High-fidelity complete wavefield velocity model building and imaging in shallow water environments – A North Sea case study

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Accurate sub-surface image reconstruction from pre-stack depth migration of surface seismic wavefields requires precise knowledge of the local propagation velocities between the recording location and the image location at depth. Such velocity information has traditionally been derived by tomographically inverting residual moveout information of common image gathers, which have been computed using an initial velocity field. This methodology proves to be challenging in shallow water environments, particularly when strong and rapid velocity variations in the very shallow overburden need to be recovered, while moveout information from reflected arrivals is very sparse or not available.

We present a new velocity-model building workflow that specifically addresses the challenges of computing accurate velocity information in areas of complex shallow overburden geology, utilizing the fact that dual-sensor towed streamer broadband technology provides direct access to various wavefield recordings as part of the deghosting procedure. Our workflow is comprised of three main elements: Wavelet Shift Tomography, Full Waveform Inversion (FWI) and Separated Wavefield Imaging (SWIM). The specific use of Wavelet Shift Tomography ensures a globally consistent initial velocity model as a starting point for FWI to avoid cycle skipping. Applying FWI to dual-sensor streamer data rich in low-frequency amplitudes is shown to improve the resolution and accuracy of the shallow velocity model, resulting in an overall more accurate model for imaging. The final step of the proposed workflow consists of computing SWIM angle gathers using information available from free surface multiple reflections that have illuminated the shallow overburden in a spatially far more extensive manner than is the case for primary reflections. This additional illumination is providing more reliable information about the quality and accuracy of the FWI velocity updates in the very shallow subsurface. Using SWIM gathers has proven to be crucial in ensuring that the final velocity model is globally consistent and suitable for producing accurate depth images from the shallow sea floor all the way down to deeper reservoir targets.

Methodology

The key to producing highly accurate velocity models in complex overburden geology lies in the way different algorithms are combined into a single workflow that mitigates any weakness that might exist in any one of the used methods. Several tomography-based strategies have been developed to invert seismic reflection data. Among them, ray-based post-migration grid tomography (Woodward et al., 2008) and stereotomography (Lambaré, 2008) are the most commonly used methods.

With the advent of highly efficient and very fast pre-stack depth migration algorithms based on beam migration formulations (Sherwood et al., 2008), the possibility of using the same wavelet attributes that are used in beam migration for tomographic velocity estimation and model building has been created. Rather than relying upon picked move-out information from gathers, the Wavelet Shift Tomography method relies on measured wavelet attributes which are generated by decomposing pre-processed data into wavelets and migrating these with a given velocity model into the depth domain. 3D residuals are subsequently tomographically back-projected as slowness updates to the initial velocity model (Sherwood et al., 2011). The velocity model produced with Wavelet Shift Tomography is well constrained, as the wavelet information used in the beam migration is also used to drive the tomographic updates, resulting in geologically-consistent velocity updates of high lateral resolution.

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The Wavelet Shift Tomography velocity model in the proposed workflow is used as the initial input to 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 tend to struggle. Sirgue et al., (2009 and 2010) successfully applied FWI to ocean-bottom cable (OBC) recordings on the North Sea Valhall field to identify shallow sand channel features, as well as gas pockets that significantly distorted the seismic image of underlying target reflectors.

Aided by the rich low frequency content in broadband dual-sensor towed streamer data, FWI has now become a viable option in the pursuit of more accurate estimation of velocity information from marine seismic data. The FWI implementation used here employed a modelling engine that is based on an efficient pseudo-analytic extrapolator ensuring the modelling 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, producing high-resolution velocity updates from the sea floor down to depths where the refracted energy diminishes.

It has become customary to check the flatness of pre-stack depth migration (PSDM) image gathers in order to quality control the FWI velocity updates, in addition to analyzing the match between recorded and modelled refraction data. However, in areas of shallow water depth, this proves to be challenging due to the poor angle illumination provided by the primary arrivals within the required angle mute zone. To overcome this issue, we have introduced SWIM into our model-building workflow.

SWIM is a breakthrough technology that uses the true wavefield separation platform from dual-sensor marine acquisition systems to image the earth with the spatially-extensive subsurface illumination provided by free surface multiples (Figure 1). SWIM effectively creates virtual sources at each and every receiver location in a marine seismic streamer spread, enabling significantly enhanced subsurface illumination from surface multiples to contribute to imaging (Whitmore et al., 2010). SWIM has advantages for improved image resolution (Lu et al., 2013), and effectively mitigates the ‘cross-line footprint’ effects typically observed in wide-tow marine 3D seismic data in areas of shallow water depth (Figure 2).

Whereas conventional depth imaging by one-way wavefield extrapolation is based on the assumption that recorded seismic data represents only the upward propagating primary reflected (scattered) wavefield, SWIM uses an adaptation of the simultaneous up/down imaging approach of primaries and multiples first introduced by Claerbout (1976) which is not restricted to calm sea conditions. The dual-sensor towed streamer system represents the ideal acquisition platform form providing the required up- and downward-propagating wavefield estimates. As a result of the complexity in the interaction of up- and downgoing waves, a deconvolution imaging condition is applied at the subsurface. This effectively reduces the cross-talk noise generated from unrelated correlation of the two wavefields. Angle gathers are generated from subsurface offset gathers after applying radial trace transforms.

A case study example from the North Sea

In 2009 the first 3D dual-sensor towed streamer survey in the North Sea was acquired over the Edvard Grieg, Johan Sverdrup and Luno fields in the southern part of the Utsira High in the Norwegian sector of the North Sea (Osnes et al., 2010).

The giant Johan Sverdrup discovery made by Lundin (Pl501 Operator) and partners Statoil and Maersk Oil in 2010 is one of the five-largest oil discoveries ever made on the Norwegian continental shelf (Figure 3). The discovery was made in well 16/2-6 located on the flank of the local Avaldsnes High on the south-eastern flank of the major Utsira High in the North Sea, followed by 30 appraisal wells including eight sidetracks in PL265, PL501 and PL502 (Blocks 16/2, 16/3 and 16/5).

The main reservoir at a depth of 1900 m is composed of the Upper Jurassic Draupne sandstone (informal unit)

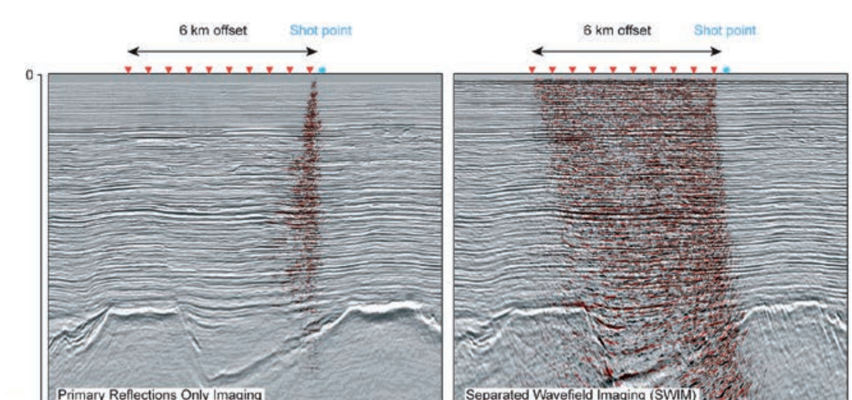

Figure 1 *Comparison of subsurface illumination from a single shot within 2D images using 6 km streamer length. In both images the grey-scale stacks are derived from shot profile migrations of all shots. On the left: amplitudes contributed by migrating the primary reflections from a single shot gather. On the right: amplitudes contributing by migrating all orders of surface multiples from the same individual shot gather using Separated Wavefield Imaging (SWIM). Note the profoundly greater spatial extent of illumination provided by subsurface multiples in comparison to primary reflections. The lateral extent of the illumination is limited only by the areal distribution of streamers associated with each shot.*

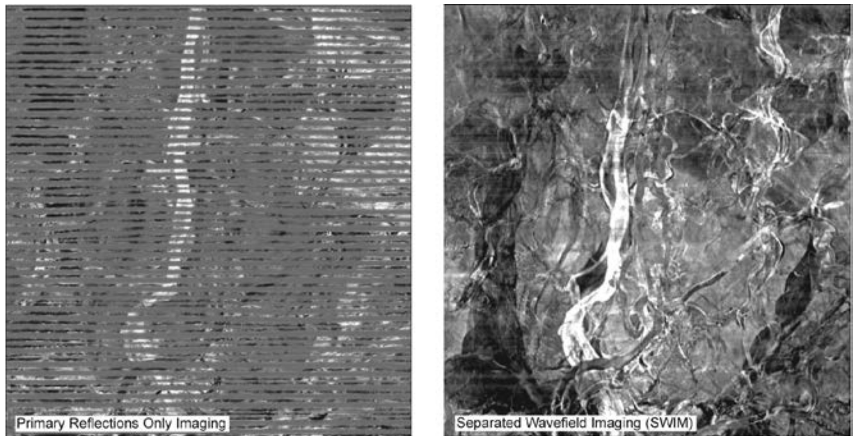

***Figure 2** Shallow subsurface image at a depth of 105 m in water depth of 70 m offshore Malaysia. The image on the left using primary reflection arrivals only shows a strong imprint of the sail line geometry, whereas the SWIM image on the right, using the additional illumination provided by all orders of free surface multiples, shows a seamless and complete image of the complex shallow channel system.*

dominated by coarse sandstones with average permeability in excess of 30 Darcies. The Avaldsnes High (informal structure) located to the east of the main Utsira High complex appears to play a key role in the distribution of the high-quality reservoir sandstones up to a distance of more than 10 km from the paleo-shoreline.

The field represents a very challenging area for pre-stack depth migration (PSDM). High-resolution imaging of the complex reservoir is complicated by signal penetration challenges through a thin overlying high-velocity chalk interval which complicates the delineation of the underlying reservoir sands. Highly accurate seismic-to-well depth ties are particularly critical given that reservoir thicknesses are generally estimated to be less than 50 m for large parts of the Johan Sverdrup discovery. However, highly heterogeneous near-surface velocity anomalies have historically made such pursuits unrealized. Collectively, improving reservoir delineation and solving depth conversion problems are essential to reducing the subsurface risk during the field appraisal stage.

A new pre-stack depth imaging project was correspondingly launched using the existing broadband dual-sensor towed streamer data with the objective to create a velocity model that would accurately account for small-scale heterogeneous near-surface velocity variations.

An existing legacy velocity model was used as the starting point to speed up the initial PSDM velocity model building process. However, due to the shallow water depth (85-115 m) in the survey area, conventional reflection tomography used on the legacy project had failed to produce a sufficiently accurate shallow overburden velocity model. To avoid possible cycle skipping issues in the later application of FWI, Wavelet Shift Tomography was used to improve the initial velocity model with particular focus on a more precise estimation of both velocities and the laterally-consistent anisotropy parameters in the shallow overburden. With these velocity updates in place, a much-improved match between modelled and observed refraction data was achieved ensuring that the subsequent FWI updates were able to resolve additional high-resolution velocity variations associated with channels, pockmarks and gas chimneys in the shallow overburden (Figure 4 and 7).

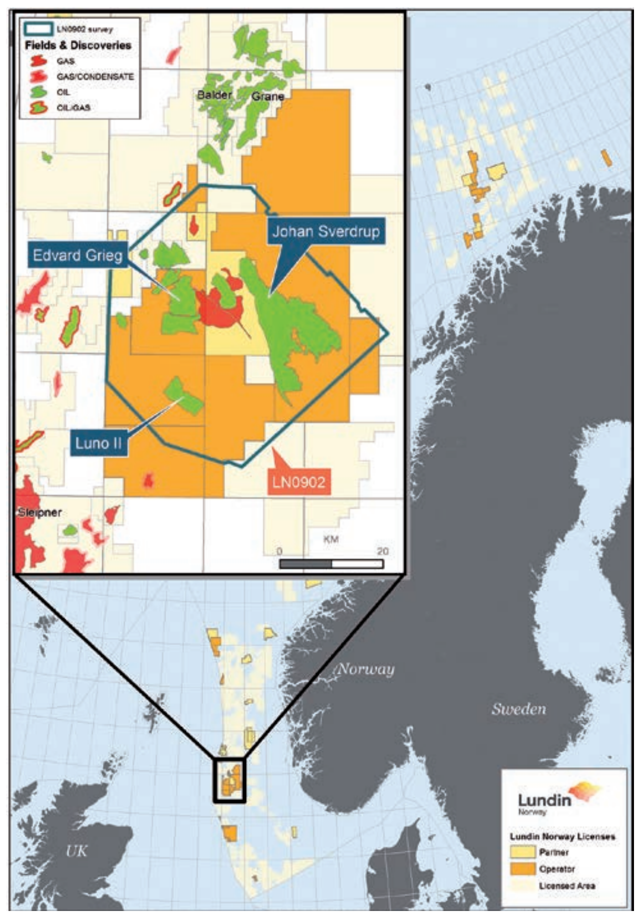

***Figure 3** The fields in the southern part of the Utsira High in the Norwegian sector of the North Sea. The extent of the 2009 LN0902 3D dual-sensor towed streamer survey used for this PSDM study is indicated by the blue polygon.*

Working in the image domain, SWIM angle gathers (Figure 5) were used to validate the longer wavelength

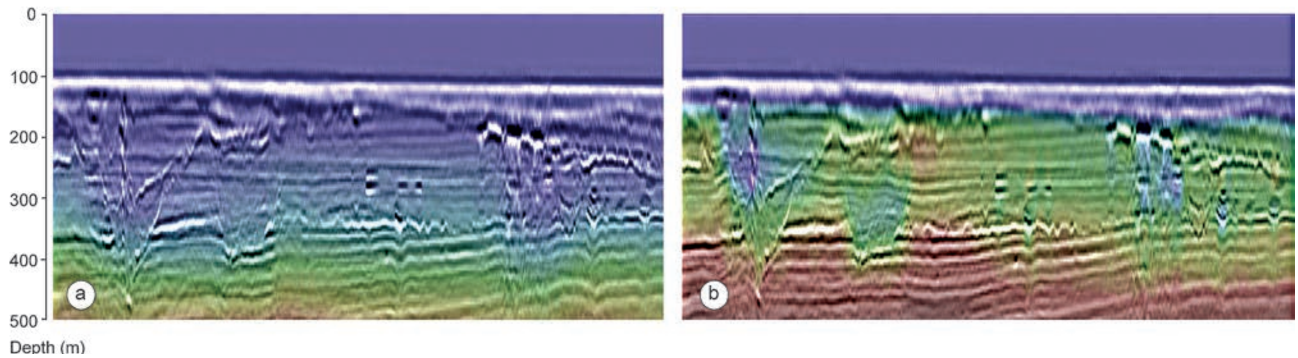

Figure 4 *a) Velocity depth model after Wavelet Shift Tomography with the Kirchhoff depth migrated image overlaid. b) Velocity depth model after application of FWI with corresponding Kirchhoff image overlaid.*

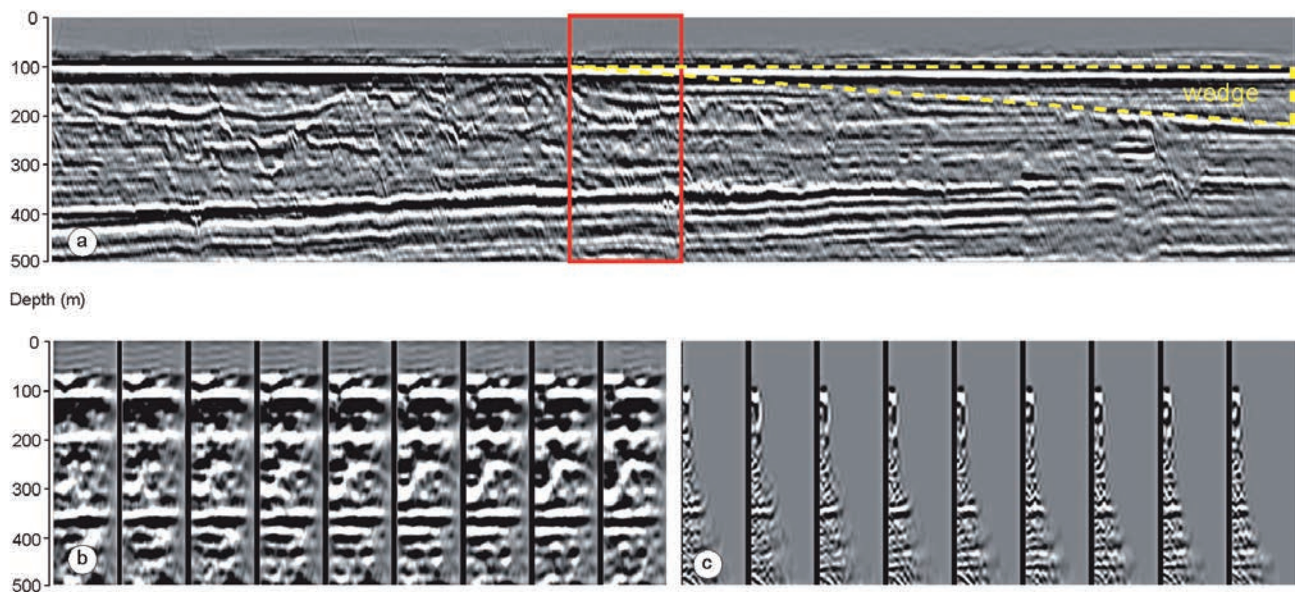

Figure 5 *a) SWIM image of shallow overburden. b) SWIM angle domain image gathers. c) Kirchhoff offset domain image gathers. Note the significantly extended lateral coverage provided by the SWIM image in the very shallow section of the subsurface image.*

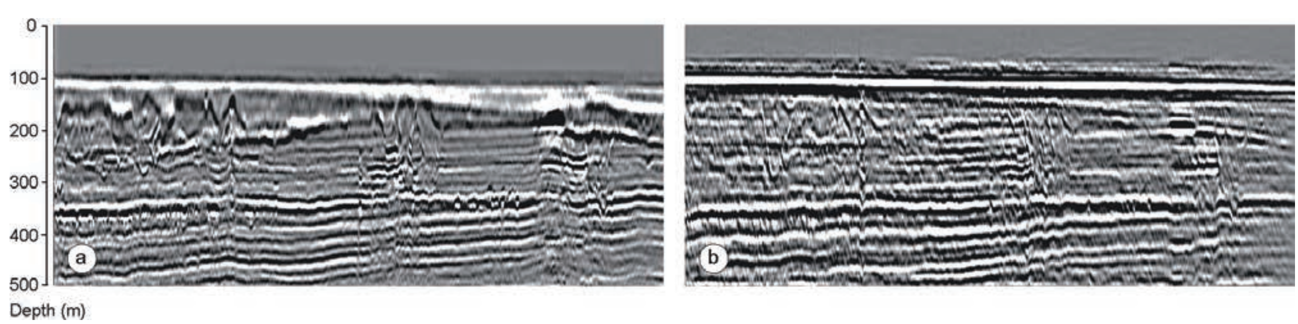

Figure 6 *a) Traditional Kirchhoff PSDM image of shallow overburden. b) SWIM depth image of the same shallow overburden section. Notice not only the image improvements in the top section of the image, but also the clearer image of the deeper regions due to the improved illumination and increased fold of the data.*

features of the updated velocity model that are not easily observed or quality controlled in the data domain using FWI. The additional illumination achieved by imaging both primary and multiple wavefields provided a significantly enhanced higher-resolution shallow overburden image (Figures 6 and 7).

This was of particular importance as a shallow wedge is covering large parts of the field (Figure 5). 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

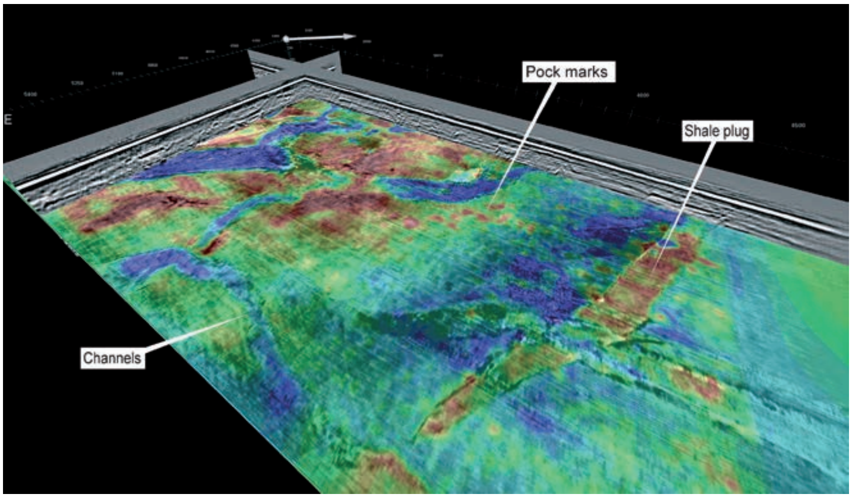

***Figure 7** 3D view of SWIM image at 250 m depth with FWI velocity model overlaid. Shallow channels, pockmarks, shallow gas and a relatively large shale plug can now be reliably identified.*

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 and the combined project objectives of improved reservoir delineation and seismic-to-well depth ties were thus achieved.

Conclusion

We have presented a novel workflow for building highly accurate PSDM velocity models in shallow water areas with complex overburden geology. We have been able to leverage our ability to use several components of the 'complete' seismic wavefield provided by dual-sensor towed streamer technology: raw hydrophone data for refraction-based full waveform inversion (FWI), up-going wavefield data from true wavefield separation for Wavelet Shift Tomography and down-going wavefield data for separated wavefield imaging (SWIM). By combining these three methods we have demonstrated that they are complementary to each other, and jointly ensure a much better understanding of the target sands at the reservoir level. Leveraging dual-sensor streamer technology and the true wavefield separation that comes with it, we used the up- and down-going wavefields in imaging and tomography to improve resolution and illumination. Further, we utilized the refracted, low-frequency energy for FWI. As the streamer is towed deep, we preserved 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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