CRUSTAL SEISMIC IMAGING FROM OCEAN BOTTOM SEISMOMETER DATA BY FULL WAVEFORM TOMOGRAPHY

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Introduction

In a marine environment, the deep crust is classically investigated by wide-aperture seismic experiments using networks of ocean bottom seismometers (OBS) spanning over 100-200 km in order to record upper mantle refracted waves. Resulting data are exploited through travel time inversion methods. Whether first arrivals are used alone or with later reflections - the latter approach demanding a phase identification that can prove arduous and misleading in a complex medium - these techniques essentially return information on the large-scale velocity distribution. Alternatively, using the full wavefield does not require phase identification and allows significant improvement in wavenumber resolution. Hence, waveform inversion based on an accurate resolution of the full wave equation should allow a breakthrough in our knowledge and understanding of deep crustal processes (Pratt et al., 1996). Three main reasons have prevented this approach from being used in deep imaging thus far: (i) it requires a densely covered acquisition over large ranges of source-receiver distances; (ii) the computational cost of full waveform modeling in large laterally-variant areas is a major obstacle; (iii) full waveform inversion is very sensitive to noise, instrument response, inaccuracies in the starting velocity model and the source estimation. Today, the acquisition of densely sampled wide-aperture seismic data sets is developing. The number of available OBSs and modern computational resources make it now possible to address the challenge of crustal-scale seismic waveform modelling.

We present here the first 2-D full waveform inversion of dense real OBS data to deeply image a subduction system, south of Central Japan. Our approach was previously tuned on a smaller-scale experiment (Ravaut et al., 2004) and adapted to the crustal imaging problem of concern here.

Methodology

Finite-difference (FD) waveform modeling and inversion are both entirely implemented in the frequency domain (Pratt et al., 1998). The acoustic wave equation is solved for the pressure field. Hence, only compressional waves are considered and only the P-wave velocity is involved in the inversion. Solving the frequency-domain visco-acoustic full wave equation by FD reduces to solving a large sparse linear system whose so-called impedance matrix depends on signal frequency and model parameters and whose right hand side vector represents the seismic source. A parallel direct factorization method is used to solve the system because of the great efficiency offered for multisource seismic modeling. A preliminary re-ordering of the matrix strongly limits its filling during factorization, yielding considerable numerical gains (Amestoy et al., 2001). Matrices of right hand side vectors are also used to speed up the solving phase.

Regarding the inverse problem, frequency domain provides a natural framework to exploit redundant wavenumber coverage, thanks to wide-aperture illumination. This yields further numerical savings by allowing to invert only a few selected frequencies with no loss of information. Com-
ponents of increasing frequency are sequentially inverted with a linearized approach. A weighted L2-norm cost function quantifying the misfit between observed and computed data is minimized by an iterative linearized gradient method. The weighting of the cost function is an amplitude linear gain with offset to balance the contribution of each class of offset. The gradient is properly scaled with the diagonal elements of the approximate hessian matrix. The OBS sensors are 3 geophones which record vertical and horizontal displacement velocities. Only the vertical component was inverted. The acoustic waveform modelling code returns synthetic pressure wavefield. We match the synthetic pressure wavefield with the observed displacement velocities by using the reciprocity of Green functions. We considered shots at OBS locations and replace explosive sources by vertical forces, and, we considered receivers at shot locations and replace vertical geophones by hydrophones. In such a way the observed vertical geophone data were processed as pressure wavefield and the amplitude versus offset information was preserved during the data preprocessing. Increasing frequency components are sequentially inverted, the model obtained for each frequency being used to start the inversion of the next one. This defines a multiscale approach that helps to verify the linearization condition (travel times must be explained within a range of half a period).

**Application to a subduction zone**

The data were acquired in the frame of the Franco-Japanese SFJ-OBS survey in order to image structures in the easternmost segment of the Nankai trough, offshore Tokai district. Our data acquisition consisted in the deployment of a dense array of 100 OBSs along a 2D 100 km-long profile perpendicular to the trench axis, thus providing one of the first ocean bottom multifold wide-angle marine seismic data sets. Ninety one of these OBSs provided exploitable data that are considered in this study (Dessa et al., 2004a; Dessa et al., 2004b). The acquisition includes 1050 shot positions and 91 receiver positions. An example of common OBS gather is shown in Fig. 2a. Preprocessing of data and source estimation is described in Ravaut et al., 2004. The initial model for the first frequency was derived by first arrival tomography (Dessa et al., 2004a). Thirteen frequencies were inverted between 3 and 15 Hz, producing quantitative images of increasing resolution (Fig. 2). For each frequency, 10 iterations were performed on a Linux PC cluster. Inversion of the 13 frequency components require 10 days of computation. The model size is 105x25 km (4201x1001 FD grid with a 25 m gridstep). 18 Gb of RAM are required. The difference between the traveltime tomography and two waveform tomography models (3 Hz and 15 Hz) are shown in Fig. 3. These perturbations models illustrate the specific and increasingly sharper contribution of waveform inversion and allow an analysis of tectonic discontinuities. This structural information is complemented by the absolute P-wave velocities available on the velocity models of Fig. 2 which give an insight on acoustic properties of structures and thus on their lithological nature.

The main features which can be observed in Fig. 3 are major thrusts in the backstop and at the plate contact (at distances between 30 km and 50 km and depths between 5 km and 15 km) associated with low velocity anomalies which provide an evidence for the presence of lower rigidity materials. The most likely hypothesis for that is the existence of fluid circulation along fault-induced paths and the presence of gouge in damaged fault zones at depth. Synthetic seismograms computed on the traveltime tomography and the final full waveform tomography models are shown in Figures 1b and 1c respectively. These synthetics can be compared with the observed ones of Fig. 1a.

**Conclusion**

This study shows the interest and feasibility of applying full waveform inversion to densely-sampled OBS networks in order to perform a sharp and quantitative imaging of the whole crust in a 2D geological setting. Such new approach should provide an improved knowledge of deep crustal processes.

**Acknowledgments** We would like to thank S. Kodaira and JAMSTEC (Institute for Frontier Research on Earth Evolution, Japan Marine Science and Technology Center) for providing the OBS data.
Figure 1: a) Observed common OBS gather. The OBS is located at x=47 km. b) FD synthetic seismograms computed in the travelt ime tomography model. c) FD synthetic seismograms computed in the final full-waveform tomography model.

References


Figure 2: a) Velocity model from first-arrival traveltime tomography. (b-c) Velocity models after inversion of the frequency components 3 Hz and 15 Hz respectively.

Figure 3: a) Difference between the velocity models of Figs. 2a and 2b. b) Difference between the velocity models of Figs. 2a and 2c. Amplitudes were clipped to improve the signal to noise ratio.