Global seismic Wave Field Effects of geodynamically derived 3D Mantle Structures

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Project Description

Abstract

When discussing seismological reference models of Earth's interior it is important to consider geodynamical constraints which provide estimates on magnitude and power of lateral mantle heterogeneity. To explore this avenue, we have built a 3-D mantle velocity model derived from a combination of geodynamic mantle circulation simulations and thermodynamically self-consistent mineral physics modeling. The purpose of this approach is to obtain seismic velocity models independently from seismological observations. Additionally, one can test the effects of varying input parameters on the seismic wave field. We have calculated seismic velocities using temperature fields from a geodynamic simulation and assuming a certain mantle composition (e.g. pyrolite). Our mineralogic modeling algorithm computes the stable phases at each depth (i.e. pressure) and temperature by system Gibbs free energy minimization. Through the same equations of state (EOS) that model the Gibbs free energy of phases, we compute elastic moduli and density. For this we built a mineral physics database based on calorimetric experiments (enthalpy and entropy of formation, heat capacity) and equation of state parameters. In our study we focus primarily on amplitude effects of 3-D mantle structure on the seismic wave field. 3-D wave fields are simulated using numerical wave propagation techniques for the whole globe (SPECFEM3D, Komatitsch and Tromp, 2002a,b) for different velocity models of the mantle. Effects of the geodynamic mantle model on the spatial distribution of P-wave amplitudes are shown as one example to illustrate the capability of this approach.

Motivation

- Tomography only provides a geometry for mantle models → no physics included
- Different tomographic studies use different datasets and different techniques for the inversion → differences in models (geometry, amplitude of perturbations, resolution and parameterization)
- Inversions for P-/S-wave speed and density lead to different geometries and to date cannot be explained uniquely

Therefore

- Creation of physically consistent velocity models independent of seismological observations → Model Planet
- Possibility of testing the effect of various geodynamical parameters on the seismic wave field
- Better understanding of the forward problem of global seismology
- Separation of crustal and mantle effects on the wave field
- Exploration of different processing methods and configurations beyond current observational capabilities

Approach

Forward Modeling only

Mantle Circulation Model (temperature field) ↘ ↙ Mineral Physics Model (elastic moduli, density)

Velocity Model (MCM_MP, physically consistent)

↓

Global 3D Wave Propagation (SPECFEM3D)

↓

Processing

What to look for in the synthetic data?

- Direct comparison between tomography models and MCM not yet feasible (current resolution of MCM leads to overestimated temperature variations)

Solution

- Averaging each 3D MCM_MP will give a theoretical 1D reference model that serves as a kind of "artificial PREM"
- Such model will provide the opportunity to study the expected in physically plausible media

characteristics of global wave fields

Important seismological parameters are:

- frequency content/spectral ratios
- envelope (energy)
- amplitude ratios (3D/1D average) → focusing/defocusing
- coda waves (scattering)
- spatial distribution of these features

Models

Geodynamic Model

- Present day temperature field from mantle convection simulations based on sequential data-assimilation of past plate motions of Bunge et al. 2002
- Whole mantle, spherical geometry
- Over 10 Million finite elements → ca. 60km horizontal grid spacing
- Rayleigh number based on internal heating of order 10^8
- Viscosity increases from upper to lower mantle by a factor of 40
- 85% internal heating by radioactive decay
- 15% of heat coming from CMB
- Model is parameterized in spherical harmonics (degree > 120) for 65 radial levels

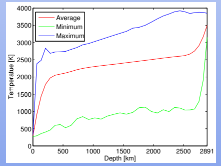
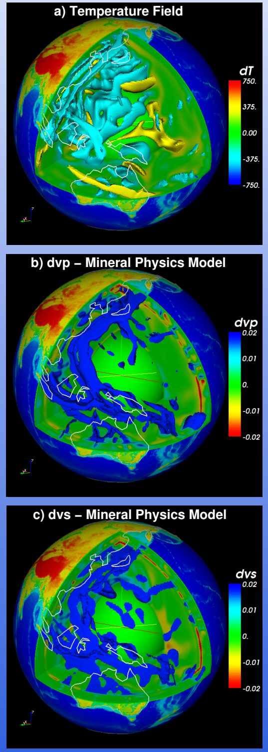


Figure 2. Radial temperature profile of the geodynamic mantle convection simulation together with the minimum and maximum temperature

Figure 1. Compilation of Earth models used in this study. a) Temperature field from mantle circulation model. Isosurfaces for -350K and +350K are displayed b) and c) Velocity models (dvp and dvs, respectively) derived from a) using mineral physics modelling. Isosurfaces for +1.75% are shown for the velocity models.

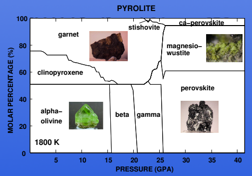


Mineral Physics Model

Velocities

- Pyrolitic composition (38.3% SiO_2, 49.33% MgO, 6.27% FeO, 3.3% CaO, 2.22% Al_2O_3)
- Computation of stable phases by minimizing Gibbs free energy of the system using equation of state parameters and calorimetric data
- Density and elastic moduli obtained by appropriate equations of state (for each phase) and Voigt-Reuss-Hill averaging for the mixture applied to temperatures and pressures from the geodynamic model

Figure 3. Molar fractions of the stable phases at 1800K for a pyrolitic composition from Gibbs free energy minimization.



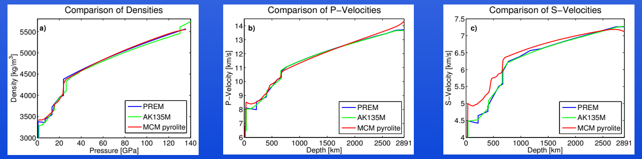


Figure 4. Radial 1D profiles of the converted (T→Vs/Vp) mantle convection model from radially averaging the 3D seismic velocities. In addition profiles of PREM and AK135M are shown for comparison.

Simulations and Results

Setup and Input Parameters

- Simple model, pure mantle effects (spherical, no topography, no crust etc.)
- Events: (intermediate moment magnitude → point source)
  - Fiji Islands M6.4, April 13 1999, depth 164 km
  - Central Mid Atlantic Ridge M5.9, January 16 2004, depth 10 km
  - North of Severnaya Zemly M6.3, March 6 2005, depth 10 km
- Stations: all GSN (Global Seismographic Network) stations and a uniformly spaced grid of 42250 stations all over Earth's surface
- Resolution allows accurate seismograms down to ca. 20s period
- Some additional simulations incorporating both 3D mantle and 3D crustal structures (model crust2.0)

Processing

- Z-component for P-wave amplitude ratios (3D model/1D)
- Stations between 35° and 88° epicentral distance
- Cut and taper window around P-arrival (30s before, 15s after pick)
- Cross-correlation and ellimination of time shift between 3D and 1D reference
- Computation of RMS amplitude ratio for shifted traces (Sigloch & Nolet 2005, Earthscope Meeting)

Conclusions

- The approach of using forward modeling to derive 3D structures opens a broad range of possibilities to test hypotheses on heterogeneity inside the Earth
- Significant sensitivity of the P-wave amplitudes to mantle structure (± 20%)
- Main effect from crust (± 50%) as expected
- Localized extreme variations in amplitudes are probably due to radiation pattern of centroid moment tensor (CMT) (unexpected, as the amplitude ratios in Figure 6 are computed from simulations using the same CMT, → effect of radiation patterns should cancel out in ratios)
- Pattern of resulting P-wave traveltime differences seem not to be directly related to the corresponding amplitudes

The relation between traveltime and amplitude, will be subject to further analysis.

Outlook

- Study of amplitude ratios for varying frequency bands
- Increase of resolution of wave propagation simulation → higher frequencies
- Building of new model using dvp and dvs perturbations of MCM MP applied to PREM
- Study of effect of different heterogeneity length scale in MCM MP by varying the degree of the spherical harmonics expansion
- Simulations for 1D mantle model with 3D crustal structure: is it possible to obtain the mantle signature in the amplitude patterns from waveforms of 3D mantle + crustal models?
- Improvement of mantle circulation models: higher resolution (earthlike Rayleigh number, correct representation of boundary layers), additionally including mineral physics modelling to compute densities
- Detailed analysis and description of the seismic velocity model obtained from improved mantle circulation model with the approach introduced in this study

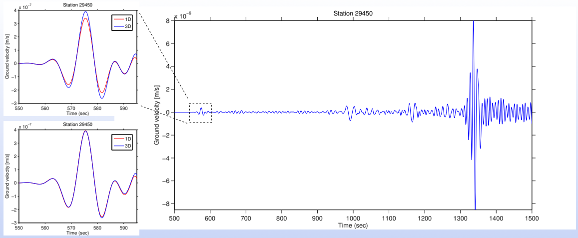


Figure 5. Synthetic seismogram (Z–component) of the 2005 North of Severnaya event obtained using the 3D seismic mantle model generated in this study. The station 29450 is located at an epicentral distance of 55 degree. A blow up of the P–wave is shown in the upper left panel together with its corresponding 1D reference. The lower left panel shows the 3D amplitude corrected with the RMS ratio (Sigloch 2005) between 3D and 1D reference (3D/1D=1.15).

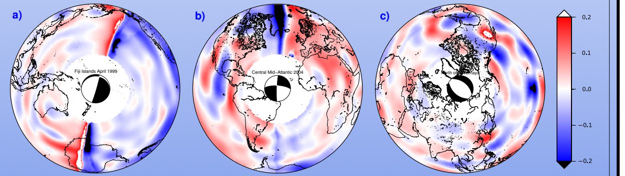


Figure 6. P–wave amplitude ratios (amp(3D)/amp(1D) – 1) for the three simulated events measured at stations located at an epicentral distance range of 35 – 88 degree (distinct P–wave onset available) The plots show Lambert azimuthal equal–area projections centered on each event. Values greater 0.0 indicate regions of focused energy due to 3D mantle structure. Despite the fact that the same CMT Solution was used for the respective 3D and 1D simulations, effects due to the radiation pattern are visible.

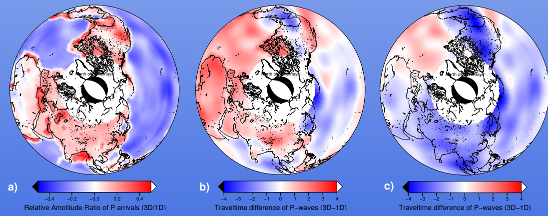


Figure 7. Comparison of P–wave amplitude characteristics and traveltime perturbations obtained from the North of Severnaya event. a) P–wave amplitude ratios (see Figure 6.) from a combined 3D mantle and crustal model (crust2.0). b) Traveltime difference from the combined 3D mantle and crustal structure. c) Traveltime difference from the 3D mantle model without crust (compare to Fig. 6c).

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