Complete Wavefield Imaging: High Fidelity Velocity Model Building and Imaging from Dual-Sensor Streamer Data

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SUMMARY

We demonstrate the success of combining wavelet shift tomography, full waveform inversion (FWI) and separated wavefield imaging (SWIM) for pre-stack depth migration (PSDM) velocity model building and imaging. The workflow is referred to as Complete Wavefield Imaging (CWI) as it utilizes reflection, multiple, and refraction arrivals in the dual-sensor seismic data.

Wavelet shift tomography, operating on reflection arrivals, was used to update the shallow overburden in a legacy PSDM velocity model. FWI updates based on matching modelled versus observed refraction arrivals were subsequently able to resolve high resolution velocity variations associated with channels, pockmarks and gas pockets in the shallow overburden. Additionally, gathers from SWIM were generated using up- and down-going separated wavefields uniquely provided by the dual-sensor data. The SWIM approach exploits the greater illumination of the near surface inherent in the multiple arrivals. SWIM image gathers were used to validate the longer wavelength features not seen by FWI.

The study illustrates how reflection, refraction, and multiple arrivals from dual-sensor data can contribute towards high-fidelity model building and imaging. Resolution of the complex shallow overburden leads to more accurate positioning and depth predictions for the reservoir, directly impacting estimation of reserves.

Introduction

The survey data were acquired in 2009 using dual-sensor cables over the Utsira High area offshore Norway. The 1600 square kilometer survey covers the largest exploration discovery offshore Norway in more than three decades. Because of localised velocity variations in the shallow overburden, and a complex chalk layer overlying the thin target sands, there is a large uncertainty in estimating oil reserves.

A novel workflow for building highly accurate PSDM velocity models for complex geological settings is developed. By combining wavelet shift tomography, Full Waveform Inversion (FWI), and Separated Wavefield Imaging (SWIM), we overcome weaknesses with the traditional velocity estimation tools, and produce reliable velocity updates from shallow to deep in the model. The application of wavelet shift tomography ensures a globally consistent velocity model as a starting point for FWI to avoid cycle skipping. FWI improved the resolution and accuracy of the shallow velocity model, yielding an overall more accurate velocity model for imaging. In the final part of the workflow, we use SWIM angle gathers to validate the accuracy of the FWI velocity updates in the reflection-image domain. This ensures that the final velocity model is globally consistent and suitable for producing accurate depth images from the sea floor to very deep targets.

The workflow is referred to as Complete Wavefield Imaging (CWI) as it utilizes reflection, multiple, and refraction arrivals in the recorded seismic data.

Methodology

The CWI model building workflow is made up of three main elements: wavelet shift tomography, FWI, and SWIM**.** The key to producing highly accurate velocity models lies in how these algorithms are combined into a workflow that mitigates weaknesses that may exist in any one method alone.

The wavelet shift tomography method relies on measured wavelet attributes, rather than picked move-out curves from gathers. The process consists of decomposing pre-processed data into wavelets, migration of the wavelets to the depth domain, and finally reconstruction into an image. It utilizes 3D time-residuals and other wavelet attributes that are tomographically back projected as slowness updates (Sherwood et al. 2011).

In our workflow, the wavelet shift tomography velocity model is used as input to FWI, which utilizes the low frequencies recorded during 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. Leveraging the good low frequency data recorded by dual-sensor streamers towed deep, 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 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 SWIM 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). This also effectively mitigates the 3D cross-line acquisition 'footprint' typically observed in wide-tow marine 3D seismic data from areas with shallow water. The multiples illuminate the subsurface at smaller reflection angles than primaries, as we now have virtual sources along all receiver lines, not just the sparser shot lines. In shot profile wave equation migration, the imaging process is a combination of wavefield extrapolation and imaging condition (Claerbout, 1971). The conventional depth migration using primaries backward extrapolates the upcoming data as receiver wavefield, and forward extrapolates a synthetic point source. In SWIM, after carrying out wavefield separation using a dual sensor recording of the wavefield, we use the down-going wavefield as source, turning each receiver into a "virtual" source. This is a way to effectively increase the source sampling and coverage at the surface. Because of the complexity of the up- and down-going wavefields' interaction, a deconvolution imaging condition is applied at the subsurface. This effectively reduces the cross-talk noise generated from unrelated correlation of up- and down-going wavefields. Angle gathers are generated from the subsurface offset gathers product of SWIM, after applying radial trace transforms. SWIM angle gathers provide better illumination than the offset gathers obtained from Kirchhoff pre-stack depth migration.

Field data example from the North Sea

A legacy PSDM velocity model was used as a starting point; however, due to the shallow water depth (85-115m) in this area, conventional reflection tomography had failed to produce a sufficiently accurate shallow overburden model. Using this model alone, we would not be able to avoid cycle skipping in refraction FWI. Moving to the first step of our new workflow, this velocity model was updated using wavelet shift tomography with a focus on estimating accurate, global anisotropy parameters for the shallow overburden. With these updates in place, we were better able to match model to observed refraction data. This helped ensure that the subsequent FWI updates were able to resolve high-resolution velocity variations associated with channels, pockmarks and gas pockets in the shallow overburden, as illustrated in Figure 1.

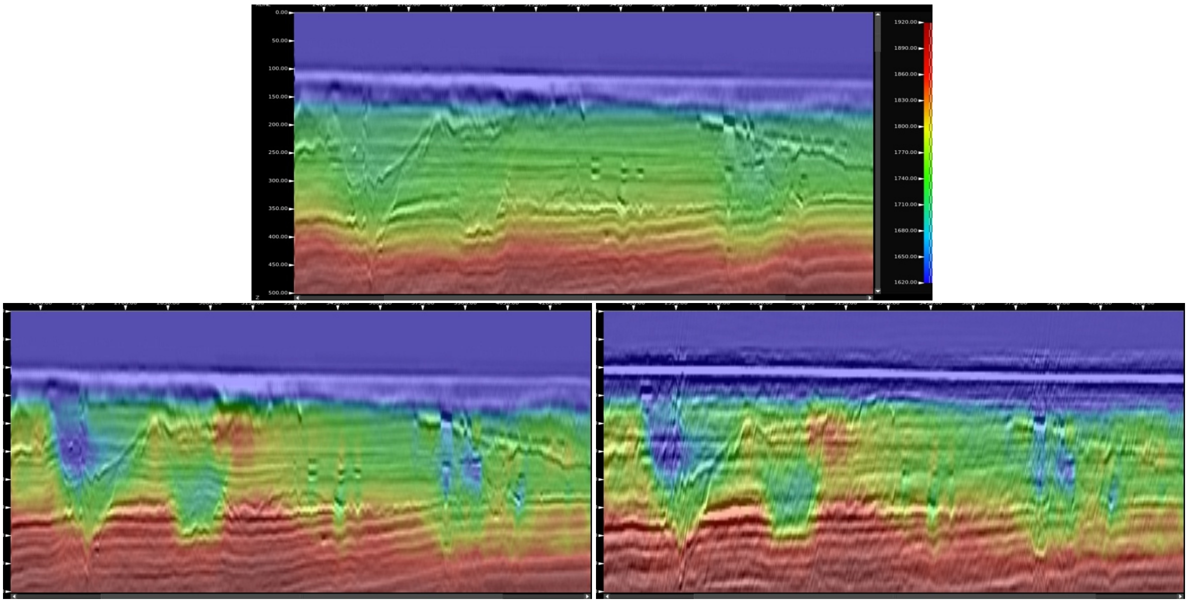

Figure 1 *Inline example with velocity overlay. Top: Kirchhoff PSDM with tomography model. Bottom left: Kirchhoff PSDM with FWI model. Bottom right: SWIM with FWI model section.*

After the application of wavelet shift tomography and FWI for velocity model building, the workflow utilized the angle gathers from SWIM to check the consistency of the resulting velocity model. To generate the SWIM gathers, we used up- and down-going wavefields provided by direct wavefield separation applied to dual-sensor streamer data (Figure 2). These SWIM image gathers were used to validate, in the reflection image domain, the longer wavelength features not easily observed or QC'ed in the data domain as seen by FWI. The additional illumination provided by imaging both primary and multiple wavefields provides a high resolution shallow image (Figures 1, 3 & 4) and angle gathers free of the sail line acquisition footprint. This was of particular importance since a shallow wedge is covering large parts of the field. The long wavelength velocity variations associated with this wedge structure have a significant impact on the vertical position of the target sands in respect to the oil water contact. For the deeper part of the overburden, particularly the chalk layer and the target zone, high-resolution wavelet shift tomography was applied. Significant improvements were observed in the quality of the final high resolution subsurface image compared to the legacy PSDM data, especially for the chalk layer and the target sands.

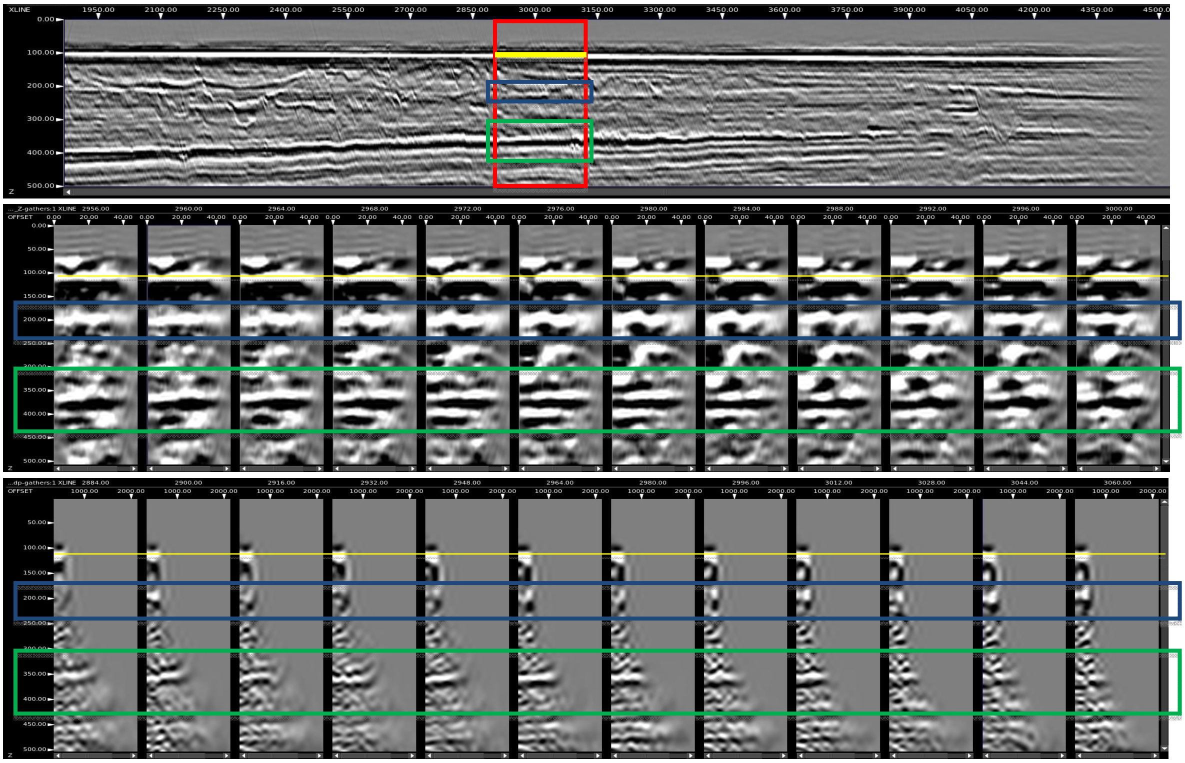

***Figure 2** SWIM image (top) and comparison of gathers from imaging with multiples (middle, function of angles) vs primaries (bottom, function of offset).*

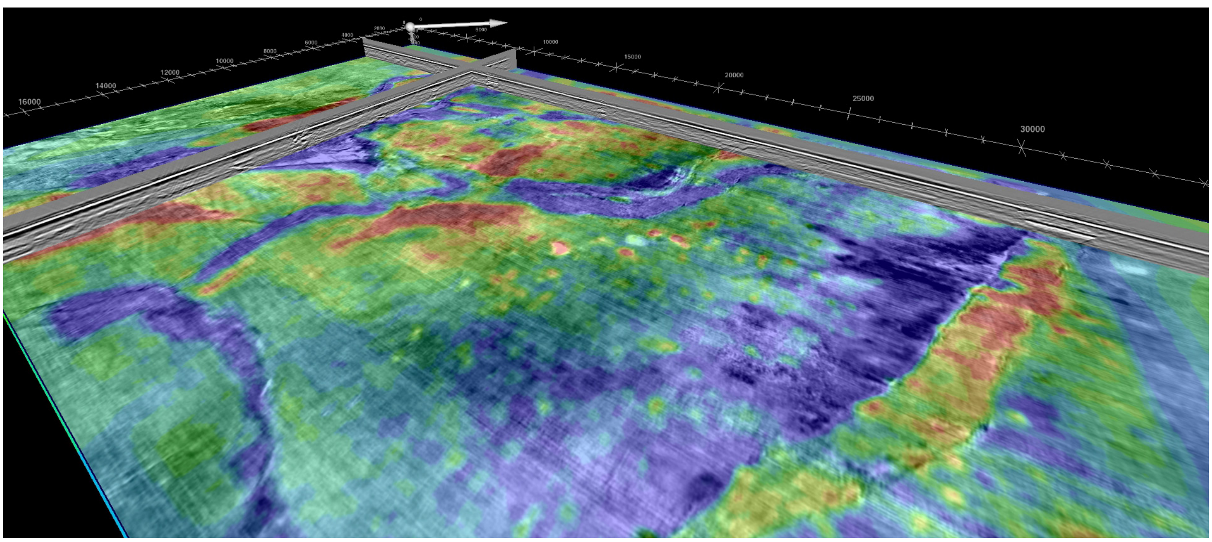

***Figure 3** SWIM image with FWI velocity model overlay. Shallow channels, pockmarks, shallow gas and a relatively large shale plug can be observed.*

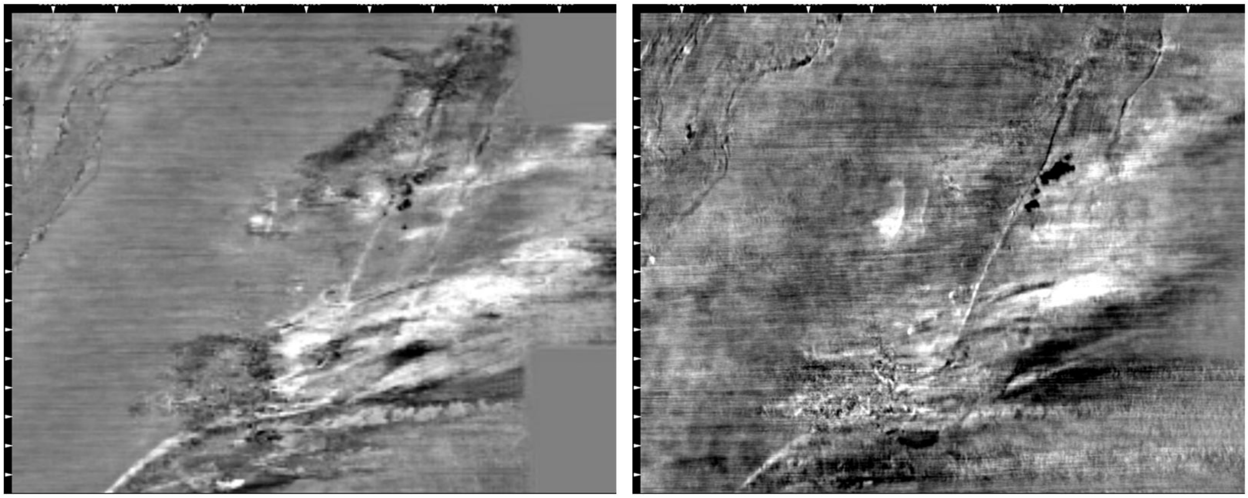

Figure 4 *Depth slice at 225m depth, Kirchhoff PSDM (left) vs SWIM (right). The spatial resolution in the SWIM depth slice is much higher, and illumination (upper and lower right) is different.*

Conclusions

We have demonstrated a novel workflow for building highly accurate PSDM velocity models for a complex geological setting. By combining wavelet shift tomography, FWI, and SWIM, we are able to produce high-resolution velocity models that are ideally suited for imaging of broadband data. Leveraging dual sensor streamer technology and the inherent capability for wavefield separation, we are using up- and down-going wavefields in imaging and tomography to improve resolution and illumination. Further, we utilize the refracted, low-frequency energy for FWI. As the streamer is towed deep, we preserve the low frequencies that are so important for the success of FWI, but without sacrificing a broadband signal that is key for producing high-resolution reflection images of the shallow overburden and deep reservoir sections.

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