High fidelity imaging using reflections, refractions and multiples: North Sea example, Johan Sverdrup Field

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Summary:

We demonstrate a novel workflow using reflections, refractions and multiples for building highly accurate PSDM velocity models for a complex geological setting. By combining wavelet shift tomography, full waveform inversion and separated wavefield imaging, 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 wavefield separation that comes with it, 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.

Introduction:

We demonstrate how we overcome weaknesses with the traditional velocity estimation tools in shallow water, 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 angle gathers from imaging with multiples to judge 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 data under investigation were acquired in 2009 using dual-sensor cables over the Utsira High area offshore Norway. The 1600km^2 surface seismic survey covers the largest exploration discovery made offshore Norway for more than three decades. Relatively thin target sands are situated below a complex chalk layer and span hundreds of square kilometers. The complex geology in the area leads to a large uncertainty in estimating the associated oil reserves. The aim of this study is to help reduce the uncertainty in the estimates by providing more accurate depth predictions and better imaging of the target sands. Figure 1 illustrates the importance of accurate depth prediction in this area.

Methodology:

The velocity model building workflow is made up of three main elements: wavelet shift tomography, full waveform inversion (FWI) and separated wavefield imaging (SWIM). The key to producing highly accurate velocity models lies in how these algorithms are combined into a workflow that mitigates any weakness that might exist in any one method alone. Several tomography methods have been developed to invert seismic reflection data into velocity models. Among them, ray-based post-migration grid tomography (Woodward et al, 2008) and stereotomography (Lambare, 2008) have served as significant tools. In the last decades, efficient (close to real time) pre-stack depth migrations have been enabled by the use of beam migration (Rieber, 1936 and Sherwood et al. 2008). 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 relying on picked move-out curves from gathers, this method relies on measured wavelet attributes, hence the term 'wavelet shift tomography'. The process consists of decomposing 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). The velocity model produced with wavelet shift tomography is very well conditioned, as all data used in the beam migration are also used to drive the tomographic updates. This produces geologically consistent updates of very high resolution.

In our workflow, these velocity models are used as input to full-waveform inversion (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) and Barkved et al. (2010) 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 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

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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 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 migrating multiples 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 '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 with 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 subsurface offset gathers after applying a radial trace transforms. The angle gathers obtained from imaging of multiples provide better illumination than the offset gathers obtained from Kirchhoff pre-stack depth migration (Figure 2).

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 workflow, this velocity model was updated using wavelet shift tomography with a focus 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/chimneys in the shallow overburden, as illustrated in figure 3.

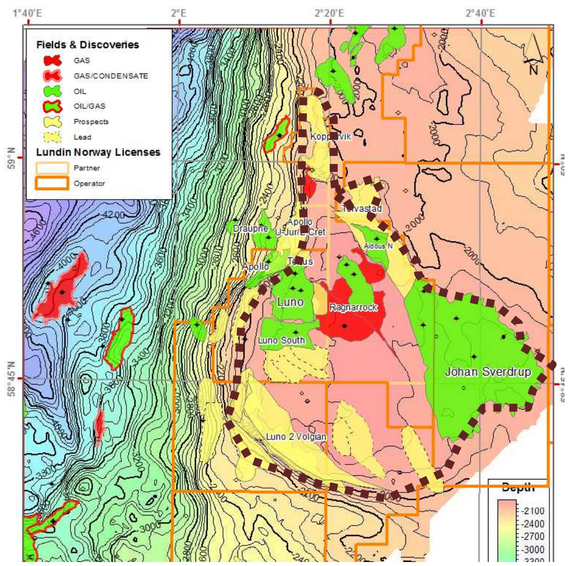

Figure 1: Study area – with predicted oil water contact

After the application of wavelet shift tomography and FWI for velocity model building, the workflow utilizes angle gathers from imaging with multiples 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 of the model that are 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 images (Figure 3, 4 & 5). 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 in the quality of the final high resolution subsurface image compared to the legacy PSDM data were obtained.

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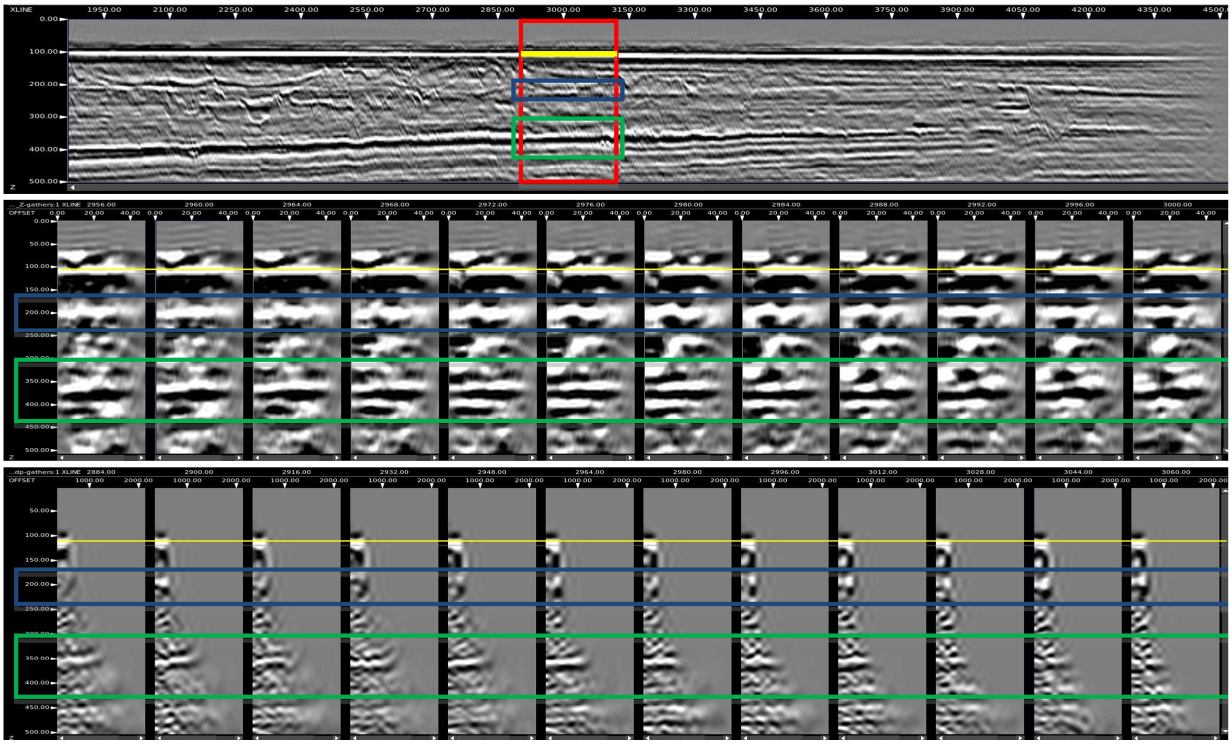

Figure 2: Image using multiples (top) and comparison of gathers from imaging with multiples (middle, function of angles) versus primaries (bottom, function of offset).

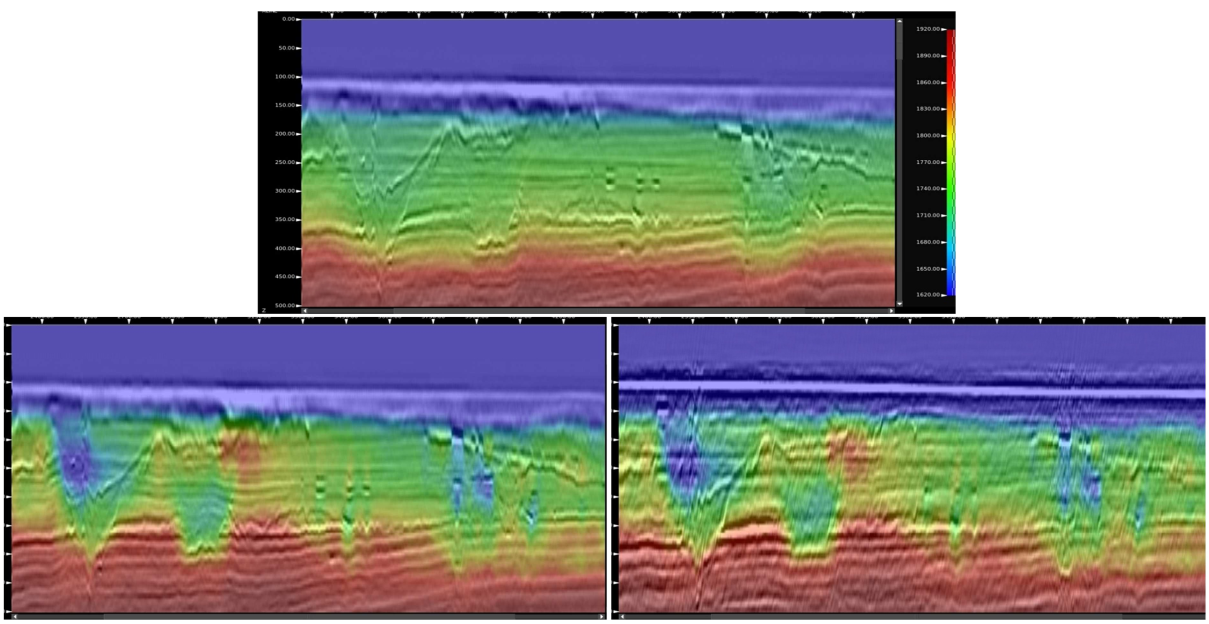

Figure 3: Inline example with velocity overlay. Top: Kirchhoff PSDM with tomography model. Bottom left: Kirchhoff PSDM with FWI model. Bottom right: Imaging of multiples with FWI model.

Conclusion

We have demonstrated a novel workflow for building highly accurate PSDM velocity models for a complex geological setting. By combining wavelet shift tomography, full waveform inversion (FWI) and separated wavefield imaging (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 wavefield separation that comes with it, 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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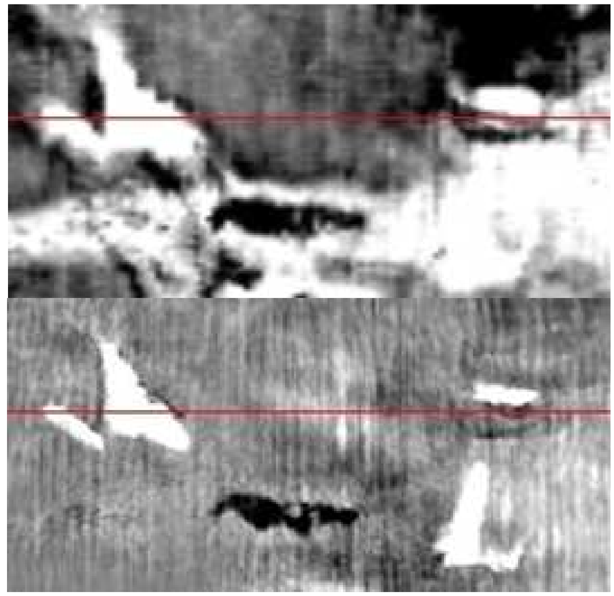

Figure 4: *Depth slice at 120m depth, Kirchhoff PSDM (top) vs imaging with multiples (bottom). Note how the spatial resolution in the bottom depth slice is much higher.*

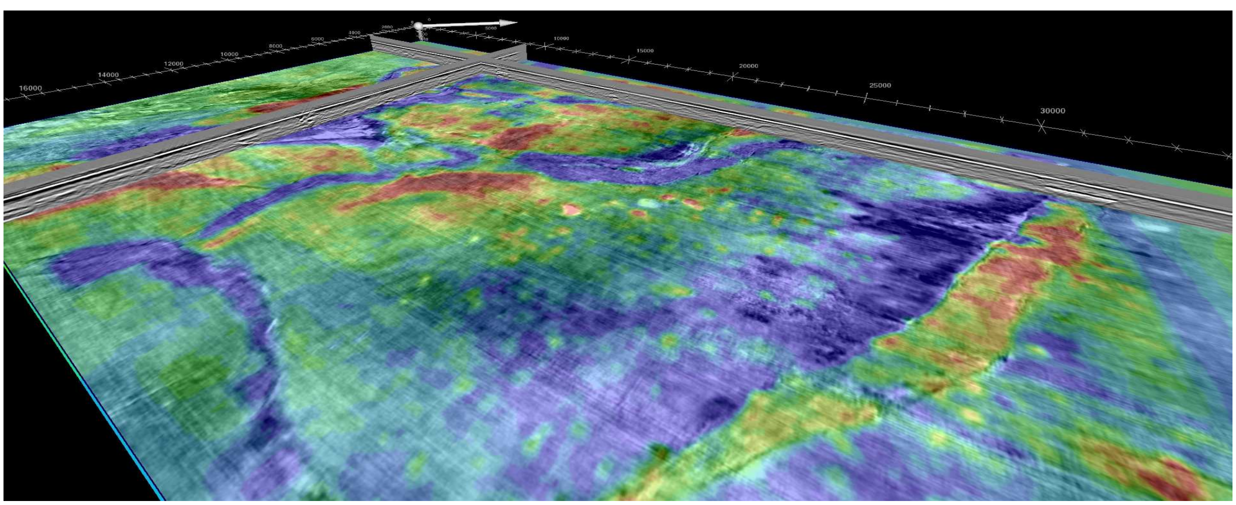

Figure 5: 3D view of SWIM with FWI velocity model overlay. Shallow channels, pockmarks, shallow gas and a relatively large shale plug can be observed.

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