Refraction Full-waveform Inversion in a Shallow Water Environment

Z. Zou* (PGS), J. Ramos-Martínez (PGS), S. Kelly (PGS), G. Ronholt (PGS), L.T. Langlo (PGS), A. Valenciano Mavilio (PGS), N. Chemingui (PGS) & J.E. Lie (Lundin Norway)

SUMMARY

Successful application of shallow water full-waveform inversion (FWI) requires a good starting model, the right data, and an optimal algorithm. Our implementation is based on a pseudo-analytic (PA) method that solves the two-way acoustic wave equation in VTI media. The non-linear inversion uses a regularization operator that combines smoothing and wavenumber filtering in order to minimize the shallow water acquisition footprint. We show, using a 3D dual sensors streamer survey from the North Sea, that the inversion of refracted and diving waves yields a high-resolution velocity model for the shallow sediments. The small-scale velocity variations obtained by FWI in this area correlate very well with the geological features in the migrated images. The FWI model yields better migrated images than the starting model from reflection tomography. Examining both the flatness of common-image gathers and the match between modelled and recorded data corroborates the accuracy of the FWI velocity model.

Introduction

The goal of full-waveform inversion (FWI) is to derive high-resolution Earth models by minimizing the misfit between the recorded and model data, in order to achieve high-resolution imaging and to provide insights into reservoir characterization (e.g., Barkved, 2010). This is a highly nonlinear, iterative process whose success depends on the seamless addition of wavelength features that are missing from the starting velocity model. The appropriate method for the introduction of these missing wavelengths depends on the characteristics of the geological setting and the seismic wave types that were acquired. Recordings of refracted waves are necessary for resolving shallow structures in shallow water settings. In order to resolve features that lie below the deepest turning point of the recorded refractions and diving waves, we must depend upon the low frequency content of pre-critical reflections (Ramos-Martinez et al., 2013).

In this abstract, we describe the implementation aspects for a successful application of FWI of refractions and diving waves in shallow water. Our algorithm uses the pseudo-analytic (PA) method for the wavefield modelling in VTI acoustic media. A regularization operator that combines smoothing and wavenumber filtering is applied during the inversion to minimize the acquisition footprint. The data used here were acquired in an area with a water depth of approximately 90-120m. In this case reflection tomography cannot be reliably used to estimate the velocities of the shallow sediments due to the limited range of available rays. FWI overcomes this problem by making use of refractions and diving waves, and can potentially resolve small-scale velocity variations to achieve high-resolution imaging. We use both the flatness of migrated gathers, and the match between modelled and recorded data to verify the accuracy of the FWI velocity model.

Method

Our inversion algorithm is performed in the time domain and uses a normalized form of the Born scattering kernel to compute the gradient (Tarantola, 1984). The source and residual wavefields are computed by solving the two-way wave equation in anisotropic media using the PA method. One of the advantages of this method over the finite-difference (FD) method is that it requires only two grid points per wavelength in order to accurately represent the spatial derivatives. However, finite-difference approximation of the second-order derivative with respect to time is subject to grid dispersion. Etgen and Brandsberg-Dahl (2009) proposed a PA method to address this shortcoming by modifying the Fourier Transform of the Laplacian so that it exactly compensates for the error associated with grid dispersion from second-order differencing of the time derivative. Our tests also show that time stepping by the PA method is more stable at higher Courant numbers than time stepping in the space-time method discussed above. The accuracy and efficiency of the PA method were demonstrated in the applications of RTM and synthetic FWI studies (Crawley 2010; Ramos-Martinez, 2011).

The starting velocity and anisotropy models for FWI were obtained through ray-based reflection tomography. FWI updates the velocity only while the remaining anisotropy parameters were held constant. When no regularization is applied during the inversion, the shallow sections of the resulting velocity models show the imprint of the acquisition geometry (Fig. 1a). These artefacts can make the interpretation of shallow geological features difficult. In order to attenuate them we apply a regularization operator that combines smoothing and wavenumber filtering during the inversion. The regularization eliminates a large part of the acquisition footprint while leaving clearly identifiable small-scale channel features untouched (Fig. 1b). The regularization is also useful in reducing the effect of shot decimation in the input data, and thus allows for smaller number of shots for inversion to reduce the computation cost.

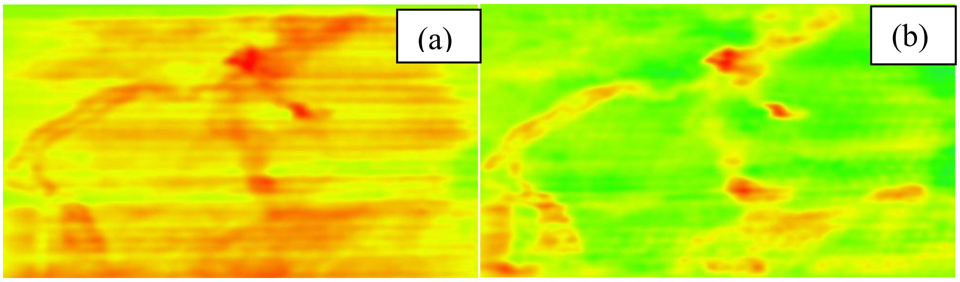

Figure 1: *Differences between the starting and inverted velocity at depth=240m without (a) and with (b) regularization. The number of shots used in (b) is half of that in (a).*

Data and Results

The data were acquired using dual-sensor streamers in the North Sea. The cable length is 5.1 km, and spacing is 100m, with a total of 6 cables. The shot depth is 6m and the cables are at a depth of 15m, which helps to better record low-frequency energy compared to a shallower tow depth. Due to the shallow water depth in this area, we applied minimal pre-processing before FWI. Key steps included the attenuation of swell and tug/tow noise, muting a bright reflection that that interfered with the first breaks, and low-pass filtering. However, we left both multiples and ghosts intact. Our forward modelling starts with a ghost-free wavelet and includes a free-surface condition at the sea surface with source and receiver positions accurately represented.

In order to minimize the likelihood of cycle skipping during inversion, we began with the lowest possible range of frequencies that exhibited coherent signal. This was accomplished by applying a Butterworth filter with corner frequencies of 3 and 6 Hz. We then carefully chose a mute directly above the first breaks for all shots. For the first stage of the inversion, we applied a sharp time taper that began at the first break mute pattern. After reaching a convergence, we then used a more gentle time taper in order to allow more data to drive the inversion. Finally, we increased the frequency content of the input data in order to achieve a higher-resolution update of the velocity model. The maximum frequency band we used had corner frequencies of 3 and 10 Hz.

Figure 2(a) compares recorded and modelled data using the starting velocity model. In general, the figure shows a good match for the transmitted arrivals, with an error of less than a half period of the dominant frequency. FWI successfully corrected this small kinematic mismatch, as well as larger errors for later arrivals highlighted in Figure 2b. The inversion also improved the resolution of the velocity model. Figures 3(a) and (b) show depth slices of the velocity model, before and after FWI, at a depth of 240m. Compared to the smooth starting model in Figure 3(a), Figure 3(b) clearly shows some small-scale geological features that emerge from the inversion.

In order to validate the velocity model obtained from FWI, we performed a Kirchhoff pre-stack depth migration (PSDM) using the starting and FWI velocity models. Figure 3(c) shows that small-scale features in the inverted model correlate well with features in the migrated stack. Figures 4(a) and (b) show that between depths of 200 and 600m, the migrated image for the model derived by FWI also exhibit much higher resolution, improved signal-to-noise ratio and more continuous events, than those observed in the image obtained by the starting model. Finally, the model obtained by FWI yielded much flatter common-image gathers at depths 200-600m (Figure 5).

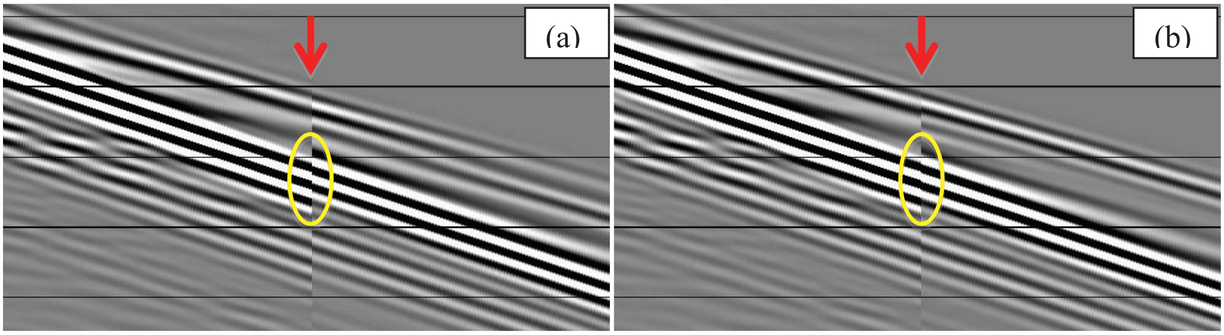

Figure 2: Comparison between recorded data and modeled data before (a) and after FWI (b). In both panels, the recorded data are to the left of the red arrow, and the modelled data are to the right of the red arrow.

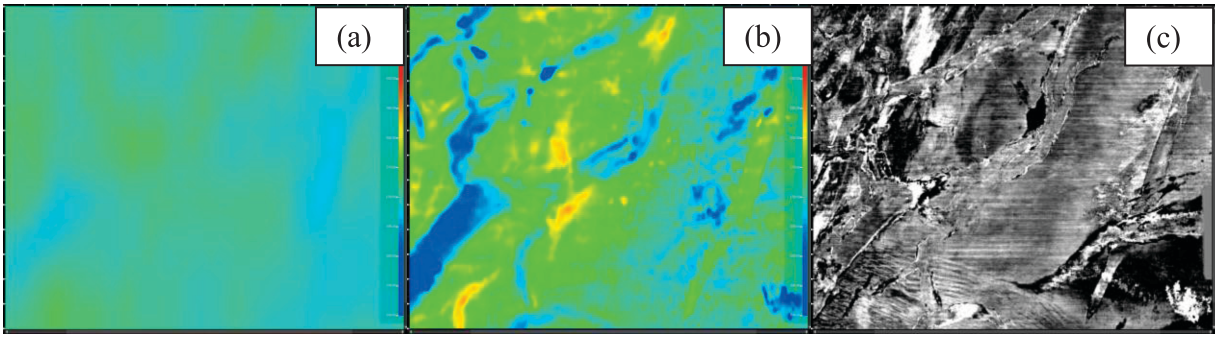

Figure 3: Velocity model at depth=240m before FWI (a) and after FWI (b). The velocity scale for panels (a) and (b) is 1550-2000 m/s. (c) PSDM image. The horizontal and vertical dimensions for all three panels are 26km and 16km, respectively.

Conclusions

We applied a gradient-based FWI algorithm that utilized PA propagation of the wavefields, in order to resolve small-scale features in shallow sediments of the North Sea. Our inversion included regularization of the gradient for each iteration through smoothing and wavenumber filtering. This yielded a velocity model with much higher resolution in the shallow sediments compared with the starting model obtained from reflection tomography. The small-scale features in the FWI velocity model correlate very well with the channels shown in the migrated seismic image. In general, the migrated images obtained using the velocity derived by FWI exhibit improved resolution and signal-to-noise ratio, and more continuous horizons. We have also demonstrated that the inverted velocity model improves the flatness of the common image offset gathers and the match between the modelled and recorded data.

Acknowledgements

The authors would like to thank Lundin Norway for permission to show these data and PGS management for the opportunity to publish this work. We also thank Boris Tsimelzon, Sverre Brandsberg-Dahl, and Sean Crawley for discussions and suggestions.

References

Barkved, O., Albertin U., Heavey P., Kommedal J.H., van Gestel J.P., Synnove R., Pettersen H. and Kent C. [2010] Business Impact of Full Waveform Inversion at Valhall. *80th Annual International Meeting*, SEG, Expanded abstracts, 925-929.

Crawley, S., Brandsberg-Dahl, S., McMclean, J., Chemingui, N. [2010] TTI reverse-time migration using the pseudo-analytic method. *The Leading Edge*, 29, 1378-1384

Etgen, J., Brandsberg-Dahl, S. [2009] The pseudo-analytical method: Application of pseudo-Laplacians to acoustic and acoustic anisotropic wave propagation: *79th Annual International Meeting*, SEG, Expanded Abstracts, 2552-2555.

Ramos-Martinez, J., Crawley, S., Kelly, S., Tsimelzon, B. [2011] Full-waveform inversion by pseudo-analytic extrapolation. *81st Annual International Meeting*, SEG, Expanded abstracts, 2684-2688.

Ramos-Martinez, J, Zou K, Kelly S., Tsimelzon, B. [2013] Reflection FWI from fully deghosted towed-streamer data: A field data example. *83rd Annual International Meeting*, SEG, Expanded Abstracts 2013: 887-891.

Tarantola, A. [1984] Inversion of seismic reflection data in the acoustic approximation. *Geophysics*, 49, 1259-1266

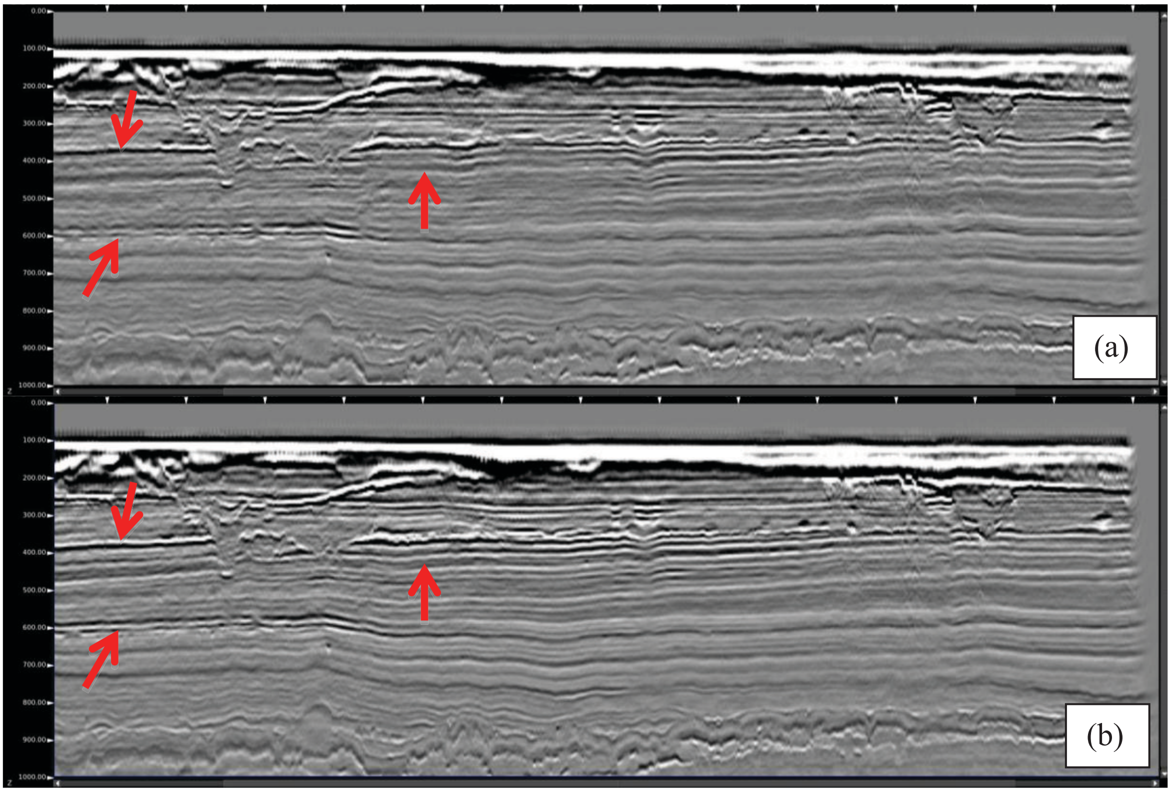

Figure 4: *PSDM images using velocity models before (a) and after (b) FWI. Each figure spans 26 km horizontally and 1km vertically.*

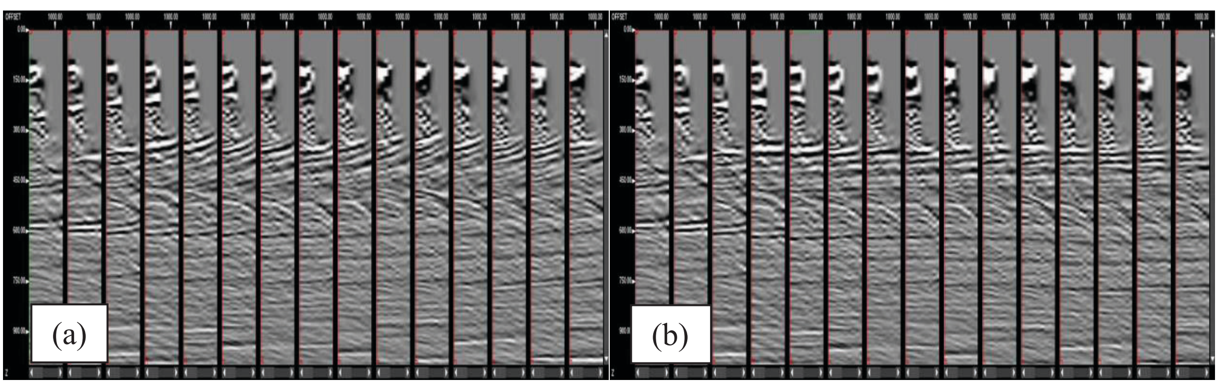

Figure 5: *Common-image offset gathers with velocity models before (a) and after (b) FWI. The gathers at 200-600m are much flatter after FWI.*