EXPLOITING THE FULL WAVEFIELD TO OVERCOME LIMITATIONS OF RAY BASED TOMOGRAPHY IN THE CENTRAL NORTH SEA

P. Fallon[1], F. Hall[1], G. Cattini[1], A. Holman[1], S. Hollingworth[1]

[1] CGG

Summary

Full waveform inversion (FWI) using diving waves has in recent years become a standard model-building tool in the Central North Sea (CNS). Below the maximum depth of diving wave penetration however, we have remained reliant on ray based tomographic methods, which although powerful, have many limitations.

In this paper, we will describe the use of time-lag FWI (TLFWI). TLFWI uses a modified cost function which aims to minimize travel time differences between recorded and modelled shots. This mitigates many of the issues encountered in other FWI solutions when reflection information is included. The ability to reliably use reflection information make it possible to reduce our dependence on ray-based approaches at depth. This is of particular benefit in areas where these ray-based tomography methods are inherently limited such as fast, layered chalk layers. The application of this technology to a large survey in the Central North Sea will be described.

Introduction

The Central North Sea is a mature basin with a long history of oil and gas exploration and a relatively well-understood geology. Imaging challenges remain despite huge progress in the evolution of processing and imaging technology and increasing availability of broadband long offset datasets. Improvements to the deep imaging and structural understanding are constantly required, for both prospect discovery and field development.

Targets for exploration are typically to be found at chalk level, around flanks of salt diapirs or in the tilted fault blocks of the Jurassic / Triassic sequences. Quaternary channel features, injectites, absorption bodies and mid Miocene contourites all cause distortion to the wavefield, which if unresolved manifest in structural distortion compromising interpretation of these deeper targets. The upper Cretaceous chalk interval comprises complicated thin layers with large vertical velocity contrasts.

Traditional approaches to velocity model building have relied heavily on ray-based tomography, but in recent years model building has evolved from ray to wave based methods. Initially full waveform inversion (FWI) was applied to update the overburden but was unable to update the chalk due to lack of diving-wave penetration at typical chalk depths, so tomography was still required. Now, further developments in FWI technology, specifically time-lag FWI (TLFWI), which is able to reliably use reflection data, make it possible to update the entire section using wave-based methods without having to resort to ray-based approaches at depth.

We describe this evolution of technology and illustrate the uplift it brings when applied to a 35000sqkm imaging project covering much of the Central North Sea.

From Rays to Waves

Tomography is a powerful tool, but it also has many limitations. It is reliant on the data pre-processing, it is limited in the resolution that can be achieved and convergence to a sensible solution requires many constraints, which must be imposed by the processor. In the fast, complicated chalk sequences, the large velocity contrasts may render ray tracing unstable and result in restricted angle ranges of reflections, which limited the usefulness of residual moveout based methods. Multilayer tomography (Guillaume el al., 2012) allows quite detailed layered models to be built and updated, but limitations of ray based assumptions and the limited RMO information means that tomographic updates in chalk are, by necessity, highly constrained and lacking in detail.

The diapiric salt bodies characteristic of the Central North Sea are also extremely challenging to image correctly using established workflows. The structural complexity and high velocity contrast with surrounding sediments result in extremely complex ray paths featuring turning rays and prismatic arrivals (Figure 1a), so ray based methods considering only a one way approximation of the wave equation are unsuitable for model building around these structures.

In recent years, wave-based methods have significantly replaced ray-based methods in the North Sea. Diving-wave Full Waveform Inversion (FWI) has become a standard model building tool and is very successful at updating the complex shallow overburden. In the central North Sea, the depth of penetration of diving waves is limited by the regional vertical velocity profile and the maximum offset range of a typical towed streamer survey (6000-8000m) to approximately 800-1000m (Figure 1b demonstrates the sensitivity kernel of the FWI using diving waves only).

Below the penetration depth of the diving waves, it is necessary to also include reflections. However, reflection FWI can be very challenging in areas of large impedance contrasts, where small inaccuracies in the positioning of interfaces will lead to a large amplitude and traveltime mismatch between modelled and recorded seismic. Time-lag FWI (TLFWI) (Zhang et al., 2018) uses a cost function which aims to minimize travel time differences between recorded and modelled shots, optimized for different frequency bands. A cross-correlation coefficient based weighting is used to promote more reliable travel time measurements in the inversion. The inversion is largely driven by the kinematics of the wavefield, mitigating the impact of amplitude mismatch and enhancing the reliability of the method at low frequencies. This inversion scheme is thus well suited to the geological challenges in the central North Sea.

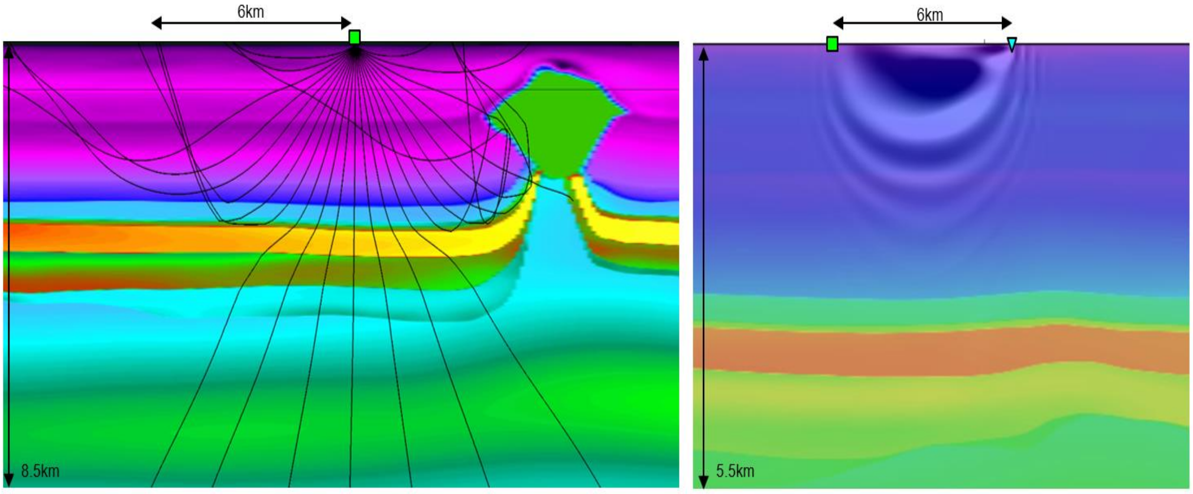

Figure 1: a) An illustration of ray path complexity in the presence of salt diapirs and layered chalk. b) The illustration of the sensitivity kernel of FWI using diving waves (6000m offset/ 4Hz).

Data Example

The example dataset comprises a large number of surveys from multiple phases of acquisition over a period of almost 20 years. Some 26 conventional streamer datasets form the bulk of the coverage. These were acquired with consistent offset and azimuth but with differences in source array configuration and recording filters, hence variation in the wavelet from survey to survey. The conventional flat tow data was supplemented by broadband data, recorded either with a variable depth streamer profile or multi sensor (MS) streamer data acquired with a deep tow. These broadband surveys were acquired orthogonally to the conventional data. Finally, several legacy datasets, with a variety of recording configurations and azimuths, have been used to infill gaps in coverage.

The history of this dataset is reflective of the evolution of technology in the industry. Initially processed using deconvolution based demultiple techniques and imaged with PSTM, the requirement for improved structural imaging naturally led to PSDM. Initially this was conducted as a series of small standalone projects due to the logistical challenges of building a depth model on the scale of the combined dataset. The advent of multi-layer tomography and the advantages it brought in terms of workflow flexibility made it feasible to update depth models on a large scale. A seamless model over the entire dataset was produced in 2015 using this technology (Hollingworth et al., 2015). Some of the issues relating to resolution of the near surface were relatively well handled in this model by the use of dip constrained tomography (Guillaume el al., 2013), this was however a partial solution, reliant on assumptions regarding the structure. Many of the imaging issues as described above remain.

The aim of the new model building project was to resolve these imaging challenges by using wavefield methods throughout the model update. At the same time the data was entirely reprocessed using the latest state of the art techniques in demultiple and ghost wavefield elimination.

Results and Discussion

The velocity model for the shallow overburden, was derived using diving-wave FWI. Given the many shallow gas-charged bodies in the region, it was necessary to solve for both velocity and attenuation

(Xiao et al., 2018). The results of the FWI are extremely sensitive to the wavelet that is used in the forward modelling, hence it was a considerable challenge to obtain an update that was consistent between the many acquisition phases. Recent surveys have near field hydrophone measurements, which may be used to directly estimate the source signature, but for the older surveys these were not available. For these surveys, the wavelet was inverted directly from the data itself, using the method as described by Pratt (1999). The results are shown in Figure 2. Figure 2a shows a shallow depth slice through 5Hz FWI velocity, Figure 2b shows the same with the survey boundaries highlighted. It can be observed that none of the boundaries between acquisition phases are apparent in the models. Figure 2c shows the inverse Q model; the model shows the attenuation effect from both slow-fill channel features, and isolated gas charged bodies.

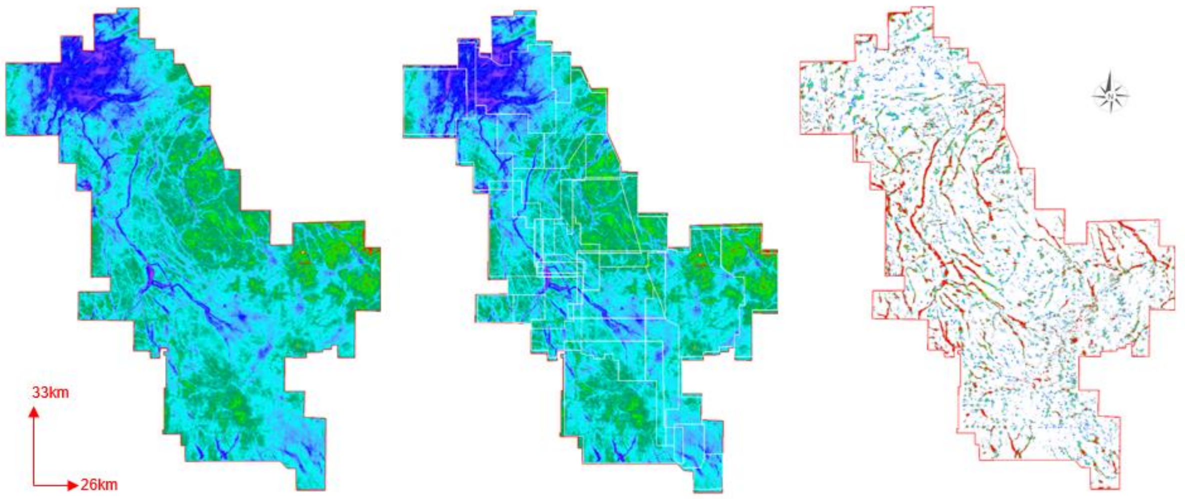

Figure 2: a) Shallow depth slice through the 5Hz FWI velocity model. b) The same velocity model with survey boundary overlays, c) inverse Q model from FWI Vp-Q joint inversion

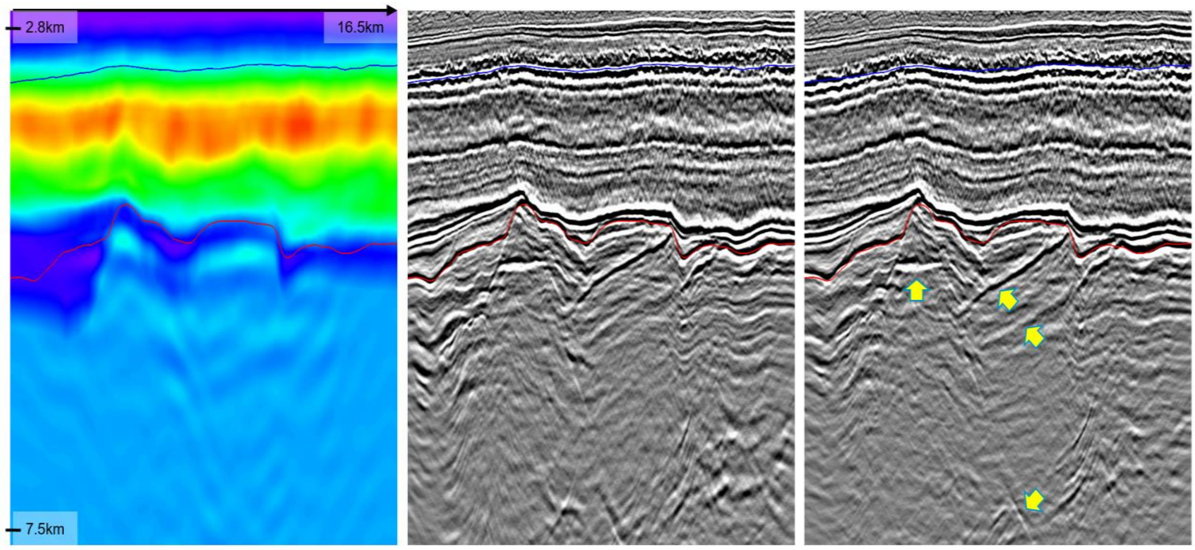

Figure 3: a) TLFWI model b) Tomography image c) TLFWI image. Top Chalk (blue) and BCU (red) horizons are annotated

The deeper data was updated using TLFWI. Figure 3 shows a typical velocity section and imaging results before and after TLFWI. The entire model depth has been updated in this case. Detail has been added in the chalk layers and the model conforms to seismic impedance contrasts in the Jurassic. The imaging results show an improvement in the sub-BCU image. Faults appear sharper and better aligned and structural distortion of tilted fault blocks is reduced. The ‘bumps’ and broad arcuate geometry of some of the reflections in the image before TLFWI suggest that there are some roll-over anticlines within the fault blocks, whereas the data migrated with TLFWI suggest only straight, rigid and tilted fault blocks, a more realistic scenario in terms of tectonic history.

Conclusion

Wavefield based methods of velocity model building have now sufficiently evolved to the point that it is viable to use them to update the entire model on a truly large scale and to reduce our dependence on ray based tomographic methods. Multiple surveys with divergent azimuths, source signatures and recording configuration can be accommodated. Multiple parameters may be inverted, in this case velocity and inverse Q. This may be extended to include epsilon. The use of reflections with TLFWI means that FWI is no longer limited to the overburden. Overall the reduction in dependence on ray based methods and exploiting the full wavefield allows us to create velocity models that are higher resolution, more data driven and less reliant on the intervention of the processor, leading to an improvement in imaging and reduction in depth distortion. Although not illustrated here, as model complexity increases, appropriate imaging algorithms must be used. Wavefield methods such as Reverse Time Migration, which use a two-way solution of the wave equation, provide clear uplift in areas of structural complexity.

When discussing the use of wavefield methods, it is necessary to acknowledge that narrow azimuth towed streamer systems are only capable of recording a small fraction of the full wavefield. As such, the resultant models are inherently limited. The model building technologies discussed here will only reach their full potential when used with data such as ocean bottom node where longer offsets, full azimuths and lower frequencies are recorded.

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