Improved Velocity Estimation and Imaging Using Multiple Wavefield Components - A North Sea Case Study, Brage Field

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SUMMARY

A case study was carried out over the Brage Field, where high fidelity velocity model was built to solve the complex velocity variations in the overburden. The shallow channel system was captured in the velocity model by the use of an integrated workflow combining refractions, multiples and reflections. Solving for the strong lateral velocity variations in the near surface resulted in significant movements of the target structures.

Introduction

We present a case study over the Brage field, North Sea, with the objective to overcome the imaging challenges caused by a complex overburden. An accurate overburden velocity model is key to obtaining the best possible structural image. Complicating factors are related to shallow water acquisition and a large shallow channel (Figure 1). It is well established that in shallow water environments reflection tomography methods struggle to produce accurate velocity estimates, since no or very limited reflection energy is recorded before critical reflected angles are exceeded. To overcome this challenge we have isolated the refracted events and used these in full waveform inversion (FWI) to obtain a high-resolution velocity model that captures the shallow background velocity trends and the channel(s). Separated wavefield imaging (Whitmore *et al*., 2010, Lu *et al*., 2013) yields superior illumination and angular coverage in shallow water and has been used to QC the FWI model (Rønholt *et al*. 2014). After solving for the shallow overburden velocity complexity, wavelet shift tomography was used to update the deeper part of the velocity model. In wavelet shift tomography, each wavelet carries a 3D residual shift needed to align seismic reflections. This gives us the opportunity to build a high-resolution model for the deeper parts, and solve for non-parabolic move-out observed below local anomalies.

The data under investigation were acquired in 2014 using dual-sensor streamers. The 500 km^2 seismic survey covers the entire Brage oil field located at the Norwegian continental shelf in the North Sea. Brage is a mature oil field currently producing from four different reservoirs, all of Jurassic age. One of the reservoirs, Statfjord, is located on an N-S oriented horst structure bounded by large, steeply dipping faults (Figure 1). Optimal imaging of top reservoir and the bounding faults are important for several reasons, amongst others to reduce uncertainty in the reserve estimates for the reservoir. A large, channel-looking feature is present in the shallow overburden above the Statfjord horst (Figure 1). One obvious effect of the channel is the dimming of seismic amplitudes that can be observed in the zone beneath the channel. In the current study we want to investigate if the imaging of the Statfjord horst can be improved by incorporating the shallow channel in the velocity model used for PSDM.

Methodology

Our velocity model building workflow is made up of three main elements: wavelet shift tomography, full waveform inversion and separated wavefield imaging. The key to producing highly accurate velocity models lies in how these algorithms are combined into a workflow that mitigates any weaknesses that might exist in any one method alone (Rønholt *et al*. 2014).

Several tomography methods have been developed to invert seismic reflection data into velocity models. In the last decades, efficient (close to real time) pre-stack depth migrations have been enabled by the use of beam migration. More recently, tomographic velocity estimation tools have been developed to work in close relationship with these migration algorithms, bringing similar benefits to the field of velocity model building. Rather than having to rely on move-out curves picked on gathers, this method relies on measured, spatial wavelet attributes, hence the term ‘wavelet shift tomography’. The process consists of mapping pre-processed data into wavelets, migration of the wavelets to the depth domain, and finally reconstruction into an image. The wavelet shift tomography technology utilizes 3D time-residuals and many other wavelet attributes that are tomographically back projected as slowness updates (Sherwood *et al*. 2011).

In our workflow, the velocity model from wavelet shift tomography is used as a starting model for FWI. Several field data studies have demonstrated the versatility of FWI in resolving small-scale velocity features, in particular in the shallow parts of the model, where reflection-based methods tends to struggle. Sirgue *et al*. (2009) inverted OBC recordings above the Valhall field and identified sand channel features in the shallow sediments, as well as gas pockets that had distorted migrated images for underlying reflectors. The power of our FWI is that it uses the low frequencies recorded during the deep tow, dual sensor streamer acquisition. The aim of the inversion is to match 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 inverted velocity model. FWI is producing high-resolution velocity updates from the sea floor down to depths where the refracted energy diminishes.

As quality control for FWI updates, in addition to analyzing the data matching, it is customary to check the flatness of pre-stack depth migration (PSDM) offset gathers. However, in areas with shallow water bottom, this can be a challenge due to the poor angle illumination provided by the primaries. To overcome this issue, we have introduced the application of separated wavefield imaging in our model building workflow. Migration of the multiples effectively creates "virtual" sources at each receiver position, enhancing subsurface illumination and resolution (Whitmore *et al.*, 2010).

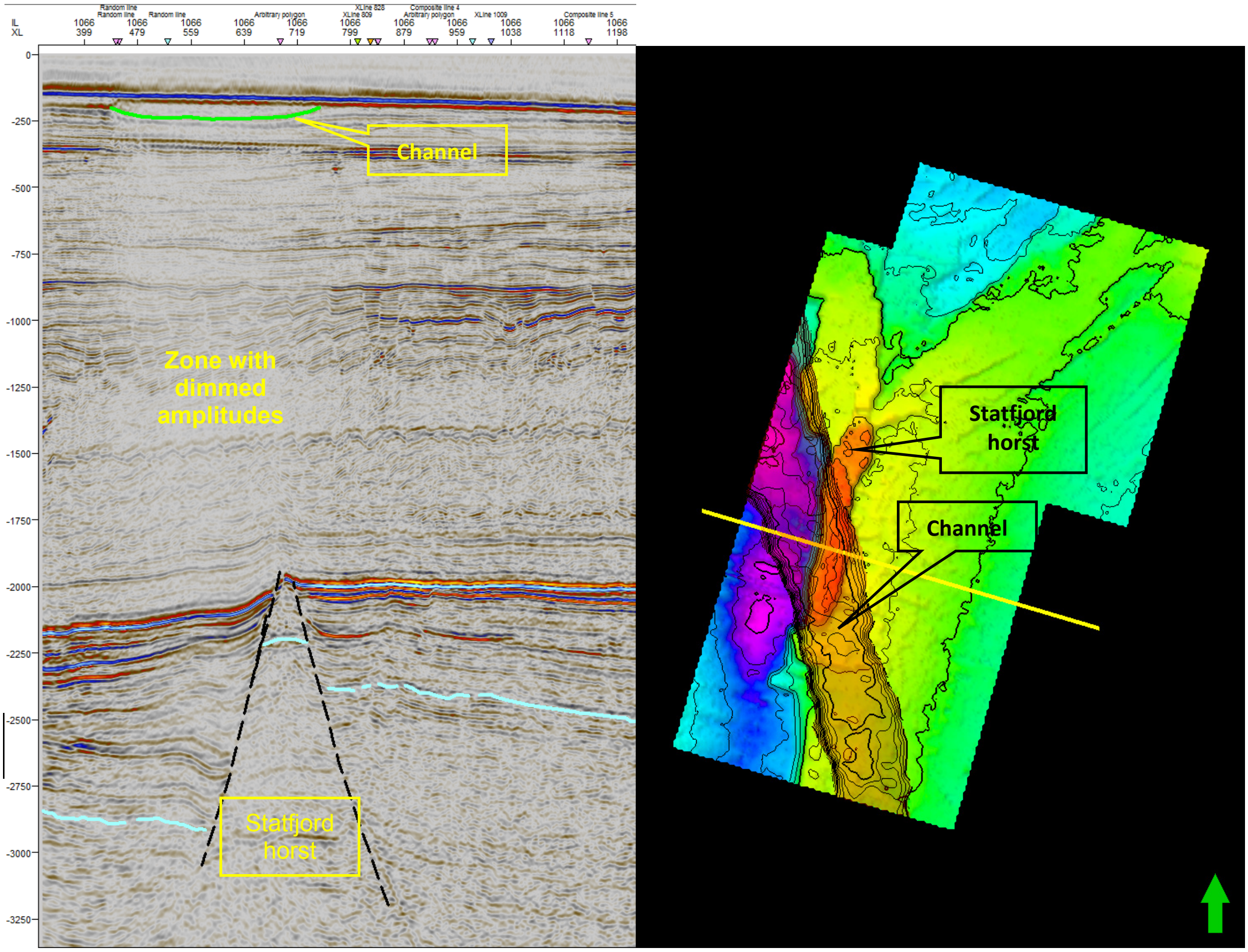

Figure 1 *Left: Seismic section from vintage 3D survey showing the Statfjord horst and the top Statfjord reservoir interpretation (blue). The shallow channel feature is shown in green. Amplitude dimming is observed in the zone below the channel. Right: Map showing how the shallow channel is crossing the field from SE to NW and covering a large part of the Statfjord horst.*

Field data example from The North Sea

A tomography based velocity model was used as a starting point for FWI. Forward modelling QC indicated that the first half of the cable could be used for the first FWI iterations. Figure 2 shows seismic stack, depth slices with the initial and updated FWI models. As the velocity model evolved and gave a better match between real and modelled shots, larger offsets and higher frequencies were included in the FWI iterations. The acquired broadband signal enabled the first FWI iterations to start as low as 2Hz while the final iterations were run up to 9Hz. The FWI velocity model was validated in the reflection image domain with both Kirchhoff PSDM and angle gathers from separated wavefield imaging. The FWI model resulted in a simplified lateral structure, where the local pull-up/push-down effects due to the variable velocities inside the channel had been compensated for (figure 3). The western flank of the reservoir is bounded by a fault that is located below the large, shallow channel (Figure 1). The FWI update resulted in a general slowdown of the velocities. This caused the horst structure to image at a shallower depth, and the reservoir-bounding fault to move about 75m westward (Figure 4).

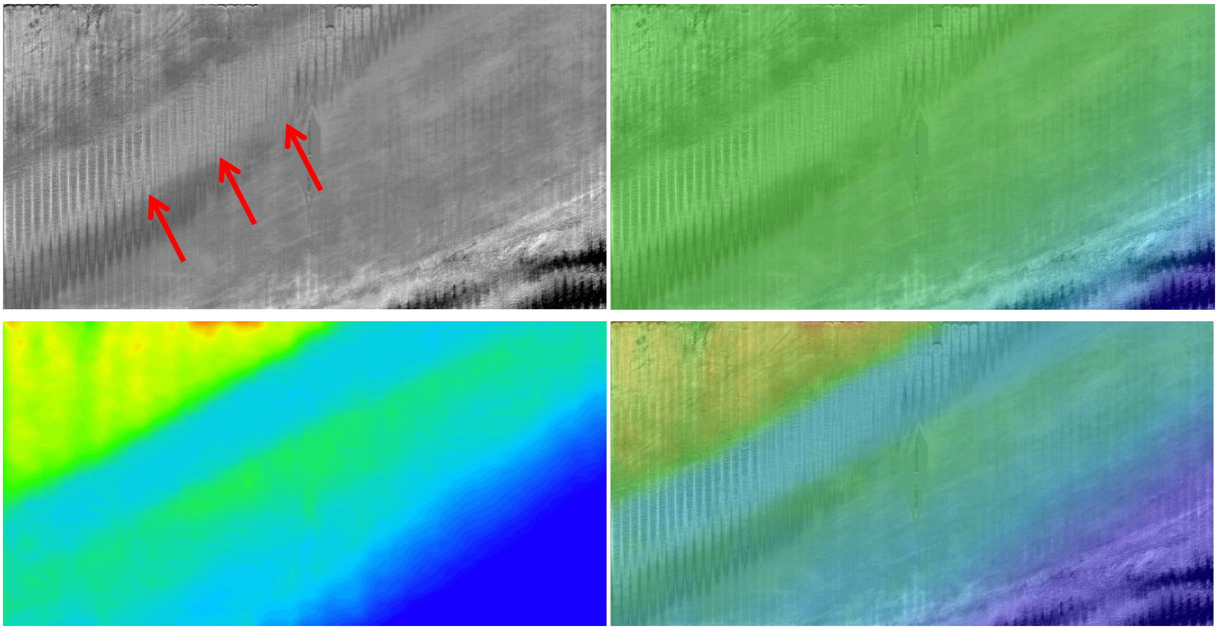

Figure 2 *Shallow depth slices of; top left – brute stack of the seismic data; top right – brute stack with input velocities (to FWI); bottom left - velocities after FWI; bottom right – brute stack with FWI velocity model overlay. An excellent correlation between the large shallow channel (red arrows) in the stack and FWI velocity update can be observed.*

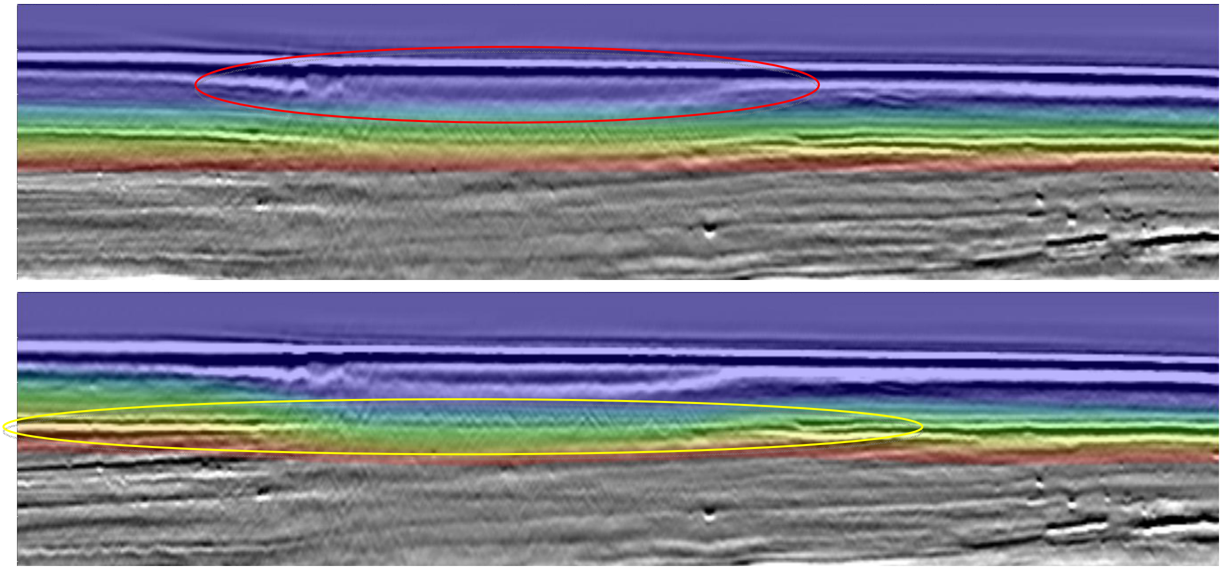

Figure 3 *Kirchhoff PSDM stacks with input (top) and FWI (bottom) velocities. The channel is located within the red ellipse. The yellow ellipse highlights an area with improved focusing and a simplified structural image (compared to migration with input velocities).*

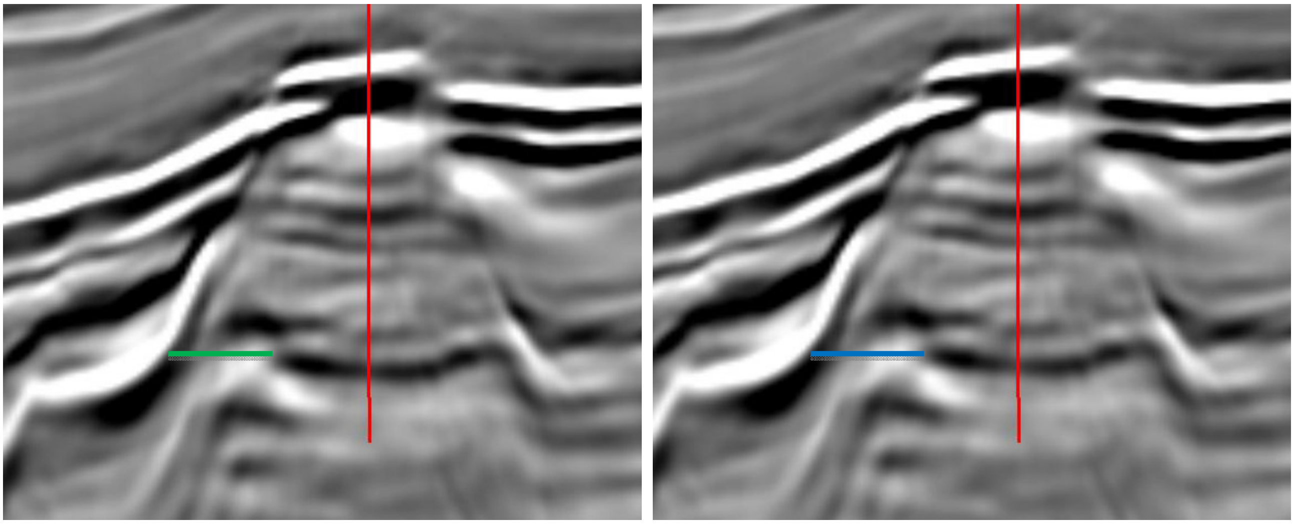

Figure 4 *Beam PSDM stack with velocity model before (left) and after (right) FWI updates. The green line is 75m shorter than the blue line – a measurement of the westward movement of the reservoir bounding fault.*

Conclusions

In this case study, we have used the complementary technologies of full waveform inversion, separated wavefield imaging and wavelet shift tomography in a combined workflow to build a highly accurate migration velocity model. We have demonstrated its capability to resolve the velocities in a complex overburden resulting in improved structural imaging of the reservoir where the location of a significant bounding fault was changed with as much as 100 meters.

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