Introduction

Multichannel seismic reflection (MCS) surveys with limited offset coverage suffer some limitations in some complex environments (i.e., deep offshore, deep crustal exploration, sub-basalt imaging). The most fundamental one concerns velocity estimation at depths greater than the length of the receiver array due to the well-known velocity-depth ambiguity at near vertical incidences. Second, for crustal imaging, the amplitudes of the deep reflections are too small at short incidences and conventional sources are not enough powerful to guarantee their recordings with a sufficient signal-to-noise ratio. Third, the energy is poorly transmitted below interfaces with strong impedance contrast making subbasalt imaging from MCS data to be a difficult issue.

Wide-angle surveys carried out with low frequency sources provide a promising alternative to MCS ones to overcome these problems. Wide-angle surveys are designed so as to have sufficiently large source-receiver offsets to record turning waves whose refraction depth cover the zone of interest. The refracted and super-critical reflected wavefields provide reliable constraints on the large-scale velocity distribution. Moreover, the large offsets allow to record deep reflections at critical and supercritical incidences where they reach their maximum amplitude improving the penetration power of the seismic imaging.

Wide-angle surveys are most of the time carried out with an array of land and marine stations for onshore and deep offshore surveys respectively. The resulting dataset is conventionally processed by first-arrival traveltime inversion (FA TI) which returns a large-scale velocity model. If the wide-angle survey is multifold thanks to densely sampled sources and receivers, this large-scale velocity model can be used as a reference model to apply waveform processing such as prestack depth migration or full-waveform inversion (FWI) (Pratt et al., 1996). By FWI is meant any inversion technique able to process the full wavefield recorded over a broad range of incidence angles (i.e., transmitted and reflected wavefields). Considering the whole wavefield is expected to provide a significant resolution improvement in the velocity models. The resolution of the velocity models is controlled both by frequency and aperture. High wavenumbers are continuously incorporated in the velocity models as FWI progresses from the low to the high frequencies and from the large to the small apertures.

We present an application of 2D acoustic FWI applied to 2-D wide-angle data recorded by 100 Ocean Bottom Seismometers (OBS). Aim of the experiment was to image the eastern-Nankai subduction zone, offshore Japan, where a large earthquake is expected in the coming years.

Full-waveform inversion method

Our FWI algorithm is entirely implemented in the frequency domain (Pratt et al., 1998). Acoustic wave propagation modelling is performed by a finite-difference (FD) method in the frequency-space domain (Hustedt et al., 2004). Solving the frequency-domain full wave equation by FD reduces to solving a large sparse linear system whose so-called impedance matrix depends on frequency and
model parameters and whose right hand side vector represents the seismic source. A parallel direct factorization method (Amestoy et al., 2001) is used to solve the system because of the great efficiency offered for multisource seismic modeling compared to iterative approaches.

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. Components of increasing frequency are sequentially inverted with a weighted least-square method, the model obtained for each frequency being used to start the inversion of the next one. This defines a multiscale approach that helps to fulfill the linearization condition (travel times must be fitted within a range of half a period). 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 scaled with the diagonal elements of the approximate hessian matrix and smoothed with an adaptive 2D Gaussian filter. The OBS sensors are three geophones (one vertical and two horizontal ones). Only the vertical component was inverted and only the P-wave velocity is involved in the inversion. 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 can be processed as pressure wavefield.

**Application to real OBS data**

The data were acquired by the JAMSTEC Institute (Japan) in the frame of the Franco-Japanese SFJ-OBS survey in order to image 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 (Dessa et al., 2004a; Dessa et al., 2004b). One coincident shot profile was acquired with a 100-m shot spacing. An example of common OBS gather is shown in Fig. 1a. The initial model for the first frequency was derived by FATI (Fig. 2a and Dessa et al., 2004a). Thirteen frequencies were inverted between 3 and 15 Hz, producing velocity models of increasing resolution. The final velocity model is shown in Fig. 2b. For each frequency, 20 iterations were performed on a Linux PC cluster. For structural interpretation (Fig. 2e), we used perturbation models (i.e., the difference between FATI and FWI models) (Figures 2c and 2d) and the P-wave velocity gradient (Fig. 2f). Both displays highlight the middle and the short wavelengths of the velocity models and, hence, allow to delineate the tectonic discontinuities. This structural information is complemented by the absolute P-wave velocities available on the velocity models of Fig. 2b which give an insight on acoustic properties of structures and thus on their lithological nature.

The spatial resolution of the FATI model was estimated by checkerboard tests to be 5 km down to 10 km whereas only 10-km structures were reconstructed between 10 and 15 km depth (Dessa et al., 2004a). The resolution of FWI was estimated to be of the order of 500 meters leading to a resolution improvement by an order of magnitude. One drawback of FWI methods is that the significance of the imaged structures is difficult to assess because a formal uncertainty analysis based on Monte-Carlo sampling methods is out of reach from a computational viewpoint and because the fit between observed and FD synthetic seismograms are difficult to assess due to the complexity of the full wavefield. To appraise the FWI velocity models, we have complemented the analysis of the full waveform fit with a traveltime modelling whose results are easier to interpret. Refraction and reflection ray tracings for a series of interpreted reflectors were computed in the final FWI model and the resulting traveltimes were superimposed on the OBS gathers to test whether they fit some observed reflections (Fig. 1a). We observed a good agreement of refraction traveltimes suggesting that the kinematic accuracy of the FWI models was not degraded by cycle skipping artefacts. We also match traveltimes of several observed wide-angle reflections such as the reflections from the Moho (M), the plate boundary (PB), a décollement level (D), a thrust (T1) in the backstop and an intracrustal reflector (IR”), hence, validating our interpretation of these reflectors (Fig. 1b).
Conclusion
This study shows the feasibility of 2D FWI for crustal imaging. We have illustrated the resolution improvement provided by FWI methods with respect to FATI ones. Future works will deal with the extension of the 2D acoustic inversion to multi-parameter inversions involving elasticity, anisotropy and attenuation effects.

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. We thank P. Amestoy (ENSEEIHT) and JY L’Excellent (ENS Lyon) for providing us the parallel MUMPS solver (http://www.enseeiht.fr/apo/MUMPS/).

References


Figure 1: a) OBS gather. The OBS is located at a horizontal distance of 47 km in Fig. 2. The main arrivals are labeled. b) Same than a. with superimposed first-arrival (dash) and reflection (solid) travel-times computed in the final FWI velocity model (Fig. 2b) and for several reflectors interpreted in Fig. 2e. Corresponding ray paths are shown in Figs. 2(g-h).
Figure 2: a) FATI velocity model. (b) Final FWI velocity model (15 Hz). The inset shows velocity graphs extracted from the FATI (black) and 15 Hz FWI (gray) models at 50 km of distance to assess the respective resolution of the two models. (c-d) 3 and 15 Hz perturbation models plotted with a strongly-clipped gray scale. Negative velocity perturbations are in black. e) 15 Hz perturbation model with superimposed structural interpretation. The gray and yellow areas delineate the subducting oceanic crust and the backstop respectively. The dark gray area delineates the subducting Paleo-Zenisu ridge. f) Gradient of the 15 Hz velocity model. The gradient is computed in the direction of its maximum value. This image mimics a prestack depth migrated section. The Tokai thrust is clearly visible. (h-g) Refraction (h) and wide-angle reflection (g) ray tracing in the 15 Hz velocity model for OBS 46 (x=47 km). Reflection ray paths were computed for the décollement (D), the thrust (T1), the plate boundary (PB), the Moho (M) and an intracrustal reflector marking the base of the Paleo-Zenisu body (IR") (Fig. 2e). The corresponding traveltime curves are shown in Fig. 1b. (i) Illustration of the waveform fit for OBS 48 (x=49 km) and frequency 5 Hz. The real part of the observed (black) and computed (gray) wavefields are superimposed at iterations 1 (top) and 20 (bottom) of the 5 Hz inversion. A cost function reduction of 55 % was obtained for this OBS and this frequency.