Global seismic wave propagation simulation

Project Representative
Daisuke Sugiyama Center for Earth Information Science and Technology, Research Institute for Value-Added-information Generation, Japan Agency for Marine-Earth Science and Technology

Authors
Seiji Tsuboi *1, Rhett Butler *2
*1Center for Earth Information Science and Technology, Research Institute for Value-Added-information Generation, Japan Agency for Marine-Earth Science and Technology , *2University of Hawaii

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1. Introduction

The base of the Earth's lower mantle is characterized by large seismic velocity anomalies, known as large low-velocity provinces (LLVPs) [1]. There are several hypotheses related to the origin of LLVPs, such as remnants of Earth's early differentiation [2-3]; and buried relics of proto-Earth's mantle after the Moon-forming giant impact [4]. However, the geodynamical implications, such as the role of LLVPs as driving mechanisms of plumes or subducted slabs, are not well resolved because some observations of the polarization of seismic velocity at LLVPs use the azimuthal anisotropy of shear wave splitting. Here, we combine new observations of antipodal PKPab seismic waves with the adjoint method to perform an inversion of the radially anisotropic *Vp* structure at the base of the lower mantle. We have carefully examined antipodal stations with sufficient signal to noise ratios for both the vertical and horizontal components over the past 30 years and selected 23 source–receiver pairs with epicentral distances greater than 178.0 degrees and Mw values less than 7.0. We calculate synthetic seismograms with an accuracy of 6.9 s and perform an inversion of the radially anisotropic *Vp* structure at the base of the lower mantle by the adjoint method. The results of our inversion show that vertically polarized *Vp* is dominant within the LLVPs of the Pacific and African regions. These features are characterized by relatively small spots of high vertically polarized *Vp* anomalies, which may be interpreted as the locations of ascending mantle plumes inside LLVPs in the Pacific region.

2. Data

The seismic wavefield recorded at the antipodal point of an earthquake is characterized by the annulus region surrounding the diameter which connects the epicenter and the antipode. These seismic waves, such as PKIIKP or PKPab, are focused near the antipodal point where the seismic energy is amplified—excepting only paths traversing a diameter through the earth, i.e., the PKIKP wave. Various studies have been conducted on the Earth's core structure using these characteristic properties of PKIIKP and related phases at the antipode [5-13].

In this study, we use the PKPab wave recorded at the antipode to investigate the radially anisotropic three-dimensional structure of the CMB. We reviewed antipodal stations with high S/N ratio during the past 30 years and selected additional source-receiver pairs with the epicentral distances greater than 178.0 degree and the Mw less than 7.0. We have 23 earthquake-receiver pairs in total used in the present study.

3. Sensitivity kernels by adjoint method

In adjoint waveform tomography [14-17], synthetic waveforms for realistic 3D Earth structure computed by numerical technique, such as spectral-element method, are combined with the computation of sensitivity kernels of waveform misfit to the 3D seismic velocity structure of the Earth. These sensitivity kernels will be used in an iterative inversion to update a model, 3D velocity structure of the Earth without using the ray-theoretical approximation in the tomography study.

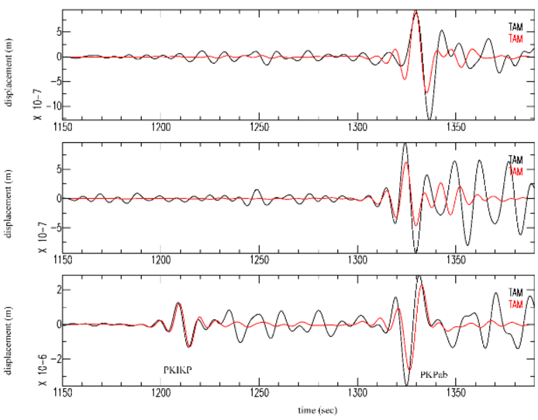

Figure 1 Comparison of observed (black) and theoretical (red) seismograms for three component seismograms (EW, NS, Z from top to bottom) for the February 23, 2010 Tonga Islands earthquake (Mw6.0) computed for the Tamanrasset (TAM) station in Algeria. The broadband displacement seismograms are bandpass filtered by a Chebyshev type-2 filter with the number of pole=4 andcorner frequency 0.02 and 0.125.

Here, we calculated the sensitivity kernel of radially anisotropic P-wave velocity to be used in the waveform inversion for heterogeneous P-wave velocity structure at the base of the lower mantle. To calculate the sensitivity kernels, we use the Spectral Element Method [18-21]. The Earth's internal structure model used incorporates a 3D tomography model SGLOBE-rani [22] for the Earth's mantle, and ellipticity. Topography at the surface of the Earth, rotation and the effect of the ocean are not included. The spectral element method program, SPECFEM3D_GLOBE, is used, and the number of elements at the surface along the two sides of block, NEX_XI, is set to 640. We use 9600 cores of the Earth simulator to calculate the theoretical seismic waveform which is accurate to a shortest period of about 6.9 seconds (about 8 sec when bandpass filtered). We apply Chebyshev type-2 filter with the number of pole=4, corner freq. 0.02 and 0.125 to both data and theoretical seismograms. We have applied two-pass filtering for a zero-phase filter. The comparison of the theoretical seismogram computed by the spectral-element method and the observation is shown in Figure 1.

Because this station is located almost at the antipode, the PKPab phase is focused at the antipode, we observe a large amplitude both for the vertical component and the horizontal component, and the signal-to-noise ratio of the PKPab phase is sufficiently high even for the horizontal component. Notably, the synthetic seismograms computed by the spectral element method generally reproduce the observed seismograms, which means that the spectral element method can simulate the antipodal focusing of seismic waves accurately. Although the synthetic and observed seismograms for this station generally agree well, we observe small differences in the arrival times of the PKPab wave, which may be used to estimate heterogeneous transversely isotropic *Vp* structures at the base of the lower mantle. A difference is also observed between the horizontal and vertical components, and we expect to use this to retrieve transversely isotropic structures. We used the 3D mantle model SGLOBE-rani to compute synthetic seismograms for the antipodal PKPab phase.

We compute the finite frequency sensitivity kernel of the P-wave velocity structure by using the adjoint method [23-24]. The adjoint kernel calculated for each earthquake and its antipodal observation point is called an event kernel. Each of the twenty three earthquake-receiver pairs used in this study covers a ray surface encompassing nearly 10% of the core-mantle boundary. Accounting for redundant coverage, most of the core-mantle boundary is substantially sampled, even though the number of the earthquake-receiver pairs is not large. By adding the event kernels calculated for each earthquake-receiver pair, the gradient of the misfit function to improve the initial model was calculated. We use the gradient of the misfit function to find the change δm that updates the model. We use the steepest decent method to find the updates of the model. Here, assuming that the initial model is updated with a step length of 3% for each iteration, the amount of modification of the model was calculated. When we update the model and calculate the synthetic by forward simulation, we calculate cross-correlation travel time difference for PKPab phase between the data and synthetic for each station. Then we compute the root mean square (RMS) of the cross-correlation travel time differences for all stations to check the performance of the updated model and iterate until the decrease of RMS becomes sufficient.

4. Results of the inversion

We present our inversion results for the *Vph* and *Vpv* structures at the base of the lower mantle with the isotropic *Vp* model of SGLOBE-rani in Figure 2[25]. Previous studies on radial anisotropy at the base of the mantle have been conducted for *Vsv* and *Vsh* on the basis of surface waves. [22,26]

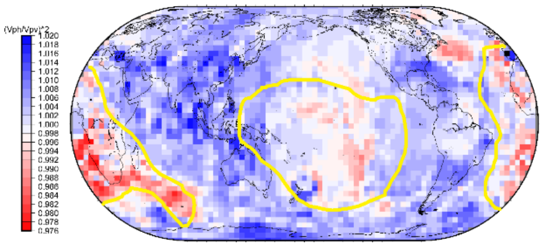

Figure 2 Distribution of the radially anisotropic *Vp* structure at the base of the lower mantle. $(Vph/Vpv)^2$ is plotted. The approximate locations of the LLVPs are shown as yellow lines.

Because radial anisotropy may be used to distinguish between horizontal and vertical mantle flow at the base of the lower mantle, we examine the distribution of the radially anisotropic *Vp* structure. We plot $(Vph/Vpv)^2$ in Figure 2 to compare with $(Vsh/Vsv)^2$ of previous works, which generally show $Vsv > Vsh$ within LLVPs and $Vsh > Vsv$ outside of LLVPs [27]. Figure 2 shows that our $(Vph/Vpv)^2$ pattern has essentially the same large-scale feature as was reported in previous works, but the detailed structure of LLVPs is not the same. For example, LLVPs in the Pacific region are not largely characterized as $Vpv > Vph$, but these regions, where the vertically polarized P wave is faster than the horizontally polarized P wave, are limited to small areas, such as near the Tonga Islands and Hawaii Islands, which may be interpreted as the locations of ascending mantle plumes inside LLVPs in the Pacific region.

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