roughly parallel to the Oregon coast. The red box captures another wave packet that travels southward. We were curious about whether they are artifacts of synthetic calculations and studied the broadband waveforms recorded by dense SCSN array in the Southern California.

We download broadband waveforms from the data center of the Southern California Earthquake Center (SCEC), and

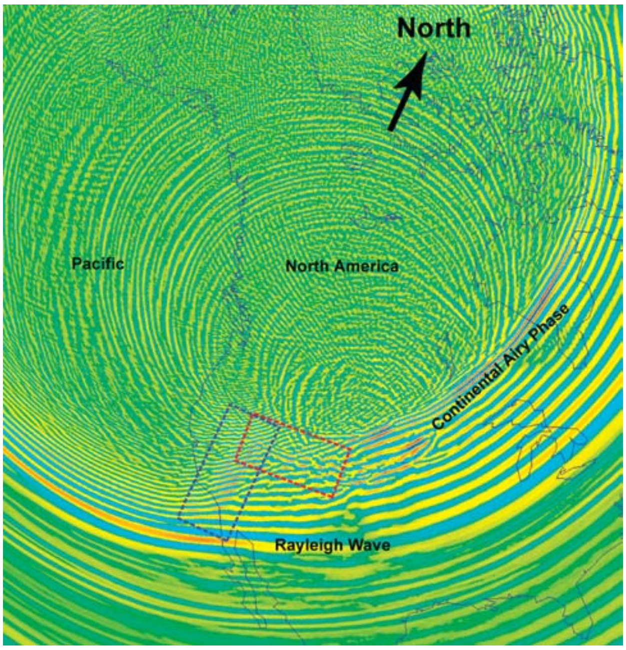

Fig. 2 Snapshot of a numerical simulation of ground motion for the November 3, 2002, Denali fault earthquake 20 minutes after the origin time. The North American coastline is delineated in blue. The colors show normalized vertical displacement. The direct long-period Rayleigh wave and continental Airy phase are labeled. The two dashed boxes highlight anomalous wave packets referred to in the text marked with blue box and with the red box. This figure is taken from Ji et al (2005).

convert them into displacements by removing the instrument responses. Their synthetic seismograms calculated during the previous study [Tsuboi et al., 2003] are also collected. While it is possible that the anomalous wave packets showed in the movie did not appear in the real records, they must show in these synthetic seismograms. So they are used to evaluate the procedures before we apply them to the real observations. We found that it was not easy to identify the signals from the broadband data. However after using a narrow bandpass filter with corner frequencies at 0.04 and 0.06 Hz, they became the dominant phases in seismograms (Figure 3) and we found that these waves were really recorded in the observation.

The comparison of observed seismograms with the synthetic seismograms in figure 3 shows that the synthetic wave packet marked with the blue box in figure 2 agrees well with the observation. This good fits to the observation suggest that this wave packet represents the direct Rayleigh wave whose ray path is distorted by the ocean-to-continent transition. Because the group velocity dispersion relationship for Rayleigh waves has a local minimum at about 20 sec in the case of a continental path, significant energy arrives at a specific time, producing an amplification and interference effect called the Airy phase. This shows that this packet gets generated as the Rayleigh wave crosses the Oregon coast.

The wave packet marked with the red box in figure 2 is also present in the recorded seismograms, but its temporal separation is much smaller than in the synthetic seismograms compared with the wave packet described above (Figure 3). We found that the reflector that is the origin of this wave packet locates at the eastern foot of the Rocky Mountains in case of the synthetic seismograms. The highest part of the mountains is located south of 55 degree North, which coincides roughly with the middle of the reflector that we attempted to locate. However, the data favor a lateral transition zone located 350 km further westward, where the high summits of the Rocky Mountains are located. Therefore, our analysis of the observed data seems to suggest that the transition from the tectonic region to the Canadian Shield is much sharper than that included in the crustal and mantle models used in our simulations. The results of this comparison will be used to further improve the 3D-crustal model. The lateral extension of the mountain root will give significant information toward the interpretation of tectonic evolution in this province.

3. Synthetic seismograms database

We have demonstrated that we can calculate global theoretical seismograms for realistic 3D Earth models based upon the combination of a precise numerical technique (the spectral-element method) and a sufficiently fast supercomputer (the Earth Simulator). It has now become possible to routinely

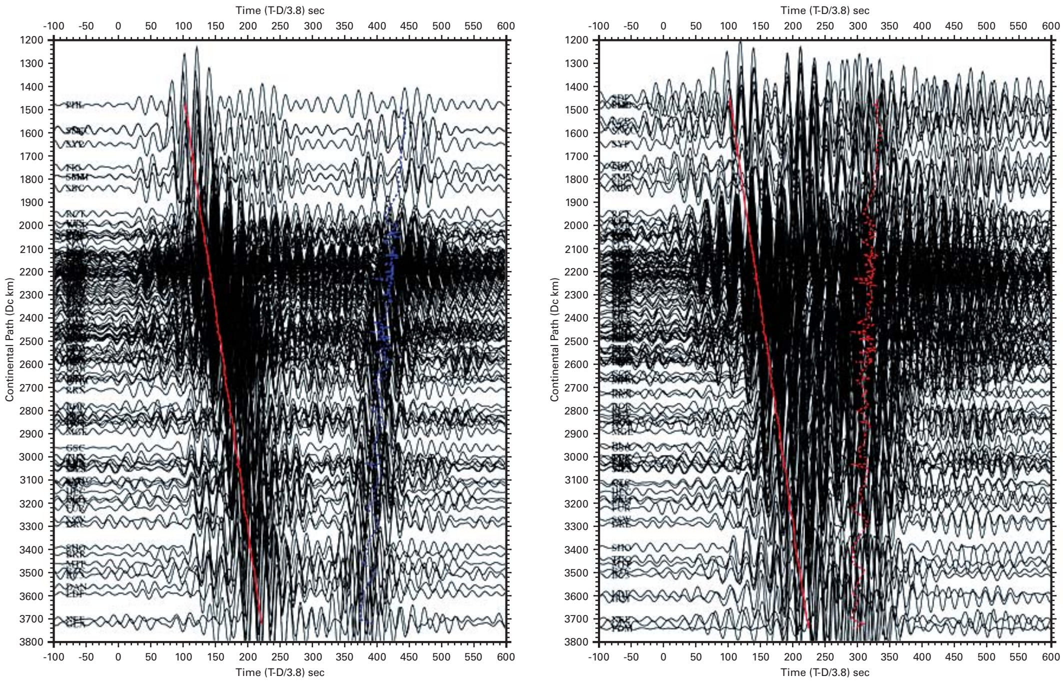

Fig. 3 Bandpass filtered vertical displacement SEM synthetic seismograms (left) and SCSN data (right) for the November 3, 2002, Denali fault, Alaska, earthquake. Both synthetic seismograms and data have been bandpass-filtered between 0.04 Hz and 0.06 Hz. The seismograms are sorted based upon the continental portion of their great-circle path and aligned based upon a reduced velocity of 3.8 km/sec. Red and blue curve shows arrival time of the largest amplitude packet. This figure is taken from Ji et al (2005).

calculate synthetic seismograms for earthquakes greater than a certain magnitude. Starting in 2003, we select earthquakes with magnitudes greater than 6.5 from the Harvard Centroid Moment Tensor (CMT) catalog and calculate theoretical seismograms for the Stations in the Global Seismographic Network. To distribute this synthetic seismogram database to the seismological community, we extend the current data format SEED (Standard for the Exchange of Earthquake Data) by representing the content in XML (eXtended Markup Language). We call this format as the XML-SEED and use this to include metadata entries which are characteristic to the synthetic seismogram database, such as numerical technique we used to generate synthetic seismograms. We plan to distribute these theoretical seismograms through mirrored IFREE/JAMSTEC and Caltech web interfaces soon. We are now developing software which realizes the users to retrieve both synthetics and observations at the same web site using the same user interface based on the web services technique. For this software to work efficiently, it is important that both data and synthetics are expressed in XML.

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全地球弾性応答シミュレーション

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我々はスペクトル要素法を地球シミュレータ上で用いることにより、周期5秒までの広帯域地震波形を現実的な3次元地球モデルに対して計算できることを示してきた。今年度は、200年アラスカ地震に対して地震波動伝播の可視化を行い、その結果の計算した理論地震波形記録に3次元地球内部構造により生じた特徴的な波動が見られることが分かった。震源過程はTsuboi et al (2003) と同様に、広帯域地震波形のインバージョンで得られた複数の点震源を断層上に配置してモデル化した。有限の断層運動をモデル化するために用いた点震源は475個で断層面に4 km × 5 kmの間隔で配置した。この震源モデルを用いて理論地震波形を計算するために3次元地球モデルとしては、マントル3次元地震波速度構造にS20RTS、地殻構造モデルにCRUST2.0, 地表及び海底の地形データにETOPO5を用いた。これにより、このモデルでは海水中を伝わる地震波を除き、考えられるすべての効果が取り入れられていることになる。理論地震波形の計算には地球シミュレータの243ノード(1944CPU)を用い、3次元地球モデルを54億個の格子点に分割した。これにより地表における格子点の間隔は約2.9 kmとなる。

発震時から1200秒後の地表における上下動成分の空間分布を図示したところ、アメリカ大陸西部を伝わる2種類の顕著な表面波が現れることがわかった。1つは、アメリカ西海岸で表面波が通過した後に、海岸線と平行な形状をして伝播してくるものである。これは、大陸を伝わる表面波のAiry phaseと海洋プレートを伝わる表面波の群速度の違いにより、表面波の波面が両者の中間的な速度で伝わることにより発生したものと考えることが出来る。もう一つの顕著な波動は、表面波が通過した後に、表面波とは異なった到来方向から伝播してくるものである。これは、ロッキー山脈を表面波が通過する際に、山体の下部にひろがった構造により表面波が散乱されたものであると考えられる。これらの波は観測波形に現れているが、ロッキー山脈で散乱された波については、到着時が観測と理論で異なっており、計算に使った地殻モデルよりも海側に強い反射面が存在することを示唆していることが分かった。

キーワード: 理論地震波形記録，地球内部3次元構造，スペクトル要素法