Full Waveform Inversion and Ambiguities Related to Strong Anisotropy in Exploration Areas – Case Study Barents Sea

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SUMMARY

In this case study from the Barents Sea, we have used refraction based Full Waveform Inversion (FWI) in an extreme anisotropy regime without the support from well information. We reveal our observations for decoupling the vertical and horizontal velocity, which enables us to achieve good data matching as well as flat gathers, focused images and a geological consistent model. Our frequency cascaded FWI flow results in a high resolution velocity model to the depth of interest, following the faulted crest in great detail, as well as low velocity zones correlating with the bright spots in the seismic image.

Introduction

It is well known that Full Waveform Inversion (FWI) can build high-resolution velocity models for depth migration and in some cases can be used as a seismic attribute for further understanding of the subsurface. A common question is whether FWI results in ‘correct’ solutions or gets trapped in a local minima. We attempt to answer this by performing model validation in different complementary domains. In the data domain, a comparison of observed and modelled shots gives an indication of whether the modelled shots have ‘reproduced’ the same events at the correct locations as seen in observed data. In addition, we migrate reflection data in order to evaluate gather flatness and structural correlation between the seismic image and the updated velocity model.

FWI relies on the low frequency content in the data to increase the size of the basin of attraction and minimize the likelihood of a local minima solution. Due to tuning and interference effects at low frequencies, comparing shot points cannot fully reveal whether the exact solution has been obtained. Another uncertainty is whether we correctly decouple anisotropy effects from the vertical velocity, to ensure flat gathers and focused images. This task becomes particularly challenging in exploration phase (with lack of well data) and in the presence of strong anisotropy. Multi-parameter FWI is an option, but the extra degree of freedom requires more constraint in the inversion process and still depends on an accurate starting model. In this paper, we present a case study from the Barents Sea, where we address the ambiguities related to anisotropy and our workflow to achieve a high-resolution velocity model used for both depth migration and fluid prediction (Rønholt *et al*., 2015).

The seismic dataset used in this study was acquired in the Barents Sea South East in 2014, and is 5600km^2 in area. The vessel deployed 10 deep-towed dual-sensor streamers, separated by 75m with 7km cable length. The main plays consist of shallow high amplitude events and/or flat spots. Due to combination of shallow target and long offset acquisition, a refraction based FWI approach could solve for the velocities down to main target level.

Methodology

The aim of the FWI process is to minimize the residuals between the recorded and modelled data. Differences are minimized iteratively until a convergence criterion is met. Our modelling engine is based on an efficient pseudo-analytic extrapolator that ensures modelling of accurate waveforms free of numerical dispersion (Crawley *et al*., 2010). The inversion portion of the FWI algorithm uses regularized non-linear conjugate gradients to obtain the best fit velocity model. FWI produces high-resolution velocity updates from the sea floor down to depths where the refracted energy is no longer recorded. Figure 1 illustrates the diving waves propagating through shallow targets in the area of interest.

By isolating the refracted energy, we achieved a lateral velocity resolution beyond the seismic wavelength, while the vertical resolution was limited by the wavelength/frequency used in the inversion; in our case 18Hz. A key element is to decouple the horizontal velocity, sampled by the refracted events, from the vertical velocity component (Prieux *et al*. 2011). This will ensure good data matching as well as flat gathers, focused images and a geological consistent model. This becomes particularly challenging in areas of strong anisotropy and without the support from well information. Modelling based sensitivity analysis of the data misfit with offset was utilized to determine anisotropy values.

Field data example from The Barents Sea

The Barents Sea is known for its hard seafloor. This is due to older, compacted sediments being exposed by uplift and erosion during the last ice age (Grogan *et al*., 1999). Locally, slightly slower Quaternary sediments are exposed. Highly compacted shales exhibit an extreme anisotropy regime with horizontal velocities as much as 35% higher than vertical velocities (Rønholt *et al*., 2008). A starting gradient velocity model with corresponding anisotropy parameters was established from scanning and evaluation of modelled versus observed refractions and by migrating the reflection data to analyse the move-out. This was followed by velocity updates and anisotropy adjustments through the use of wavelet shift tomography (Sherwood *et al*., 2014).

From a set of spatially distributed full bandwidth shot points, we identified two main refractors and linked them to a certain depth column and corresponding structural surface. It was obvious that a multiple set of solutions could give us good data matching without necessary producing flat gathers. Several forward modelling scenarios and corresponding migrations were performed to study the effect of velocity scaling and anisotropy scanning within the main layers related to refractions. Figure 2a shows a shot point with the two main refractors that were used to drive the velocity updates. Figure 2b demonstrates the results of ray tracing through the final FWI model. The deepest event corresponds to a diving wave through Base Cretaceous Unconformity (BCU). The two ellipses mark the corresponding diving waves. It is evident that the second refracted event samples the horizontal velocities over a lager subsurface interval.

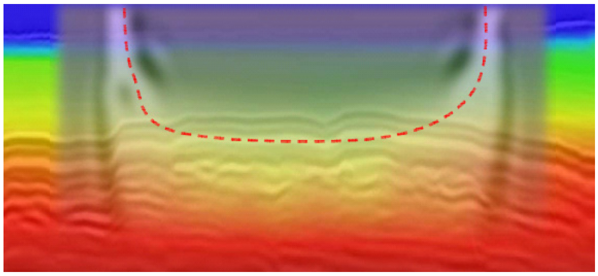

Figure 1 *Seismic image of a shallow target structure with its interval velocity model overlaid. An illustration of a forward modelled, 2-6Hz diving wave has been superimposed on the plot. The white event (highlighted with a red, dashed line) represents the wave propagation. The source to receiver offset for the modelled wave is 6km and the depth range shown is from 0 to 1.5km.*

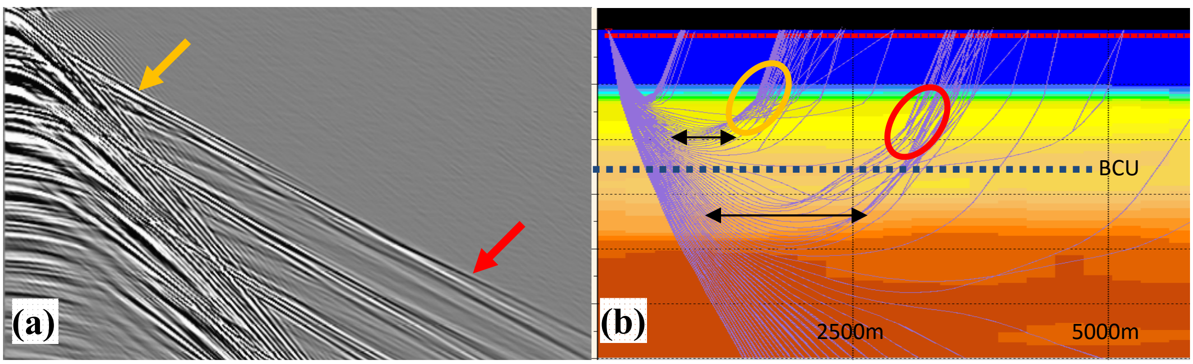

Figure 2 *Shot record from the survey (a) showing the two main refracted events. The second event (red arrow) propagates into the BCU and can be tracked over a large offset range. Ray tracing results superimposed on the FWI model (b). The two main refractors are marked by ellipses.*

Figure 3 illustrates the effect on forward modelling when scaling the vertical velocities while keeping the anisotropy fixed, versus keeping the vertical velocity unchanged and only adjusting anisotropy below BCU. These results show that velocity scaling causes a similar misfit at mid and far offsets, while adjusting the anisotropy below BCU gives an increased impact at longer offsets. If the BCU refractor samples a semi-homogeneous high velocity layer over a large subsurface interval, we can link the misfit with offset to anisotropy rather than a wrong vertical velocity gradient. The slope of the refraction depends on the horizontal velocity below the refracting interface and the wrong anisotropy assumption would consequently lead to an increased misfit with offset. The opposite, but much weaker effect, was observed when adjusting the anisotropy above the BCU, giving a higher impact at near offsets compared to far. These observations guided the decoupling of the vertical FWI velocities from the anisotropy, enabling us to achieve a good match in the data domain as well as flat gathers in the image domain. The final anisotropy model was divided in three layers, consisting of a shallow layer below the seafloor with Epsilon of 0.1, then 0.28 above and 0.24 below the BCU. The Delta parameter was set to a constant 0.05.

As the velocity model improved and produced a better match between real and modelled shots, higher frequencies were progressively included in the subsequent FWI iterations. The ultra low frequency in the data enabled the first iterations to start at 2Hz, whilst the final iterations were performed using frequencies up to 18Hz. Figure 4 shows how the FWI model evolved with the various frequency updates. The final model shows a high level of detail at the faulted crest of the structure (blue colours) and it correlates well with the bright spots seen in the reflection image, figure 5.

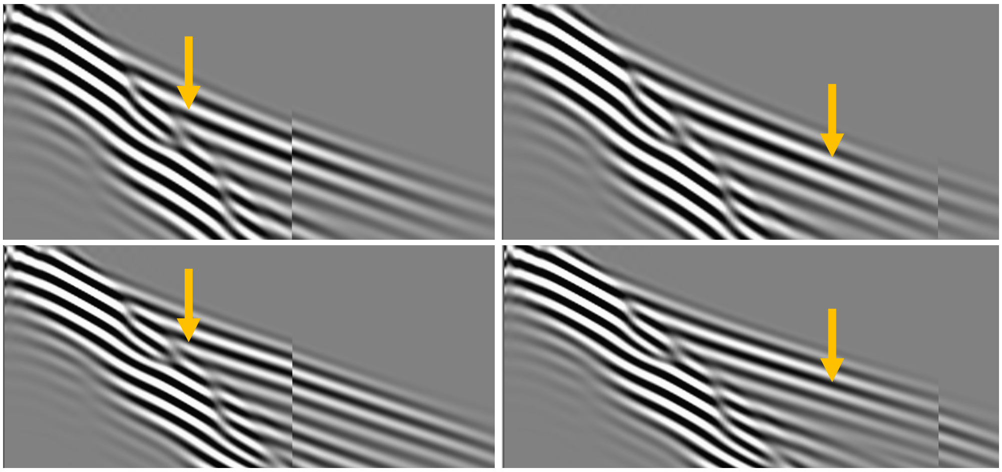

Figure 3 *Comparison at mid- and far offset of synthetic shot points before and after velocity scaling. Anisotropy was kept fixed in the examples shown in the top row. The same comparison with fixed velocity and anisotropy parameters adjusted below BCU is shown in the bottom.*

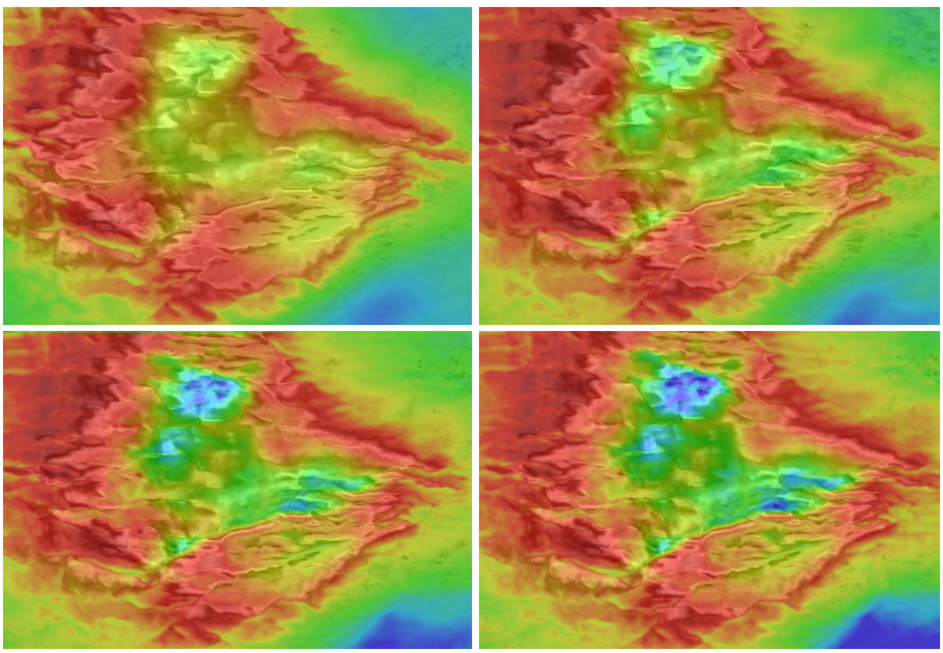

Figure 4 *Seismic depth slice at 585m with the FWI velocities overlaid. Initial model from wavelet shift tomography (top left), 2-6Hz FWI model (top right), 2-10Hz FWI model (bottom left), and 2-14Hz FWI model (bottom right).*

Conclusions

In this case study from the Barents Sea South East, we have used refraction based Full Waveform Inversion (FWI) to build a high resolution velocity model down to the depth of interest. The resulting model follows the faulted crest in great detail and the low velocity zones correlate well with the bright spots in the seismic image. Our attempts of understanding the implications of the extreme anisotropy effect in this exploration area resulted in a FWI model that produced well focused images.

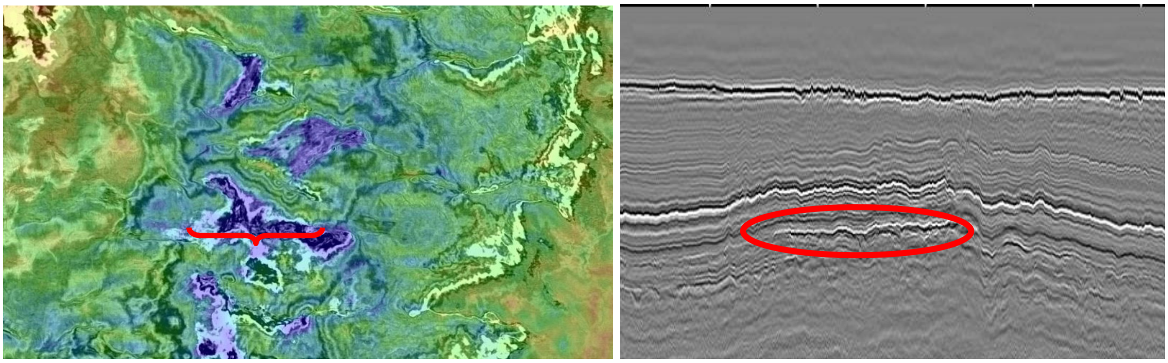

Figure 5 *Depth slice of the FWI model overlaid on the corresponding reflection image (left). Subline image thought the anomaly (right). The red ellipse high-lights the bright spot that correlates to the low velocity zone in the FWI model.*

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