行政院國家科學委員會專題研究計畫　成果報告

利用地震波研究熱點和慢速擴張洋脊下的上地幔：整合地體動力模型與波形模擬(2/2)

計畫類別：個別型計畫
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計畫主持人：洪淑蕙

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行政院國家科學委員會補助專題研究計畫成果報告

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※　利用地震波研究熱點和慢速擴張洋脊下的上地幔：　※

※　　整合地體動力學模型與波形模擬(2/2)　　※

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計畫類別：∨個別型計畫　　□整合型計畫

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計畫主持人：洪淑蕙

共同主持人：

計畫參與人員：Karen Fischer at Brown University

本成果報告包括以下應繳交之附件：

□赴國外出差或研習心得報告一份

□赴大陸地區出差或研習心得報告一份

∨出席國際學術會議心得報告及發表之論文各一份

□國際合作研究計畫國外研究報告書一份

執行單位：台灣大學地質科學系

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Abstract. Mid-ocean ridges and surface hotspots are two places where active volcanisms occur on our planet. Using seismological observations as constraints, the goal of our study is to understand the form of mantle upwelling and melt production at a possible deep-rooted mantle plume and beneath a slow-spreading ridge segment which are responsible for magma eruption on the earth's surface. Seismic experiments on the fast-spreading East-Pacific Rise and ridge-centered Icelandic hotspot generated numerous high-quality records which indicate the underlying structures are partially-molten, elastically heterogeneous and anisotropic as well as attenuated. In these geodynamically-interesting but structurally-complicated environments expected under discontinuous ridge segments and hotspot tracks, many of the usual approximation employed in modeling finite-frequency seismic wave propagation break down. This study explores the effects of velocity heterogeneity and anisotropy associated with temperature and compositional variations in the upwelling mantle on seismic waveforms by virtue of direct solution method. Fully understanding of seismic wave behaviors in a complicated structure like the earth will help data acquisition accusation and interpretation to image the deep mantle structure.
Key words: parallel computation, seismic wave propagation, anisotropy, mantle plume.

Introduction

With the advent of instrument technology, long-term land-based network array and ocean-bottom seismometer (OBS) experiments have been conducted successfully to acquire high-resolution seismic data used for probing the deep mantle structure beneath fast-spreading ridges (the Lau Basin and MELT experiments) and hotspots (ICEMELT experiment and HOTSPOT project) (e.g., *Zhao et al.*, 1997; *Forsyth et al.*, 1998a; *Allen et al.*, 2000). Another ambitious attempt, call PLUME, for Plume-Lithosphere Undersea Melt Experiment, is underway in the fall of 2004. The experiment will deploy dense, durable OBSs around the island to receive seismic data from distant earthquakes and to look for the deep roots of Hawaii's volcano. High-resolution tomographic images of anomalous P and S wave velocities place significant constraints on the shape of melt production zone and the pattern of mantle upwelling, which have not been well-resolved from previous global studies only using unevenly- and sparely-sampled observations from global seismograph network (e.g., *Wolf et al.*, 1997; *Toomey et al.*, 1998; *Forsyth et al.*, 1998b; Montelli et al., 2004; *Hung et al.*, submitted). However, many questions relevant to the structure and dynamics of mid-ocean ridges and mantle plumes remain an enigma. For instance, is mantle upwelling and melting three-dimensional beneath a slow-spreading ridge offset by transform faults? How does an ascending thermal plumes adjacent to the ridge, for instance, the Iceland hotspot, disperse at shallow depths, through channelized along-axis flow or broad radial spreading at the base of the lithosphere ? How deep is the origin of the mantle plume associated with the volcanic activities at the surface hotspots, like Haiwaii and Iceland? To answer these questions will depend on high-quality, densely-sampled data from the OBS array network combined with the adequate theory and analysis tools to interpret seismic signals properly.

As passive teleseismic experiments particularly for the OBS deployment are usually expensive and risky, we need to carefully design the experiment so that to gain as much information as possible from collected data. Both the interpretation (inverse) theory and forward wave propagation modeling play a crucial role to imaging seismically partially-molten mantle structures. This study emphasizes the aspect in the improvement of our understanding of how mantle flow, melt generation and fraction associated with the process of plume and ridge dynamics affect seismic velocity structures and anisotropy. We develop a multi-domain, parallel pseudospectral method to simulate seismic wave propagation in heterogeneous, anisotropic, and attenuated medium. Synthetic waveform modeling provides fundamental guidance to better understand the basic physics of finite-frequency waves propagating in such complicated structures and constrain the thermal state and elastic properties in the upwelling, partial-melting mantle beneath a oceanic ridge and hotspot.

Methodology

The equation of motion and the constitutive law for elastic wave propagation in anisotropic media are (Hung et al., 1999)

$$\begin{aligned} \rho\partial_t v_i &= \sigma_{ij,j} + f_i, \\ \partial_t \sigma_{ij} &= c_{ijkl} v, \end{aligned} \qquad (1)$$

where c is the elastic coefficient and have 21 independent coefficients in the most general anisotropic medium, ρ the density, v the velocity of particle motion, σ the stress tensor, and f the body force. To solve for eq (1), we choose the Chebyshev-Fourier basis functions to expand the physical variables of v and σ in space, the spatial derivatives in eq(1) can be simply calculated by fast Fourier transforms. Then the 4th-order Runge-Kutta method is employed to advance the time evolution of seismic wavefields. The FFT-based numerical scheme is parallelized to allow running in multi-processors to expand the model size and speed up the calculation. We have built up a PC cluster with16-node dual processors connected together (Figure 1), partly supported from the budge of this NSC proposal. Most of the simulation runs presented here is performed in this machine set up in the Department of Geosciences, National Taiwan University.

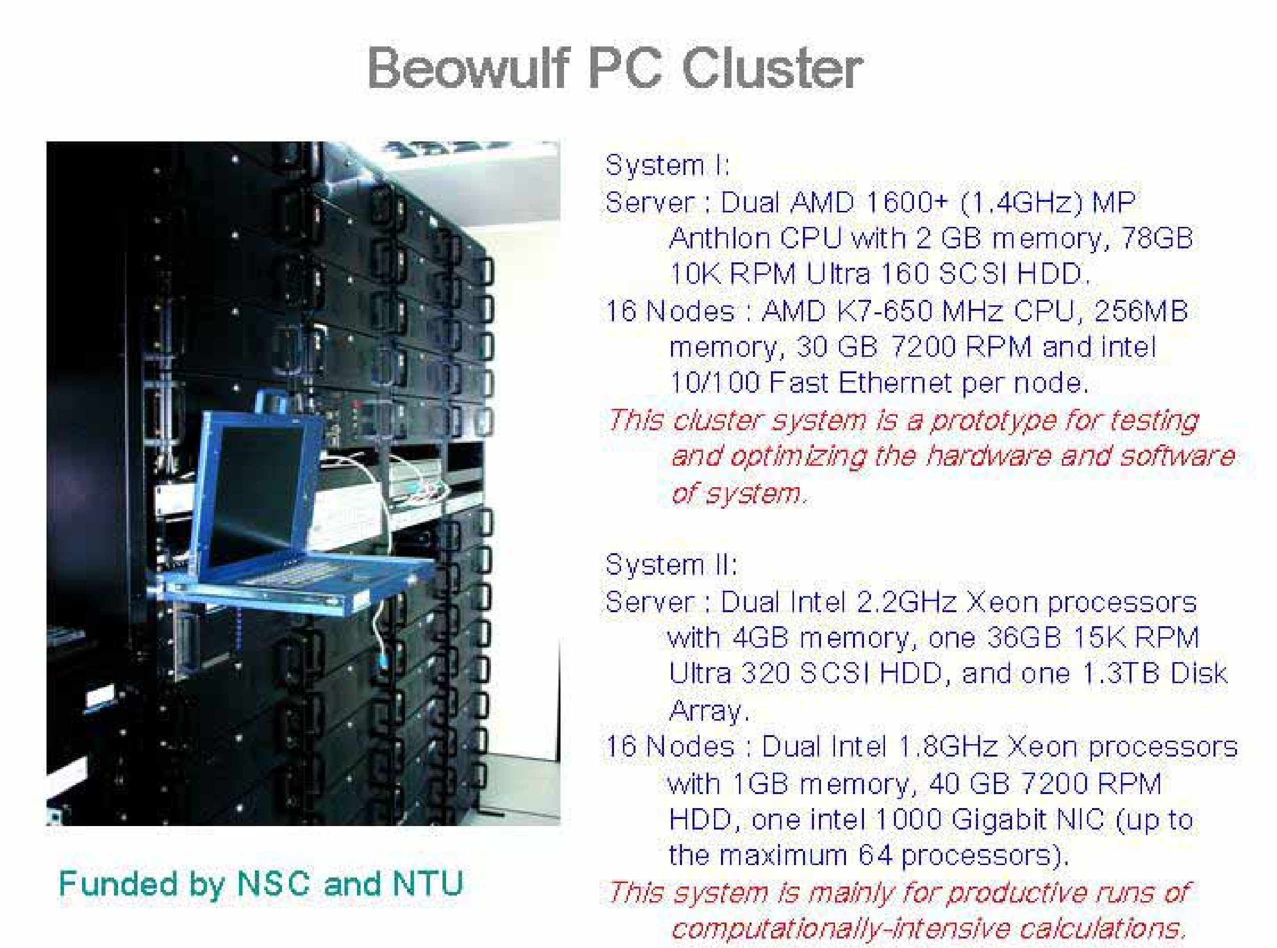

Figure 1. The 16-node PC cluster is built in the department of Geosciences partly funded by this project. It allows productive runs for numerical simulations by means of parallel computation that often require large memory storage and intensive CPU times.

Simulation Results

Here we present 2 cases of seismic wave propagation simulations which show the finite-frequency wave behaviors while incoming seismic wavefields encounter anisotropic and heterogeneous structures. As a shear wave enters an anisotropic medium, it will split into two orthogonal waves traveling with different speeds. Seismologists often measures the polarization direction of the leading phase and the difference of arriving times between the fast and slow phases SKS wave to infer the pattern of mantle flow or the stress state of lithosphere. SKS splitting is useful to extract anisotropic information underlying beneath stations. In addition, azimuthal anisotropy derived from dispersive surface waves is used to map the anisotropy variation in depth. Many related studies have documented seismic anisotropy in a variety of tectonic regimes, but the anisotropic pattern resulting from the SKS and surface-wave observations can be quite different. It has been suggested that this discrepancy can be attributed to the frequency-dependent anisotropy caused by the velocity heterogeneity or 3-D or multi-layered anisotropic structures. Collaborating with Karen Fischer at Brown University, we investigate the characteristics of SKS splitting using direct numerical waveform models. We calculate finite-frequency wave propagation in 3-D anisotropic structures. The box model is set to be 288x288x256 km in x, y, and z directions, respectively. The grid space is 1 km. The model has an isotropic uniform mantle velocity insert in the middle with vertically-aligned anisotropic blocks of 5% hexagonal-symmetric anisotropy. The fast directions of adjacent blocks are orthogonal, either in x or y directions. The teleseismic SKS phase arrival is approximately simulated as a vertically-incident plane wave. We test several cases with different lateral dimensions of the anisotropic blocks. Figure 2 show the snapshots of SKS waves. Compared the 25-s frame with the 40-s one, the finite-frequency healing of the curvature of the SKS wavefront occurs as it propagates through the upper isotropic layer.

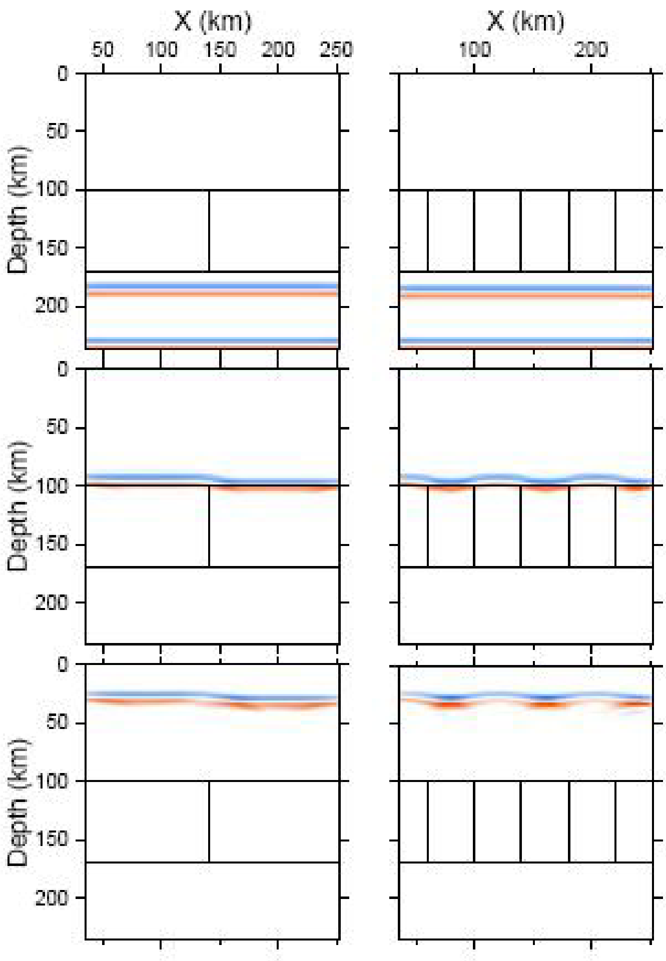

Figure 2. Snapshots of SKS wave propagation. Each frame shows vertical components of particle motion on XZ plane at y=150 km. Imposed velocity structure can be referred in the text. Frames correspond to three time steps at 5 (upper), 25 (middle), and 45 s (lower) after the initiation.

To get a better view of what signals can be expected or detected if a hot, deep-rooted thermal plume underlies beneath the stations, we model both body and surface waves propagating through a cylindrical-shaped low-velocity conduit. The body-wave case has a model dimension of 640x640x640 km with grid spacings of 5 km in horizontal directions and varying in depth. The plume is centered in the model and has a diameter of 200 km extending from the surface to 400 km. P and S velocity within the conduit is 5% and 10% slower than the background velocity based on 1-D PREM (Figure 3). A teleseismic body-wave arrival is approximately modeled as a planar wavefront. While the vertically-incident P wave encounters the plume conduit, the planar wavefront is bent and delayed substantially in the middle part of the wavefront. Meanwhile, a secondary, parabolic wavefront is developed behind the direct arrival and is generated by wave diffraction around the low-velocity zone (Figure 4). Except for the waveform and traveltime information contributed by direct P or S arrivals, the appearance of the secondary phases provides additional constraints on the geometry and velocity anomaly of the plume structure.

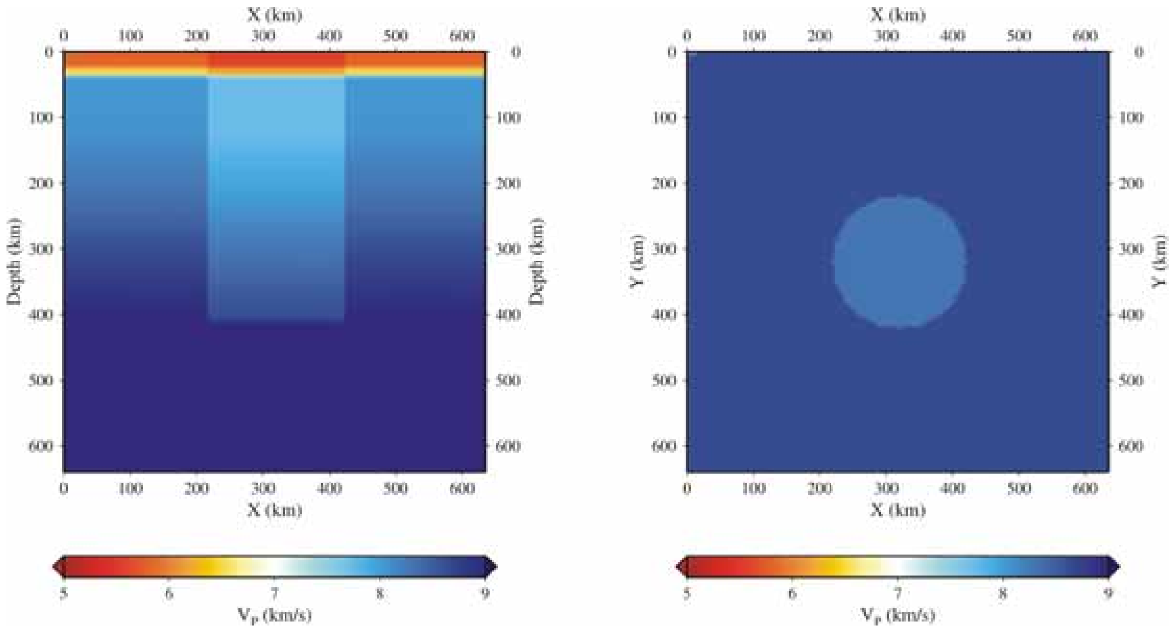

Figure 4. A cylindrically-shaped low-velocity conduit, simulated as a deep-rooted mantle plume is superimposed on 1-D PREM model. The conduit is 5% and 10% slower in P and S wavespeed than those in the surrounding region and has a diameter of 200 km extending from the surface to 400 km.

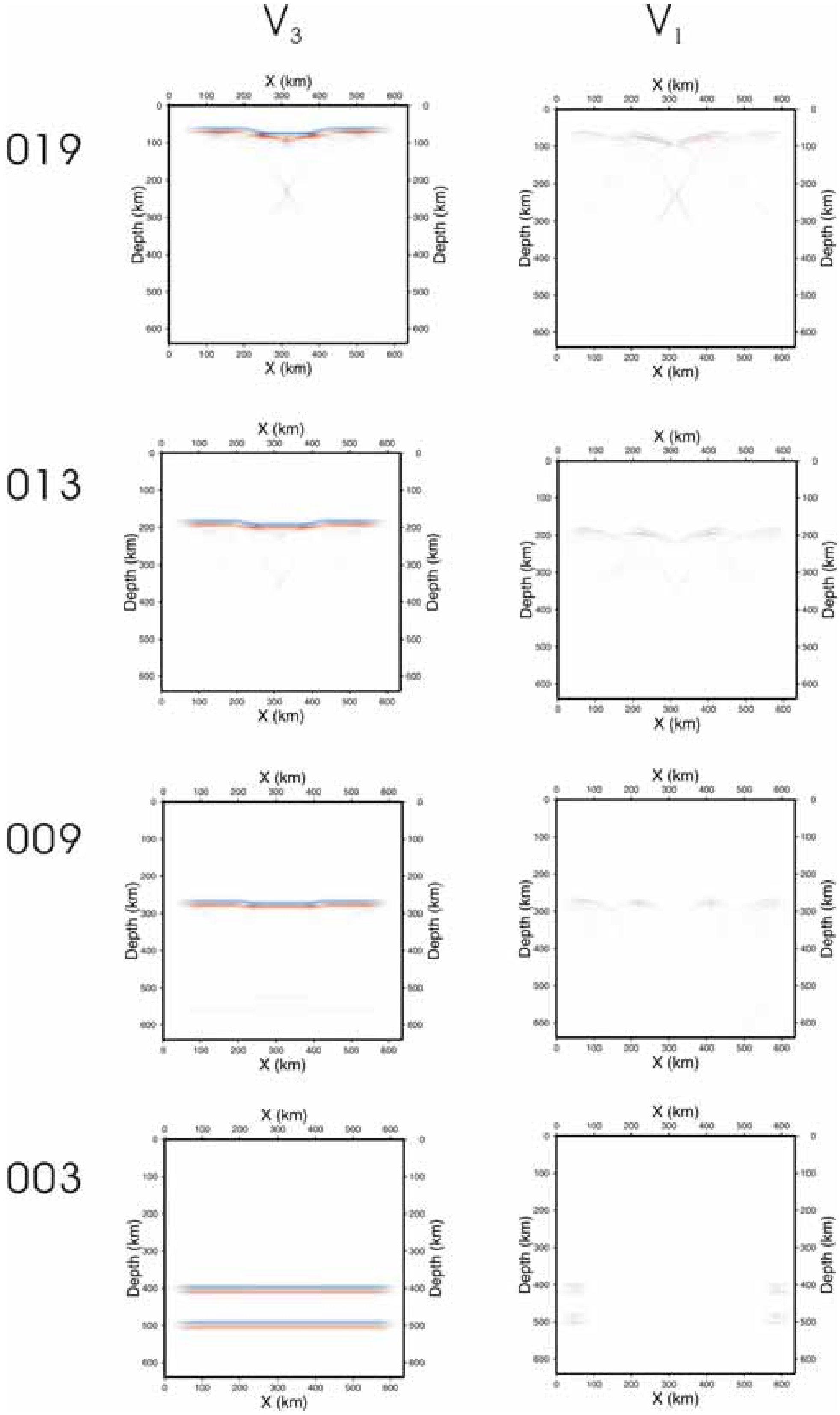

Figure 4. Snapshots of a teleseismic vertically-incident P wave. The wavefields are displayed on the XZ plane slicing through y=315 km. Frames 003, 009, 013, 019 corresponds to the times at 5, 20, 30 and 45 s after initiation of wave motion. On the left is the ground velocity on the vertical z component and on the right is on the x component.

Conclusion

Two main conclusions can be drawn in this study:

1. We present two examples of body-wave wave propagation in heterogeneous and anisotropic structures, which happen to be observed in oceanic lithosphere and a mantle plume. The wavefields encountering the velocity anomaly or 3-D anisotropic structure show a complicated pattern.
2. Except using direct traveltimes of seismic waves, other secondary phases can provide a robust measure of the velocity structure in low velocity zone.

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Global Time Tomography of Finite Frequency Waves with Optimized Tetrahedral Grids.

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Besides true velocity heterogeneities, tomographic images reflect the effect of data errors, model parameterization, linearization, uncertainties involved with the solution of the forward problem and the greatly inadequate sampling of the earth by seismic rays. These influences cannot be easily separated and often produces artefacts in the final image with amplitudes comparable to those of the velocity heterogeneities. In practices, the tomographer uses some form of damping of the ill-resolved aspects of the model to get a unique solution and reduce the influence of the errors. However damping is not fully adequate, and may reveal a strong influence of the ray path coverage in tomographic images. If some cells are ill determined regularization techniques may lead to heterogeneity because these cells are damped towards zero. Thus we want a uniform resolution of the parameters in our model. This can be obtained by using an irregular grid with variable length scales.

We have introduced an irregular parameterization of the velocity structure by using as delaunay triangulation. Extensively work on error analysis of tomographic images together with mesh optimization has shown that both resolution and ray density can provide the critical information needed to re-design grids. However, criteria based on resolution are preferred in the presence of narrow ray beams coming from the same direction. This can be understood if we realize that resolution is not only determined by the number of rays crossing a region, but also by their azimutal coverage. We shall discuss various strategies for grid optimization.

In general the computation of the travel times is restricted to ray theory, the infinite frequency approximation of the elastodynamic equation of motion. This simplifies the mathematic and is therefore widely applied in seismic tomography. But ray theory does not account for scattering, wavefront healing and other diffraction effects that render the travel time of a finite frequency seismic waves sensitive to three-dimensional-structure off ray.

Dahlen et al (2000) used the Born approximation to find a double-ray sum representation of the 3D Fréchet kernel. Destructive interference among adjacent frequencies in the board-band pulse render a cross-correlation traveltime measurement sensitive only to the wave speed in an hallow banana-shaped region combined the banana-doughnut kernel with the formalism for the adaptive parameterization based on resolution criterion for a long-period body wave data set.

Both absolute and differential times are computed using cross0correlation of each observed arrival with a synthetic pulse constructed by convolving the impulse and an attenuation operator for the preliminary reference earth model (PREM).

We shall present some first results illustrating the effects of using banana-doughnut Fréchet kernels instead of ray theory on the construction of optimized Delaunay meshs.