Full Waveform Inversion: a North Sea OBC case study

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Summary

Full Waveform Inversion (FWI) aims to obtain superior velocity models by minimizing the difference between observed and modelled seismic waveforms. We apply FWI to a North Sea OBC field data set with wide azimuths and more than 10 km long offsets. We discuss the methodology used and the associated practical issues. Our FWI result has revealed detailed velocity features associated with thin, gas-charged layers and faulting in the shallow sections of the model. We demonstrate that this velocity update has improved the imaging of the deeper structures.

Introduction

FWI is currently a topic of great interest in the oil and gas industry. The promise is to produce high-quality, high-resolution velocity models, not only to benefit the imaging of complex geological structures, but also to provide an interpretable product in itself. Spurred on by advances in computing power, there has been renewed work in this area in the past few years. This has resulted in a number of publications demonstrating spectacular applications of FWI to various synthetic datasets (see Virieux and Operto, 2009 and references therein). Real data examples have proved more challenging, although noticeably impressive success stories exist, for example, Sirgue et al. (2009).

In this paper we show an application of FWI to a wide azimuth, marine OBC dataset from the North Sea and share the practical experience gained with this technique.

Real Data OBC Example

We apply this process to the Tommeliten Alpha area in the Norwegian North Sea (Block 1/9), see Figure 1. Tommeliten Alpha is a gas condensate discovery located 25km South-West of the Ekofisk field. The reservoir consists of two fractured chalk formations (Ekofisk and Tor) situated at approximately 3000 m depth. A large part of the reservoir is located in a seismic obscured area (SOA) caused by gas in thin silt and sandstone layers of the middle Pliocene (920 m).

In 2005, a high-density, full azimuth, OBC survey was acquired in an attempt to improve imaging in the SOA. This objective was partly achieved, mainly thanks to pre-stack depth migration of PS data. The present objective of using FWI is to improve the velocity characterization of the shallow, thin, gas-charged layers and the imaging of the SOA using PP data only.

The OBC acquisition contains 3 side by side receiver swaths with 8 parallel cables in each. The nominal receiver cable separation is 300m, with receivers spaced every 25m along the cables. The shooting patch for each swath gives offsets of more than 10 km. Figure 2 shows an example of one of these acquisition patches. Combining all 3 swaths makes almost 6000 receivers and over 100,000 shots available. We use a decimated version of this dataset for the FWI, making sure we preserve the long offset data.

Methodology

We use the FWI implementation described in Warner et al. (2010). This is a 3D, acoustic, finite difference, time domain method that updates the P-wave velocity using a linearised least squares inversion process. A new feature in this algorithm is that it now honours VTI anisotropy.

Our FWI is driven by the inversion of transmitted energy (e.g. diving- and head waves). Therefore, the pre-processing of the real data is geared towards preserving and enhancing this energy on the field records (M. Warner, 2011, Full-wavefield tomography/full-waveform inversion: a game changing technology, Education Days (London), EAGE, Short Course). At present, all other energies are seen as “noise” and subsequently attenuated. It is worth commenting on this transmitted energy FWI strategy: in the future, as our technology develops further, using additional elements of the wave-field should be advantageous, aiding the inversion process and improving the final result.

Our data pre-processing steps complement this strategy and consist of: de-bubbling, low-pass filter and inner/outer muting. This leaves a real dataset that still contains ghosts and multiples. For the modelling we start from the shot de-ghosted gun signature wavelet and propagate in a model with a free surface. The aim of this workflow is to give comparable real and modelled datasets for the FWI. These choices are discussed in the next section.

Practicalities

FWI involves a wiggle for wiggle comparison between the real seismic data and the modelled field records. In order for this differencing to work effectively we need a consistency between the real and modelled data. Hence, we try to include as much real physical phenomena as is practical in the modelling. At present we concentrate on inverting the pressure wave-field only. As is often the case, the devil is in the detail, and it was the complete workflow that produced a significant result.

- In the time domain the source wavelet is a critical aspect of FWI. We could estimate this from the field data itself by picking and processing the first breaks, but this is a non-trivial and time consuming task. We have found that a simpler, and perhaps safer, route is to use the gun signature. Of course, this is a valid approach only if the gun signature is a good representation of the real data wavelet at the frequencies of interest.
- Ghosts and other multiples are a complicating factor in the raw P-wave data that we use in the inversion. Rather than try to address these effects in the real data, we include them in our modelling through the use of a free surface.
- Because our FWI is driven by transmitted energy, we can only expect a sensible update to the velocity model in areas where this energy has penetrated. The critical factor is the size of the longest offsets in the real data. The larger the offset, the deeper the penetration of the transmitted energy. Offsets exceeding 10 km were acquired in the real data example shown here. Based on the combination of a simple modelling exercise and careful examination of the FWI results we find that sensible updates can be obtained down to ~2 km depth.
- Strong Vertical Transverse Isotropy (VTI) is known in the Tommeliten area, as high as 20% in some layers. This causes a significant change in travel-times of the modelled events. Consequently, a key factor in producing reliable results was having an FWI algorithm that honours this behaviour.
- Even though we use a time domain algorithm we are not immune to the local vs. global minima convergence problem and so we only invert the low frequencies in the seismic data. In our real data example we perform the inversion with frequencies up to 4.25Hz. New acquisition and processing techniques that aim to extend the seismic bandwidth (Soubaras 2010), especially at the low frequencies, will prove valuable in this regard.
- The starting (VTI) velocity model needs to be close enough to reality such that the modelled field records are not cycle skipped with respect to the real data. In the current paper this starting model comes from a traditional PSDM velocity model building and covers a ~220 km^2 area to a depth of 4.6 km.

Results

Putting all of these practical choices to the test involves a comparison between the real and modelled field records. We use the near offsets to QC our choice of wavelet and use of a free surface in the modelling. The mid and far offset traces allow us to check that: (i) our starting modelled events are not cycle-skipped compared to the real data, and (ii) our modelling improves after the FWI process.

We iterate the FWI process until convergence is observed in the cost function, dropping to 60% of its initial value. From a positive stance, this reduction is a significant improvement in the agreement between the modelled and real data. However, the size of this residual still offers scope for future improvement.

Figure 3 shows depth slices through the top part of the SOA (at 1200m depth) for: (a) the starting, and (b) FWI velocity models, as well as: (c) a reference seismic image migrated with the starting model. From this comparison, it is seen that the detailed features added by the FWI process are clearly correlated with the thin, gas-charged layers and faulting observed in the seismic data. This gives some confidence in the FWI updates.

Figure 4 shows a comparison between Kirchhoff migrated Common Image Gathers (CIG's) generated from: (a) the starting, and (b) FWI velocity models. These migrations use the same input P-Z sum data and VTI anisotropy model. The gathers are from a line that runs through the SOA. It is clear that the gathers from the FWI velocity model are flatter, giving added confidence in this model.

Figure 5 shows a comparison between final seismic images generated by a VTI Reverse Time Migration (RTM) for: (a) & (c) the starting, and (b) & (d) the FWI velocity models. Again, we use the same input PZ-sum data and VTI anisotropy model for both migrations. It is clear that the FWI process has improved the imaging in a number of ways. In the deeper structures (~4 km depth) the events are considerably stronger and more geologically plausible. Although not shown due to reasons of space, we also see subtle improvements in the character and resolution of events in the nearer-surface area around the SOA (1→2 km depth). Overall, use of the FWI velocity model gives a significant uplift in the final image quality.

Improving the quantitative content of our QC's between the real and modelled field records, as well as determining the accurate zone of valid FWI updates from a given acquisition, are subjects of future research work.

Conclusions

We have discussed the methodology and practical issues associated with applying Full Waveform Inversion to a North Sea OBC data set containing wide azimuths and long offsets. Our updated velocity model has revealed detailed velocity features associated with thin, gas-charged layers and faults. By applying Reverse Time Migration and Kirchhoff Migration we have demonstrated that this nearer-surface velocity update has improved the imaging of the deeper structures.

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Figure 1: *Map of Norwegian North Sea around the Tommeliten area.*

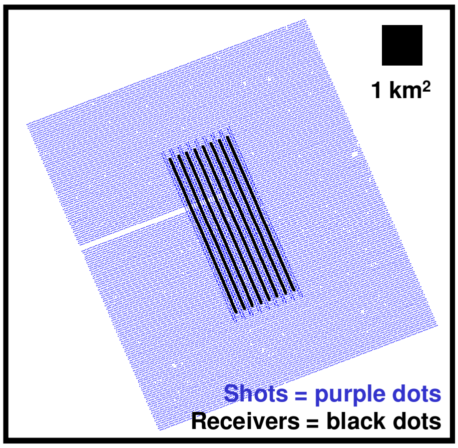

Figure 2: *Example of an acquisition patch including the shots (purple) and the associated receiver swath (black).*

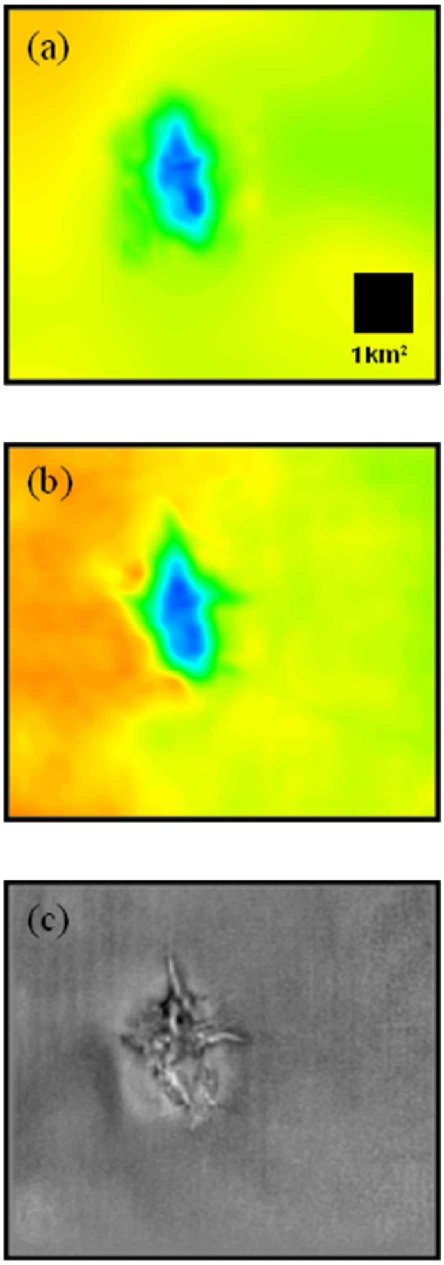

Figure 3: *Depth slice through top part of the seismic obscured area (at 1.2 km) for:* ***(a)*** *the starting velocity model,* ***(b)*** *the FWI velocity model, and, for reference,* ***(c)*** *seismic image migrated with the starting model.*

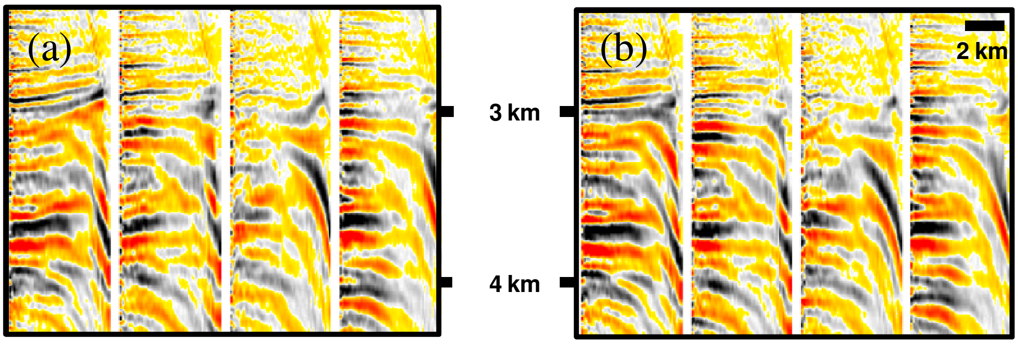

***Figure 4:** Comparison of VTI Kirchhoff migrated Common Image Gathers generated from: **(a)** the starting velocity model, and **(b)** the FWI velocity model. The gathers from the FWI velocity model are generally flatter.*

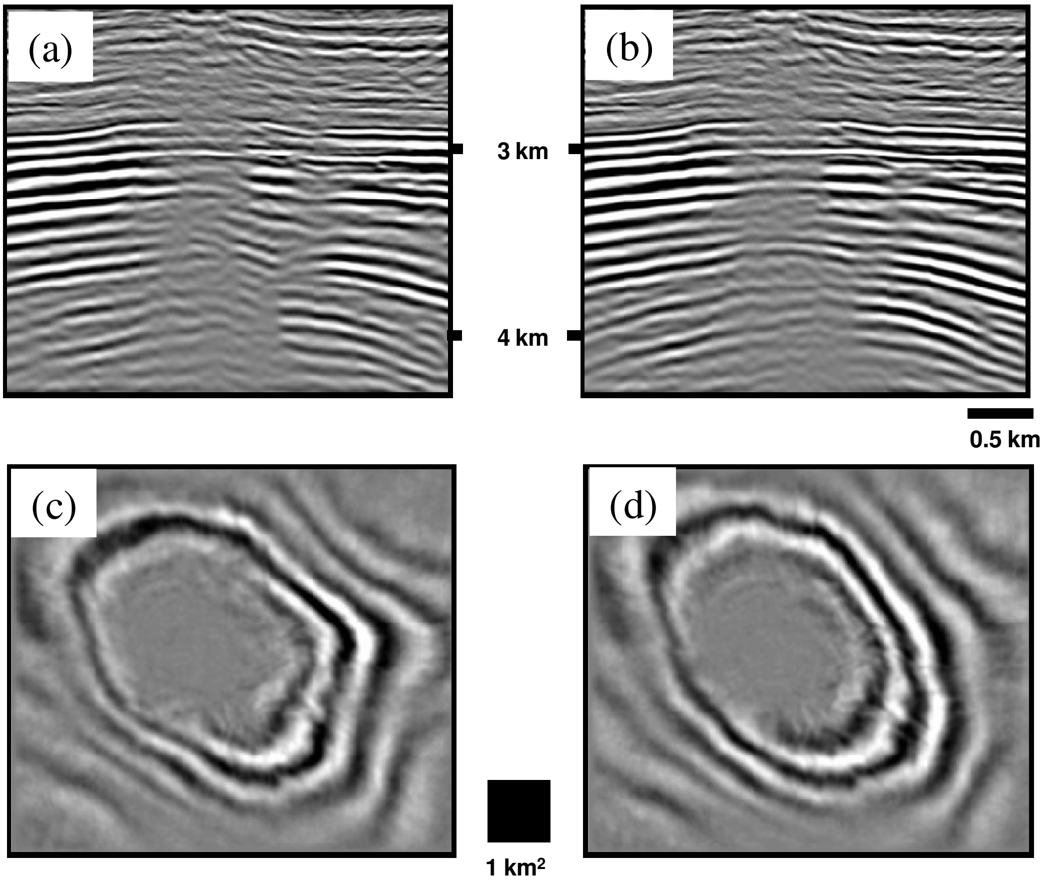

***Figure 5:** Comparison of VTI RTM images obtained from: **(a)** & **(c)** the starting velocity model, and **(b)** & **(d)** the FWI velocity model. We show both a crossline section, **(a)** & **(b)**, and a depth slice at 3.7 km, **(c)** & **(d)**. We see a significant uplift in the image generated from the FWI velocity model.*

EDITED REFERENCES

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