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Where can Full Waveform Inversion Have the Biggest Impact in the Exploration and Production Cycle?

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SUMMARY

Full Waveform Inversion (FWI) has recently emerged as one of the most exciting new techniques in the seismic industry thanks to its potential to deliver very detailed velocity models.
Most of the examples shown in literature are based on FWI applications for imaging purposes and where the starting velocity models for the inversion are derived by several iterations of traveltime tomography. While this is indeed valid we question whether this is the most effective use of FWI.
We present two cases where we see greater values derived from FWI: velocity estimation for imaging (low frequency range) starting from a smooth RMS velocity model, and velocity estimation for direct interpretation (high frequency range).

Introduction

Full Waveform Inversion (FWI) has recently emerged as one of the most exciting new techniques in the seismic industry thanks to its potential to deliver very detailed velocity models. It is also a paradigm shift in the way we process seismic data since it allows us to start the velocity model building phase on raw shots, with little need (if any) for pre-processing steps. For these reasons FWI has spawned a huge interest in both the industry and academic community, which is also reflected by the number of dedicated sessions and workshops which are held each year on this subject.

Most of the examples shown in literature are based on FWI applications where the starting velocity models for the inversion are derived by several iterations of traveltime tomography and are kinematically accurate. The reason for this is that FWI relies on solving a highly non-linear inverse problem using a gradient based technique; therefore it is very sensitive to the presence of local minima (Sirgue, 2012). These occur when the data predicted by the starting model differ in arrival time by more than half a cycle with respect to the real data (Warner and Guasch, 2014).

Comparison between migrations using FWI velocities derived in this way and migrations using the starting tomographic models often yield disappointingly small differences, even though the FWI velocities appear to contain a lot more "geological" detail. Analysis of Common Image Point (CIP) gathers shows traveltime tomography is usually doing a good job at recovering long wavelengths of the velocity model which account for the bulk of the gather flattening required for a good image.

There are particular settings where tomography struggles and where FWI can instead provide an accurate solution. Examples include areas where RMO picking is particularly difficult such as gas clouds (see Ratcliffe et al., 2011, for an excellent example on the Tommeliten field) and zones of strong attenuation and/or very low signal-to-noise ratio. Also the higher resolution provided by FWI can help when velocity anomalies are smaller than the resolvable resolution of tomography, for example in the presence of volcanic intrusions.

Traveltime tomography has also the downside that it is a time consuming process, taking around 6 months for an average size project. And tomography can only begin when pre-processing is complete.

So in the more general cases, where can FWI (in its current version) provide the greatest value for an oil and gas operator? In this paper we show two different examples where we see FWI as a real game changer: 1) FWI in the low frequency (~10Hz) range, used for imaging but starting from a smooth RMS velocity model in order to bypass the traveltime tomography phase, and 2) FWI in the high frequency (~30Hz) range, to be used directly for interpretation, in particular for pore pressure prediction and shallow hazard analysis.

1. FWI in the low frequency range

FWI solutions at around 6-10Hz are generally accurate enough to be used for imaging, when Kirchhoff based methods are used. The real advantage of FWI is then in the fact it can be run with a bare minimum pre-processing applied to the seismic data. So if we could avoid running traveltime tomography to create the input velocity model and make FWI work with an initial velocity model derived by coarse manual picking we could start the velocity model building phase in parallel to the main pre-processing efforts. Then not only we would produce an accurate velocity model, but we would also shorten the turnaround time for the final image by approximately 50%.

Two possible ways to achieve this are either to derive new schemes to precondition FWI (Warner and Guasch, 2014, Bi and Lin, 2014) and/or to acquire seismic data as rich as possible in low frequency content and with the highest S/N ratio at those low frequencies (Plessix et al., 2013). While in the past low frequency acquisitions were mostly limited to Ocean Bottom Cable (OBC) or Nodes, in the last few years the general trend in marine streamer acquisition has moved towards deeper tow depths, sometimes in combination with broadband streamers, resulting in data richer in low frequencies.

In 2013 Woodside and Mitsui E&P Australia acquired several 2D lines in the Exmouth basin with the scope of evaluating the benefits of the low frequencies and long offsets, with the following acquisition parameters: Source depth = 10 m, Receiver depth = 25 m, Streamer length = 10 km.

The Exmouth basin is characterized by a relatively complex geology. A major base Cretaceous unconformity separates two distinct structural domains: a pre-Cretaceous sequence characterized by large tilted fault blocks and a Cretaceous and post-Cretaceous sequence characterized by a complex geomorphology (canyon systems and valleys) and shallow faulting which may present drilling hazards (mud loss zones). Volcanic intrusions, or sills, of variable size are present at different depths in the pre-Cretaceous complex. The water depth is between 1 and 1.6 km.

We followed a quite "classical" workflow for FWI: we started from raw shots with only minor de-noising and muting. What differed here is that as a starting model we used the available manually picked RMS (PSTM) velocities rather than tomographic interval velocities. We converted them into interval velocities which are extremely smooth (Fig. 1a). We started the inversion at 3 Hz and ended at 30 Hz. Each iteration took about 15 minutes on the Woodside research cluster, which allowed for fast turnaround even at these high frequencies.

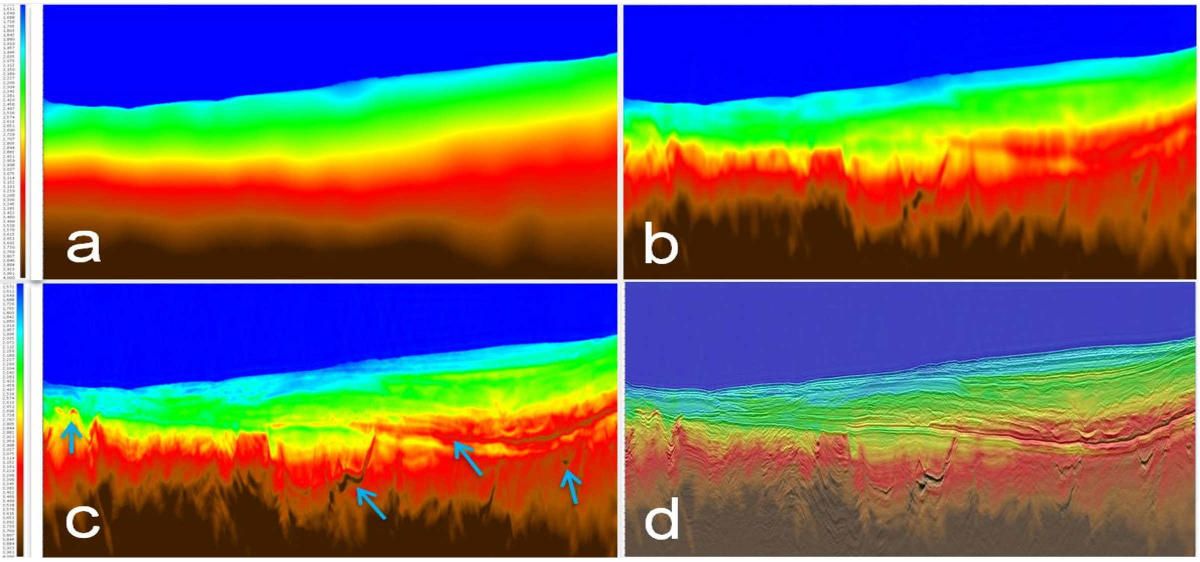

Figure 1 *a) starting velocity model derived from smoothed RMS velocities, b) FWI derived velocity models at 10Hz, and c) 30Hz. d) Velocity model overlaid on the PSDM image.*

The final velocity model is shown in Figure 1c. FWI managed to recover a huge amount of detail and converged effectively despite the smooth starting model. The base Cretaceous unconformity is accurately delineated and shallow channels and deep volcanic sills are defined with accuracy (blue arrows). In Figure 1d the FWI velocity model is overlaid over the Pre Stack Depth Migration (PSDM) stack highlighting the precise matching of the geological features (channels and sills) with the velocity features, which gives us confidence in the accuracy of the FWI solution.

For imaging with Kirchhoff based methods the 30Hz model is too detailed to be correctly handled by the ray tracing and in terms of long wavelength kinematics most of the velocity macro model is recovered already at about 10Hz, Figure 1b. We used this model to run the Kirchhoff PSDM and the results are shown in Figures 2a and 2b. The migrated stack with the FWI velocity is largely improved compared to that derived with the smooth PSTM velocities as expected. In particular the main unconformity, highlighted in the yellow ellipses, is now more continuous. Steep events underneath now terminate correctly against it while they were smeared across in the initial migration. Common Image Gathers (CIG) extracted from this area, Figures 2c and 2d, show greatly improved flatness after FWI. The large moveout curvature of the gathers migrated with the input velocity is strong evidence that the initial PSTM velocity field was far from the correct solution. The differences (not shown here) in the final image quality between migrations using the 30Hz and the 10Hz model are relatively minor compared to the differences shown below.

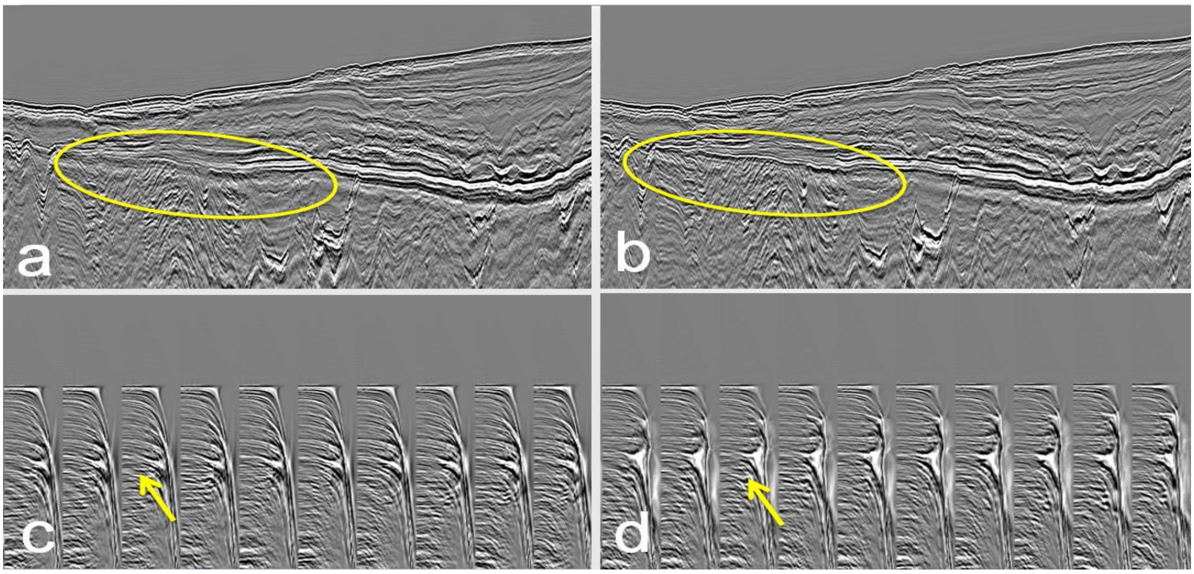

Figure 2 *a) PSDM stacks (Kirchhoff): a) with initial velocity model, and b) with FWI velocity model; PSDM CIGs: c) with initial velocity model, and d) with FWI velocity model.*

2. FWI in the high frequency range

Full Waveform Inversion techniques in the high frequency range (~30Hz) have the potential to influence and enhance industry techniques and scientific disciplines which utilise seismic velocity data. An example of the application of high resolution FWI velocities for the purposes of pore pressure prediction (PPP) and analysis is demonstrated here.

One of the methods for pore pressure prediction uses velocity data (1D, 2D, 3D and/or 4D datasets) to predict the pressure of fluids within the pores of sedimentary sequences for the purposes of hydrocarbon exploration, basin analysis, seal integrity, engineering well integrity design and exploration drilling (Swarbrick and Schneider 1999). The methodology requires accurate, high resolution, interval velocity information in the depth domain (Bowers 1994). FWI offers the opportunity to exploit an enhanced velocity resolution dataset well beyond conventional Pre Stack Time Migration (PSTM) or Pre Stack Depth Migration (PSDM) velocities.

A standard industry pore pressure prediction methodology was applied to the velocities in the 2D FWI line shown in Figure 3a. Pore pressures were predicted from a 1D extraction of the FWI velocities at Well-A (Fig. 3c), and predicted for the full 2D line (Fig. 3b). A comparison between petrophysically-derived predicted pore pressures and FWI-derived predicted pore pressures at Well-A is shown in Figure 3c. The pressures predicted between the two different velocity datasets are broadly comparable, with the petrophysical prediction building near lithostatic parallel pressure trends which are almost matched by the FWI velocities. A discrepancy in the onset and termination of overpressure between ~2200-3200m and the maximum predicted pressures is apparent and this can be attributed to the resolution in sampling rate between log derived data (~0.15m) and the FWI (~25m) and/or anisotropic effects (VTI) on the FWI velocity.The FWI velocities highlight lateral and vertical velocity variability, due to the normal faults and tilted fault blocks in this extensional basin (Figure 3a). The predicted pore pressures calculated from the FWI velocities, expressed as a pressure gradient in terms of drilling mud weight (SG), are shown in Figure 3b. The pore pressure prediction from FWI velocities demonstrates the variability in predicted pressure across this portion of the basin, highlighting a potential for a pressure differential within individual fault blocks and between the up-thrown and down-thrown sides of the tilted fault blocks.

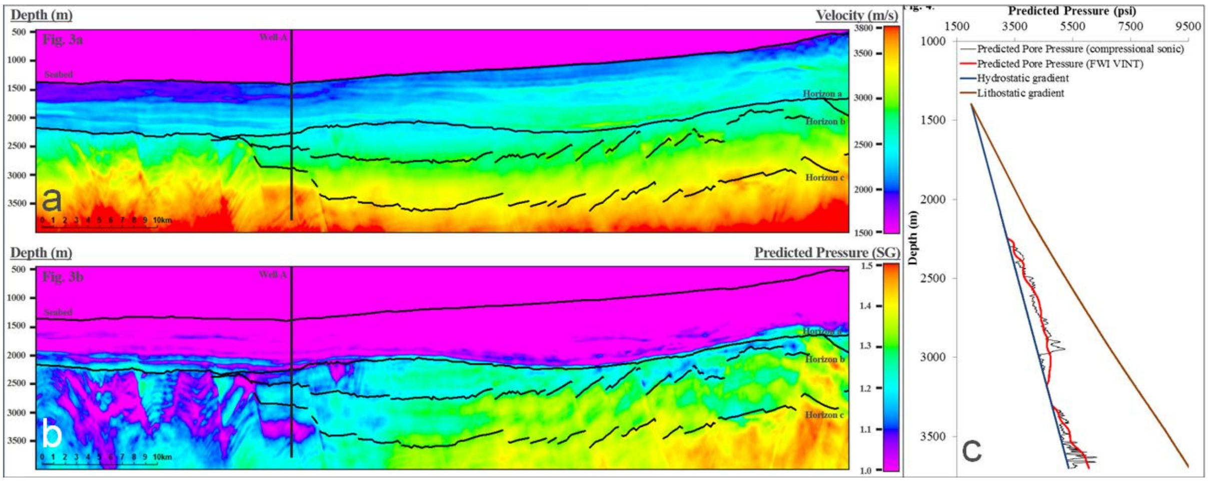

Figure 3 *Predicted pore pressures from FWI velocities. a) FWI interval velocities (m/s), b) predicted pore pressure gradient (SG) and c) depth plot (psi) showing a comparison between the predicted pressure from sonic velocities and FWI velocities at the well.*

Conclusions

Provided that we acquire adequate datasets, FWI can develop into a real game changer for the oil and gas industry. We have shown that data rich in low frequencies and with long offsets allow us to relax the constraint of running FWI with an accurate tomographic starting velocity model. This means that we can perform FWI in the low frequency range (~10Hz) for imaging purposes while preprocessing takes place and shorten the data delivery turnaround by 50%. The high frequency range (~30Hz) FWI provides a velocity model with such a resolution that it can be used directly for interpretation. In particular applications in the field of pore pressure prediction and shallow hazard analysis look extremely promising.

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