Full Waveform Inversion - A Case Study Over the Valemon & Kvitebjørn Fields, Norwegian North Sea

Ø. Korsmo* (PGS), J.F. Synnevåg (Statoil), J.P. Fjellanger (Statoil), E. Fossgaard (Statoil) & G. Rønholt (PGS)

SUMMARY

A case study was carried out over the Valemon and Kvitebjørn Fields, where a high fidelity velocity model was built to solve the complex velocity variations in the overburden. A shallow channel system, several gas pockets and a glacial wedge causes distortions in imaging unless they are incorporated to the velocity model. Through full waveform inversion (FWI) we solve the strong lateral velocity variations in the near surface. Dual sensor streamer broadband acquisition, processing and Q-Kirchhoff pre stack depth migration (PSDM) has resulted in a significantly improved structural imaging.

Introduction

We present a case study over the Valemon and Kvitebjørn fields in the Norwegian North Sea where Full Waveform Inversion (FWI) was applied to overcome various velocity estimation challenges in the shallow overburden. Obtaining an accurate velocity model for the overburden allow us to produce a high quality and accurate structural image at all depths. The imaging challenges that had to be addressed ranged from dealing with the imprint of the acquisition in shallow water, to addressing the effects on velocity and image of a large glacial wedge and numerous near surface gas pockets. It is well established that in shallow water environments reflection tomography methods struggle to produce accurate velocity estimates in the near surface since no, or very limited reflection energy is recorded. A relatively large glacial wedge in the survey area resulted in significant attenuation of seismic reflection energy and dimming to the structures below the wedge. Check-shot based velocity analysis and attempts to use travel time refraction tomography to compute reliable velocities for this wedge structure were all ineffective. To overcome both of these near surface imaging challenges, we have used full waveform inversion that is mainly driven by refracted waves. We produced a high-resolution shallow velocity model that correctly resolved the background velocity trend as well as accurately recovered the velocity variations associated with the shallow gas pockets and the significant velocity variations within the glacial wedge.

The dataset used in this study was acquired in 2013 over the Valemon and Kvitebjørn area offshore Norway using dual-sensor towed streamer technology. The 1250 km^2 seismic survey covers several prospects across two HTHP gas/condensate fields. Over the last decade, a number of data processing projects have been completed over these fields. The aim of this study was to improve the structural understanding of the reservoir section by deploying state-of-the-art velocity model estimation and the latest broadband imaging methodology.

Methodology

Several case studies have demonstrated the versatility of FWI in resolving small-scale velocity features, in particular in the shallow parts of the overburden, where reflection-based velocity estimation techniques tends to struggle. Sirgue et al. (2009) successfully applied FWI to OBC data over the Valhall field, resolving small-scale sand channel features in the shallow overburden sediments, as well as gas pockets that had historically distorted the image of underlying reservoir structures. In this work, we demonstrate that FWI performs very well also when applied to low frequency rich, deep tow streamer seismic data recorded with a dual-sensor streamer. In addition to the rich low frequencies, such a recording system also provides a true broadband dataset that is used for high-resolution structural imaging.

The aim of the inversion process is to match the recorded field data with modeled data, reducing the differences until a convergence criterion is met. Our modeling engine is based on an efficient pseudo-analytic extrapolator that ensures modeling 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 is producing high-resolution velocity updates from the sea floor down to depths where the refracted energy diminishes. By isolating the refracted energy, we achieve a lateral velocity resolution beyond the seismic wavelength, while the vertical resolution will be limited by the wavelength/frequency used in inversion, in our case 12Hz. As quality control of the FWI updates it is customary to check the flatness of PSDM offset gathers and analyze the structural changes of the shallow image, in addition to analyzing the match between modelled and measured data. For improved image resolution and quality control, we deployed separated-wavefield imaging (Rønholt et al 2014), where the multiple energy is imaged to achieve improved illumination of the subsurface. This methodology also provides increased angular coverage that enables better quality control of the near surface velocities (Whitmore et al., 2010, Lu et al., 2013). A successful FWI velocity update should result in a well-focused and structurally simplified image with substantially reduced false pull-up/push-down effects caused by near surface velocity anomalies.

Field data example from The North Sea

A vintage PSDM velocity model was used as a starting point for FWI velocity estimation. This vintage model captured the general velocity trends inside the glacial wedge reasonably well. Forward modelling showed that cycle skipping was avoided for the first half of the cable spread and data from this part from the survey could be used for the first FWI iterations. Figure 1 shows an inline with the initial and updated model after FWI applied. As the velocity model evolved and produced a better match between real and modelled shots, larger offsets and higher frequencies were included in the subsequent FWI iterations (Figure 2). The ultra low frequency in the data enabled the first FWI iterations to start at 2Hz, whilst the final iterations were performed using frequencies up to 12Hz. The FWI model was validated in the reflection image domain with PSDM methods (Figures 3 and 4). As anticipated, imaging with the FWI velocity model presented a simplified lateral structure, where the local pull-up/push-down effects due to the variable velocities inside the wedge and shallow gas pockets had been significantly reduced (Figure 3). Figure 5 shows the correlation between the new seismic image and the FWI velocity model. A shallow channel, the glacial wedge and gas pockets can be seen in great detail in the velocity model and correlating well with the seismic images.

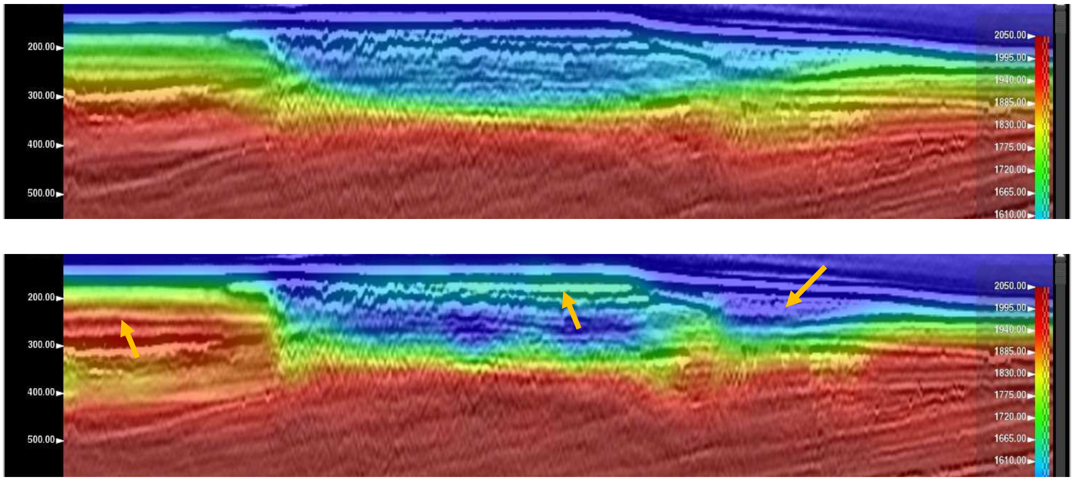

Figure 1: *Inline data example with velocity overlay. Top: Kirchhoff PSDM image with starting model. Bottom: Kirchhoff PSDM image with final FWI velocity model.*

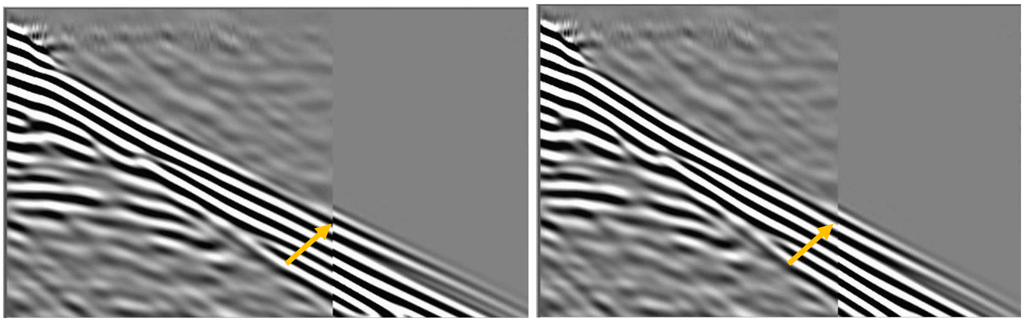

Figure 2: *Real and synthetic shots from an early FWI model (left) and a more advanced FWI model (right) demonstrating a better phase match of the latter.*

Final imaging was produced using a Kirchhoff pre-stack depth migration algorithm after additional source side de-ghosting of the input data. A Q-model was used to compensate for anelastic attenuation and absorption effects during the application of the migration operator resulting in 3D amplitude compensation along the ray path instead of the conventional 1D correction post migration. Scans of constant Q-values were evaluated based on the similarity of near and far offset traces, noise level and image quality. Figure 6 shows a comparison between the original reference stack and the new dual-sensor FWI image.

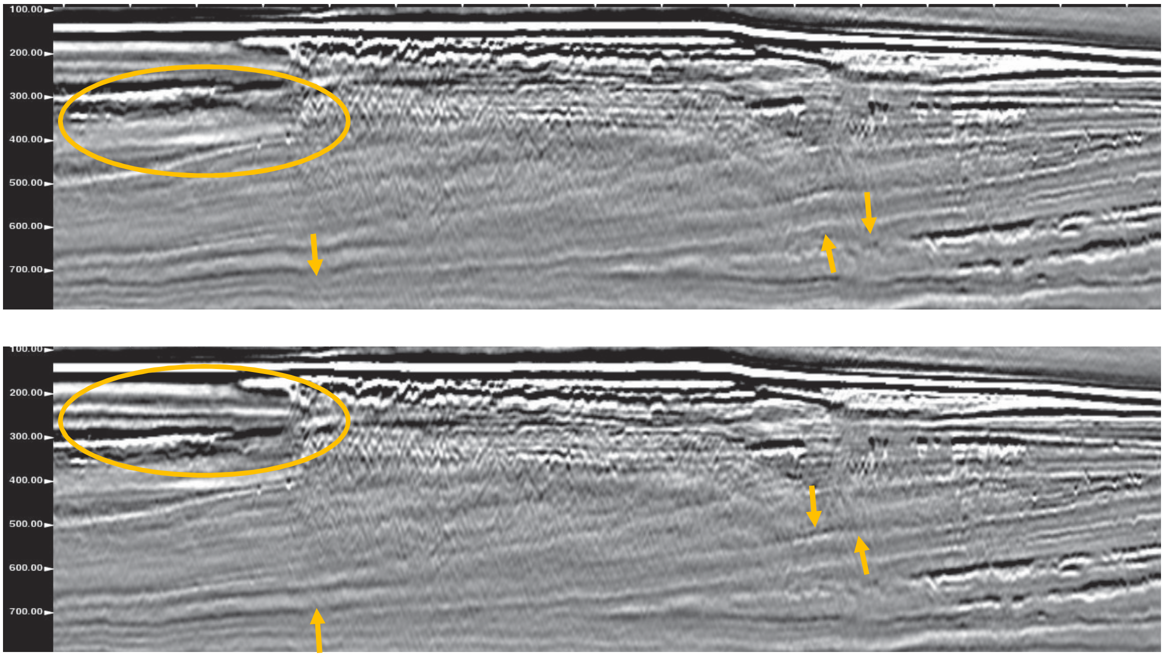

Figure 3: *Kirchhoff PSDM stack using the initial (top) and updated FWI velocity model (bottom).*

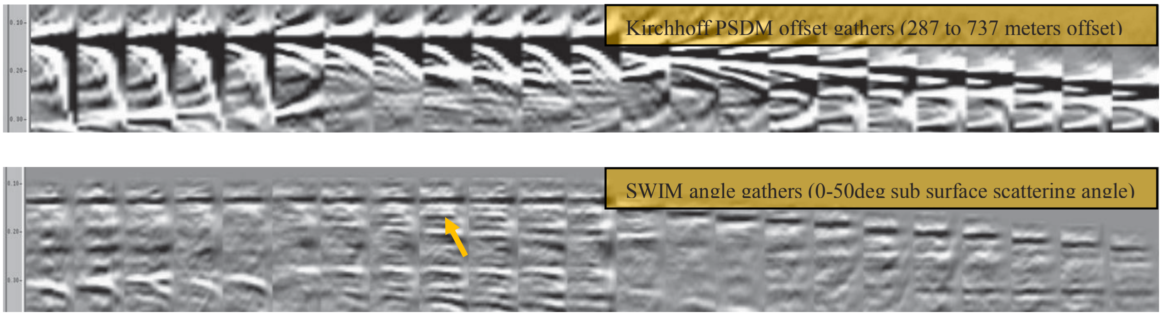

Figure 4: *Kirchhoff offset gathers (top) and separated wavefield imaging angle gathers (bottom) with the updated FWI model.*

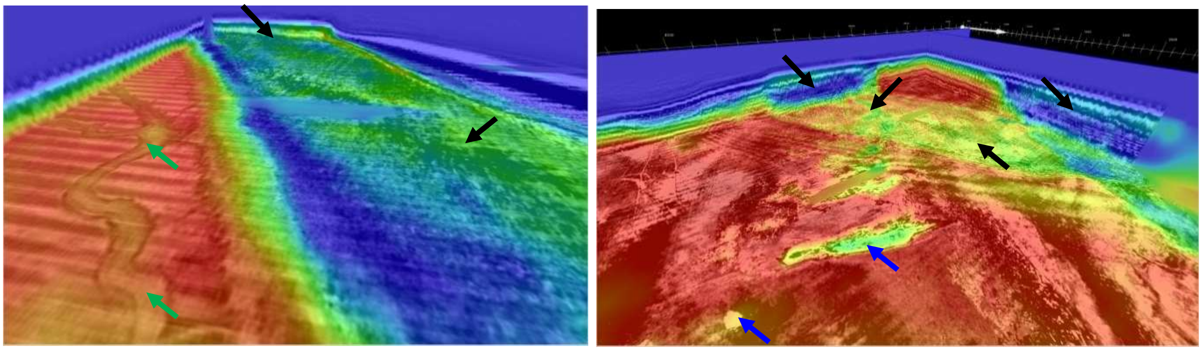

Figure 5: *3D view with depth slices at 190m (lef) and 340m (right), of the seismic stack with FWI velocity model overlaid. A shallow channel (green arrows), lateral velocity variations inside the glacial wedge (black arrows) and shallow gas pockets (blue arrows) are identified in the FWI model and the seismic data. The 3D view illustrates the data with inlines, xlines and depth slices.*

Conclusions

In this North Sea case study, we have used refraction based full waveform inversion (FWI) to resolve several small-scale velocity anomalies in the shallow overburden caused by a near surface channel system, gas pockets and a large inhomogeneous glacial wedge. The successful application of FWI, resulted in significantly improved imaging and exceptionally detailed near surface velocity models. Maximum signal bandwidth was preserved by performing wavefield separation based dual-sensor deghosting and Q-migration.

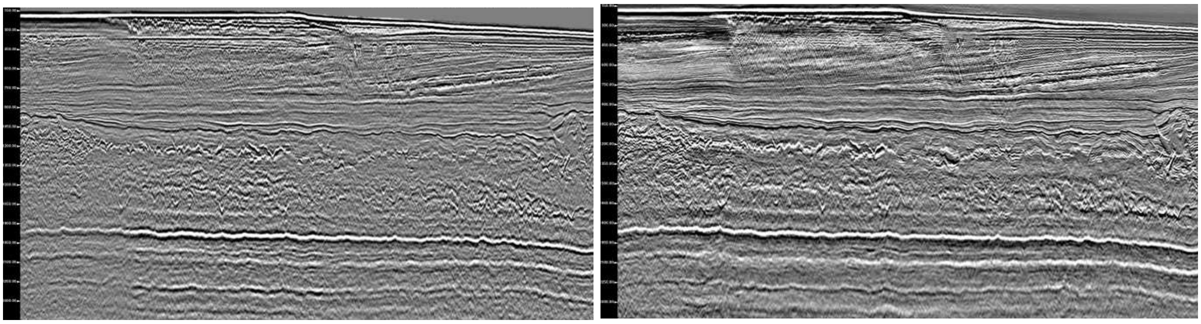

Figure 6: *Shallow image section comparing the vintage data, reference PSDM stack (left) and the dual-sensor Kirchhoff PSDM result (right).*

Acknowledgements

We thank Statoil Petroleum AS and their partners; Petoro AS, Centrica Resources (Norge) AS, Total E&P Norge AS and A/S Norske Shell, and PGS for the authorization to present this work. Furthermore we thank Rita Naustdal, Tobias Jokisch, Alejandro Valenciano Mavilio, Steve Kelly, Kathy Zou and Julien Oukili at PGS for valuable contributions to this work.

References

Crawley, S., Brandsberg-Dahl, S., McClean, J. and Chemingui, N., [2010], TTI reverse time migration using the pseudo-analytic method, The Leading Edge, Vol. 29, No. 11, pp. 1378-1384.

Lu, S., Whitmore, N.D., LeGleut, H., and Long, A. [2013] 3D high-resolution imaging using separated wavefields. *75th EAGE Conference and Exhibition*, Extended Abstracts, Th 08 09.

Rønholt, G., Korsmo, Ø., Brown, S., Valenciano, A., Whitmore, D., Chemingui, N., Dirks, V., Brandsberg-Dahl, S. and Lie, J.E. [2014] High-fidelity complete wavefield velocity model building and imaging in shallow water environments – A North Sea case study. First Break volume 32, June 2014.

Sirgue, L., Barkved, O.I., Van Gestel, J.P., Askim, O.J. and Kommedal, J.H. [2009] 3D Waveform Inversion on Valhall Wide-azimuth OBC. *71st EAGE Conference and Exhibition*, Extended Abstracts, U038.

Whitmore, N.D., Valenciano, A.A., Söllner, W. and Lu, S., [2010], Imaging of primaries and multiples using a dual-sensor towed streamer, ASEG Extended Abstracts, 21st Geophysical Conference