

# High Fidelity Velocity Model Building, Imaging and Reflectivity Inversion – a Case Study Over the Viking Graben Area, Norwegian North Sea.

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## Summary

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A case study was carried out over the Viking Graben area with special focus on the Volund field, where a high fidelity velocity model was built to solve the complex velocity variations in the overburden resulting from a widespread presence of channels and numerous small-scale sand injectites. Significant improvements to the image quality were achieved with the use of the detailed velocity model and by incorporating a variable quality field to compensate for visco-elastic effects. Alternative imaging algorithms and reflectivity inversion techniques were explored to overcome limitations of the imaging system. This further improved the spatial resolution, enhanced the signal and helped the interpretation of the remobilized sand system over the Volund field.

## **Introduction**

It is well proven that an accurate velocity field is essential for successful depth imaging in complex geological settings. In addition, we know that conventional depth imaging techniques suffer from limitations of the imaging system.

In this paper, we present a case study from the Viking Graben in the Norwegian North Sea where we have applied advanced tomography techniques, explored different migration- and inversion methodologies to improve our understanding of the geology within a mature basin. Challenges in the seismic imaging include the relatively shallow water depth and the geologically complex near-surface section, which includes widespread presence of channels of varying scales. Historically, these channels have had a profound impact on the deeper seismic image quality when not sufficiently characterized and accounted for during pre-stack migration.

To address these challenges, a detailed velocity model was built with a set of complementary algorithms consisting of Full Waveform Inversion (FWI), wavelet shift tomography and automated detection of small scale geo-bodies. A 3D variable 'quality field' was built from the velocities and used in the pre-stack Q-Kirchhoff depth migration to compensate for local amplitude dimming and phase distortion related to gas accumulation in the sediments. Different imaging and inversion techniques were explored on a smaller area. The motivation was to search for alternative solutions that could improve the stratigraphic interpretation and mapping of sands within the Eocene section. Wave equation migration (WEM) and two different types of reflectivity inversion techniques; wave equation reflectivity inversion (WEI) and Least-squares Migration were compared to the Q-Kirchhoff pre-stack depth migration results.

The seismic data used in this study consists of several deep tow dual-sensor streamer acquisitions together with a few conventional surveys. In total, 11,000km<sup>2</sup> of data was reprocessed while the extensive migration- and inversion tests were focused over the Volund field, Norwegian Continental Shelf.

## **Methodology**

A novel gradient-based FWI algorithm was employed for this study which uses both reflected and transmitted waves. This is achieved by introducing dynamic weights in the velocity sensitivity kernel derived from impedance and velocity parameterization of the classical objective function. The kernel implementation effectively eliminates the migration isochrones produced by the specular reflections and enhances the low wavenumber components in the gradient in heterogeneous media (Ramos-Martinez et al., 2016). This FWI implementation provides reliable velocity updates free of high wavenumber artifacts and the imprint from reflectivity when both reflections and refractions are included in the data-window for the inversion process. The shallowest section of the velocity model, down to 1km depth, was updated using FWI.

Below this depth, the velocities were updated with wavelet shift tomography (Sherwood et al., 2008). Rather than relying on picked move-out curves from gathers, this method relies on measured wavelet attributes. 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).

In this part of the North Sea, we observe numerous small-scale sand injectites. They often stand out as bright amplitude events and frequently represent high-velocity anomalies that might cause false structure and poor focusing on the events below if they are not accounted for in the migration process. Due to their small size and steep dip, they are difficult to pick up with traditional tomographic methods. In this study, we mapped these anomalies with a variance attribute and formed a mask to constrain the updates at these locations.

Amplitude and phase distortions are best corrected for during pre-stack migration as it correctly accounts for the actual ray paths of the reflected signals and thus honors the 3D nature of the wavefield propagation (Valenciano and Chemingui, 2012). Initial migration results indicated remaining dimming and distortion below the slow velocity channels, even though the focusing was much improved with the use of the very detailed velocity model. These effects were assumed to be related to Q-anomalies caused by small amounts of gas in the channels. Postulating a correlation between the low velocity channels and low quality factor, the FWI model was used to build a 3D 'quality field' that captured the correct geometry of the Q-anomalies.

From the 11.000km<sup>2</sup> Q-Kirchhoff pre-stack depth migration results, a smaller area over the Volund field was selected for testing alternative imaging solutions. Firstly, one-way wave equation migration (WEM) was performed to evaluate the potential for reducing migration noise. Secondly, two different types of reflectivity inversions were performed to improve the spatial resolution of the image and to reduce false amplitude effects, related to uneven illumination caused by irregular acquisition geometry or shadow zones from velocity boundaries. Wave equation reflectivity inversion (WEI) is an image domain approach where the Hessian of the cost function is explicitly computed at discrete locations in the model space with Point Spread Functions (PSF). The cost function describes the difference between observed and synthetic shot points. The PSF measures the blurring effect of the imaging system, and with direct access to this information, we can correct the migrated image and get closer to true reflectivity (Valenciano et al., 2006). This can also be described as a 3D deconvolution process. An alternative method to correct for wavefield distortions caused by acquisition and propagation effects is Least-squares Migration, which implicitly solves the Hessian in the data-domain. This consists of an iterative approach of migration and de-migration until the data-residuals are sufficiently reduced (Lu et al., 2017). Both approaches assume that the velocity is known and both will modify the migrated image to represent the true reflectivity.

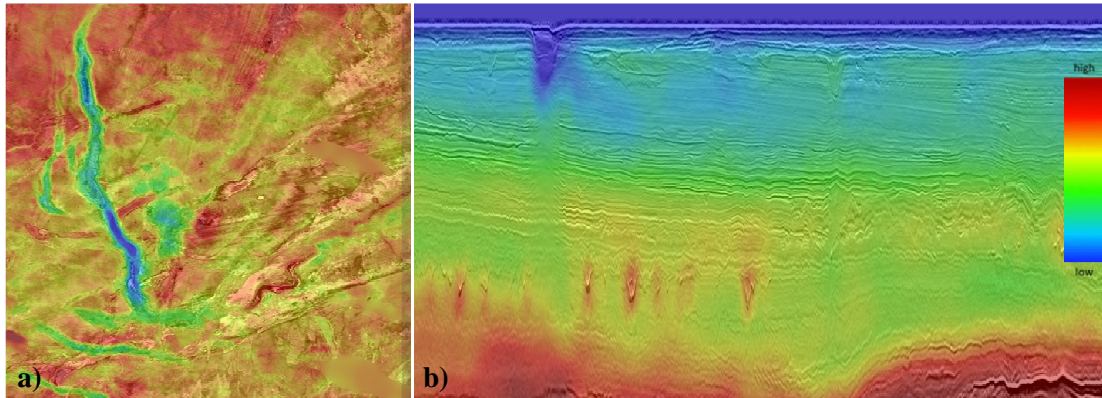
### **Field data example from Viking Graben, North Sea**

The FWI started with a simple 1-D global velocity trend over the entire 11.000km<sup>2</sup> dataset, with some interpretation guided velocity corrections around the largest channel features to avoid cycle-skipping. As the velocity model improved and produced a better match between real and modelled shots, higher frequencies were progressively included in the subsequent FWI iterations. The ultra-low frequency available in the data enabled the first iterations to start at 2Hz, whilst the final iterations were performed using frequencies up to 12Hz. Below 1km depth, the mid- and low wavenumbers in the model were inverted for with wavelet shift tomography before the high wavenumber sand injectites were included in the Eocene Hordaland Group. A pragmatic solution was first to scale up the velocities by 20% within the detected geo-bodies, followed by a constrained tomography to further adjust the velocities. This significantly reduced the false pull-up effects and improved the focusing of deeper events. Figure 1 shows the fine details of the final velocity model and the correlation to the seismic image.

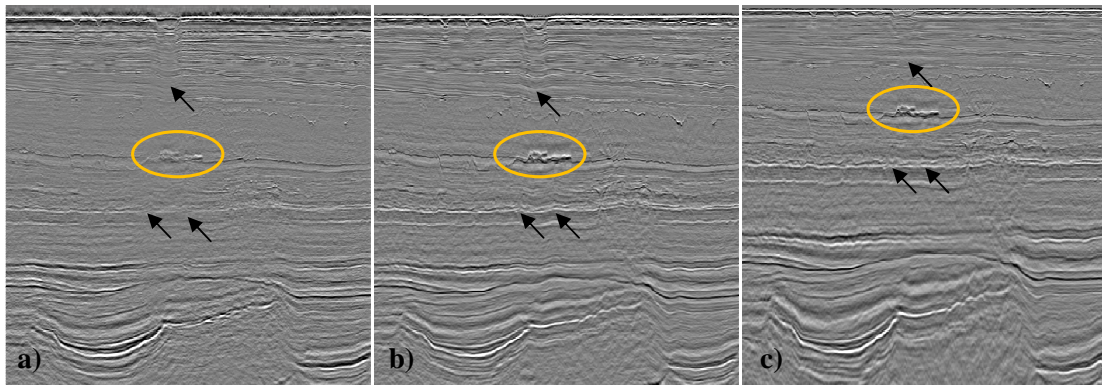
From this velocity model a 3D variable 'quality field' was generated. The FWI model had mapped the geometry of these channels, and migration scans were performed until a reasonable Q-value (inside the channel) had healed the dimming and distortion on the events below. Figure 2 shows a comparison of the vintage data and the new results that incorporates the improvements to the velocity field and the Q-corrections.

The Volund field is affected by several imaging challenges that we wanted to investigate further with alternative imaging algorithms. The entire field is composed of a large-scale sand injection complex in the Early Eocene section, characterized by stacked sandstone sills and steeply dipping dykes. It is located at around 2km depth and close to one of the largest shallow channels in the area. The aim was to improve on the general noise level compared to a Q-Kirchhoff depth migration and to improve the spatial resolution to better map the extension of the sand system. As expected, one-way wave equation migration (WEM) performed better than Q-Kirchhoff pre-stack imaging using the detailed velocity

model with small scale velocity anomalies and high velocity contrasts at the Chalk interface. It is clear that the sand system is enhanced and can be tracked with more confidence and further into the surrounding sediments on the dual-azimuth WEM image. The dual-azimuth WEI reflectivity inversion adds further resolution and fine detail to the image due to the increase in spatial resolution from the 3D deconvolution process. Figure 3 shows a comparison of the Q-Kirchhoff pre-stack depth migration, dual-azimuth WEM and dual-azimuth WEI. When comparing the single-azimuth WEM to the single-azimuth Least-squares Migration, we observe a significant reduction in the acquisition footprint caused by the uneven acquisition geometry (see figure 4).



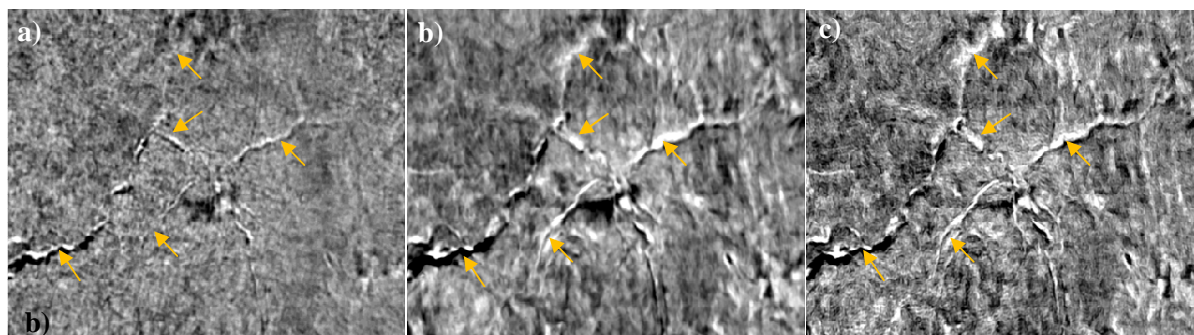
**Figure 1** Depth slice at 265 meters and inline section of the velocity model overlaid on the migrated image. The model contains a high level of details and shows good correlation with observable geological structure.



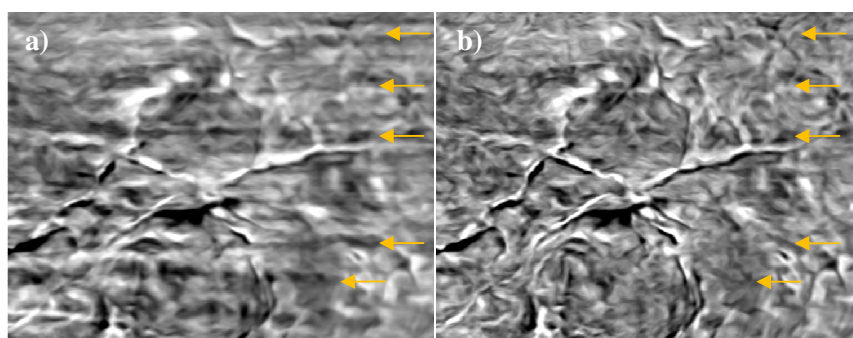
**Figure 2** Pre-stack time migration, vintage data (a) Pre-stack depth migration in time domain (b) and depth domain (c). The new velocity model produces a better focused image in time domain and pull-down and pull-up artefacts are successfully corrected in the final depth domain image (indicated by arrows). The ellipse points at the Volund field, where we see significant improvements in imaging by solving the shallow velocities and incorporating the Q-corrections.

## Conclusions

We observe significant uplift in the image quality by combining advanced velocity model building and visco-elastic PSDM compared to vintage PSTM. Furthermore, we see benefits of wave equation migration algorithms for signal enhancement and migration noise reduction in the presence of larger velocity variations. We also evaluate two methods for reflectivity inversions, both of which improve the spatial resolution compared to the wave equation migration. The Least-squares Migration method particularly well attenuates uneven illumination artefacts related to inadequate acquisition design. The new imaging technologies applied add value by mapping out possible reservoir sands not seen with previous imaging efforts.



**Figure 3** Depth slice over the Volund field with  $Q$ -Kirchhoff pre-stack depth migration (a), dual-azimuth one way wave equation migration (b), dual-azimuth wave equation reflectivity inversion (c). The sand system (highlighted with arrows) is enhanced on the WEM image compared to the Kirchhoff results and further resolution is added with WEI.



**Figure 4** Depth slice over the Volund field with single-azimuth one-way wave equation (a) and single azimuth Least-squares Migration (b). Acquisition footprints area clearly suppressed with Least-squares Migration as highlighted by the arrows.

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