Setting new standards for regional understanding – mega-scale broadband PSDM in the North Sea

Steve Hollingworth[1], Owen Pape[1], Chris Purcell[1], Ewa Kaszycka[1], Trevor Baker[1], John Cowley[1], Gregor Duval[1*] and Luke Twigger[1] describe how PSDM technologies have been applied to more than 35,000 km^2 in the North Sea to generate a contiguous high-quality broadband dataset.

Recovering the remaining and bypassed hydrocarbons in mature areas requires well-informed decision-making supported by good data. A great deal of seismic exploration has taken place within the North Sea, using a variety of acquisition configurations including the latest broadband solutions. Most surveys in this mature area have been processed and reprocessed multiple times as techniques have evolved and, every so often, significant advances in technology warrant the application of these new approaches in a wholesale way.

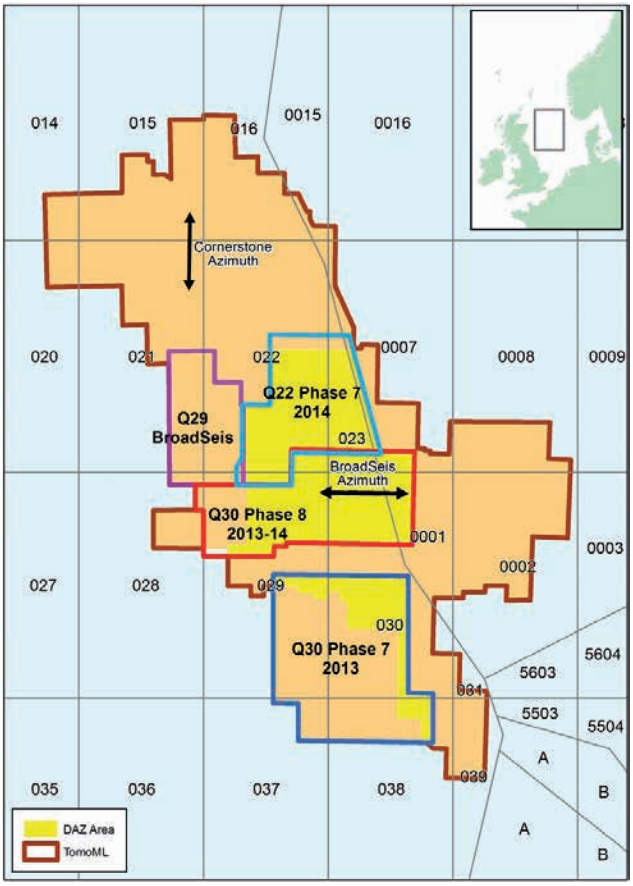

***Figure 1** The project covered an area in excess of 35,000 km^2 straddling the border between the UK and Norway in the Central North Sea and incorporates 37 phases of acquisition.*

The Central North Sea (CNS) still contains many opportunities and is notoriously challenging to image with seismic. Fuelled by the need for greater accuracy of deep imaging and structural interpretation, for both prospect discovery and field development, there has been a steady increase in the number of pre-stack depth migration (PSDM) projects. The majority of these projects have focused on small areas, primarily restricted by the high work effort involved in integrating all available data (wells, horizons, vertical seismic profiles, etc.) into the velocity model, combined with the lengthy timescales required to update the model using traditional, interpretation-heavy workflows and tomography methods.

Recent advances in multi-layer tomography (Guillaume et al., 2012) now allow us to complete complex PSDM projects within a significantly reduced timescale while at the same time achieving improved image quality. In addition, advances in deghosting and demultiple processing technologies have enabled us to extract even more value from vintage conventional flat-towed streamer datasets. We describe how these technologies have been applied to integrate 37 acquisition phases covering more than 35,000 km^2 in the CNS to generate a unique and contiguous high-quality broadband PSDM dataset which sets new standards for regional datasets in mature basins.

Input seismic

The project incorporated seismic data acquired across ten quadrants of the UK and Norwegian Central North Sea, from UKCS Quad 38 in the south to UKCS Quad 15 in the north (Figure 1). The total seismic coverage exceeded 35,000 km^2, making it one of the largest PSDM projects ever undertaken. Some 9000 km^2 of the area benefits from dual-azimuth coverage where broadband seismic data has been

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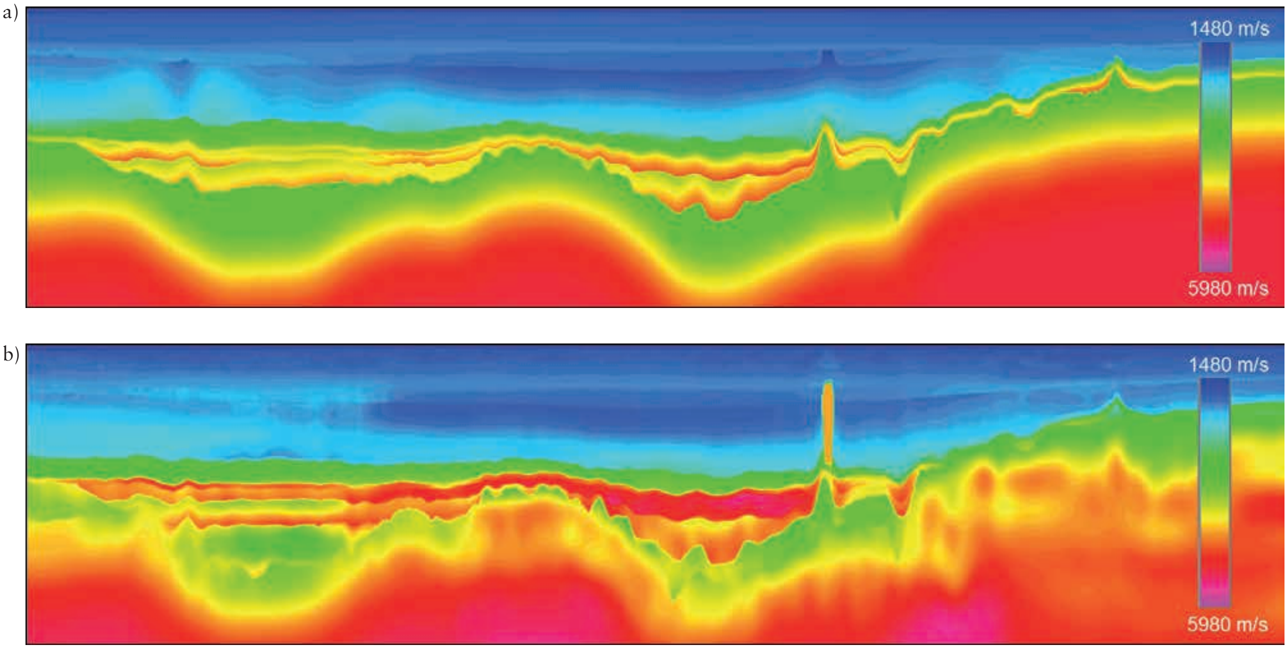

***Figure 2** a) Data from 225 wells were used to construct an initial velocity model with smooth spatial characteristics. b) The final velocity model created by multi-layer tomography combines regional consistency with local detail.*

acquired orthogonally to the underlying legacy survey. The majority of the surveys were conventional narrow-azimuth towed-streamer acquisition. However, two of the more recent surveys were acquired using the BroadSeis variable-depth streamer broadband solution, with a 6-50 m streamer profile (Soubaras, 2010).

The main focus of the project was PSDM imaging. The central high-pressure high-temperature (HPHT) area benefited from dual-azimuth coverage. This provided enhanced illumination of the complex structures beneath the Base Cretaceous Unconformity (BCU), thus obtaining optimal imaging due to more accurate velocity and anisotropy estimates.

For the majority of the conventional surveys, archived pre-processed data was used, with shot and receiver τ-p deconvolution for short-period multiple suppression. The two broadband datasets utilised the latest multiple modelling techniques for shallow water demultiple (Wang et al., 2011). Additional residual peg-leg multiple suppression was applied to the conventional data in selected areas.

A further objective of the processing was to improve the seismic resolution by extending the seismic bandwidth. Deghosting of both conventional and variable depth streamer datasets was undertaken using ghost wavefield elimination (GWE) in the τ-p domain (Wang et al., 2013; Poole et al., 2013).

Initial model

The North Sea exhibits a complex layered geology with abrupt changes in acoustic impedance that have strong correlation with major changes in velocity observed in well logs. The majority of these key reflection boundaries have an excellent spatial interpretability. This facilitates the construction of a layer-based initial model which can be matched to the geology at the outset. For this study, a total of nine regional horizons were interpreted over the whole model area to allow clear sub-division of the major geologic units.

Data from 225 wells were used to construct an initial model with smooth spatial distributions of velocity and gradient (Figure 2a). A 1D anisotropy analysis was performed at a number of wells to derive a spatially smooth anisotropy model with the TTI axis perpendicular to the horizon structure.

Multi-layer tomography

Velocity updating was performed using multi-layer non-linear slope tomography (Guillaume et al., 2012). Multi-layer tomography utilises a hybrid model format which uniquely defines the velocity and anisotropy parameters for each model layer as a mesh while also carrying the precise information for the layer boundaries as horizons. The non-linear inversion performs a kinematic de-migration and re-migration of both the residual move out (RMO) picks and the layer boundaries, thereby negating the need for a layer stripping workflow. For this project two passes of multi-layer tomography were required to optimise the velocities for final imaging, where a typical North Sea layer stripping workflow would require seven passes of tomography, PSDM and interpretation.

Each pass also incorporated dip-constrained inversion (Guillaume et al., 2013) which performs a 3D joint inversion of RMO and offset-dependent dip picks, to estimate shallow velocity variations often associated with channel features. This is important in the North Sea environment as these shallow velocity variations distort the deeper image with pull-up and push-down effects if not accounted for, making interpretation of subtle stratigraphic features uncertain.

The first pass of velocity tomography utilised PSDM data generated with Dix inverted pre-stack time migration (PSTM) velocities, calibrated to the well using a basic VTI anisotropy function. PSTM velocities were utilised at this early stage since they were known to produce a robust image and gathers with coherent events which could be used for RMO picking.

The RMO picks, local dip estimates and horizons were kinematically de-migrated using the migration velocities to create a set of surface invariants (so-called as they are independent of any velocity model) and then re-migrated using the initial well-based model to obtain the location and dip of the migrated facets, the local derivative in offset of the RMO (dRMO) and the horizon interfaces. The multi-layer tomography updated the entire depth range of the model from 0 to 10 km with shallow channels handled by the dip constraint. Conservative tomography parameters were used to ensure a robust long wavelength solution for the entire area, rather than over-fitting local data.

For residual well calibration, a series of depth horizons were generated for each model layer which matched the well check shots and varied smoothly between wells. Multi-layer tomography was again used to minimise the misfit between model horizons and check shot data from the wells by applying a ray-traced spatially-varying scalar. The Thomsen δ anisotropy parameter was adjusted to preserve the imaging velocity and the Thomsen ε parameter was updated to preserve η.

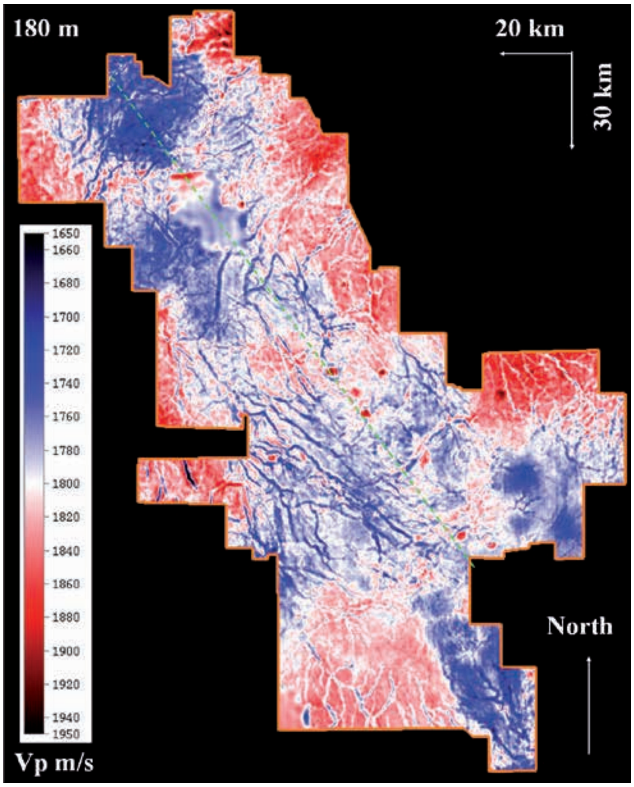

Figure 3 *Depth slice through the Quaternary where glacial channels leave a detailed imprint in the shallow velocity structure, which can disrupt the image of deeper formations.*

The second pass of velocity tomography broadly followed the workflow outlined in the first pass but incorporated the

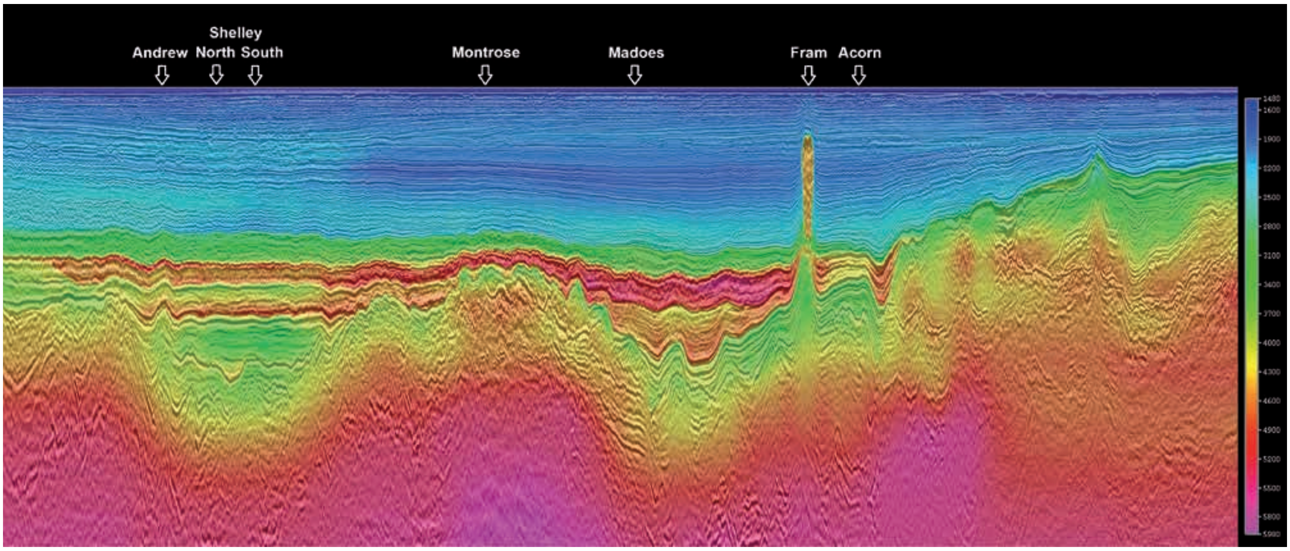

Figure 4 *Random line oriented North-West South-East across the dataset intersecting several fields. The final velocity model is co-rendered with the PSDM data, highlighting both geologically consistent regional trends along with local detail and definition.*

finalised pre-processed dataset with GWE and sub-BCU demultiple applied. The enhancement of the low frequencies by GWE aided deeper RMO picking as reflector continuity and gather coherency were improved. Image gathers for RMO picking were generated using the velocity model output from pass one to benefit from the improved imaging, but the multi-layer tomography exploited the power of non-linear inversion by continuing to use the initial smooth well model as the starting point for the update. This helped to ensure a stable final result by avoiding use of inconsistent or unrealistic velocities introduced due to any sub-optimal imaging during the first pass.

Useable information from the updated anisotropy parameters from pass one were retained to enable the velocity update to achieve an improved well tie. Final multi-layer well calibration achieved an absolute average depth mis-tie of less than 2% for all horizons without introducing distortions into the model velocities or seismic image. This is a great achievement for a project of this size.

Challenges

Handling a project of this size and complexity presented the processing team with a series of logistical and technical challenges. The 37 acquisition phases spanned a 15-year period of acquisition, so achieving a good signal-to-noise ratio and a robust dataset merge were essential for final imaging. The application of GWE to older conventional acquisition phases highlighted the need for additional denoise steps to be incorporated in order to stabilise the bandwidth extension. Frequency matching between the conventional and BroadSeis broadband acquisitions was challenging due to the lack of recorded lows in the older conventional seismic and the excellent low-frequency content of the broadband data down to 2 Hz. In addition, to avoid the need to image the conventional and variable tow seismic from different streamer depths, all datasets were re-datumed to mean sea level during GWE.

Model building challenges were more logistical since multi-layer tomography was designed from the outset to efficiently handle the technical challenges presented by North Sea geology. The main logistical challenges overcome by the team centred on two areas of quality control: efficient QC of velocity profiles from automated well analysis during the initial model construction phase; and qualitative analysis and selection of the RMO picks input to each pass of tomography.

Results

The final model reveals geologically-consistent regional trends in the velocities (Figure 2b) with excellent stability and a good correlation with the seismic image. A velocity depth slice through the Quaternary glacial channels (Figure 3) reveals high-frequency details which are well correlated with the complex channel structure and show consistent velocity trends extending over many kilometres.

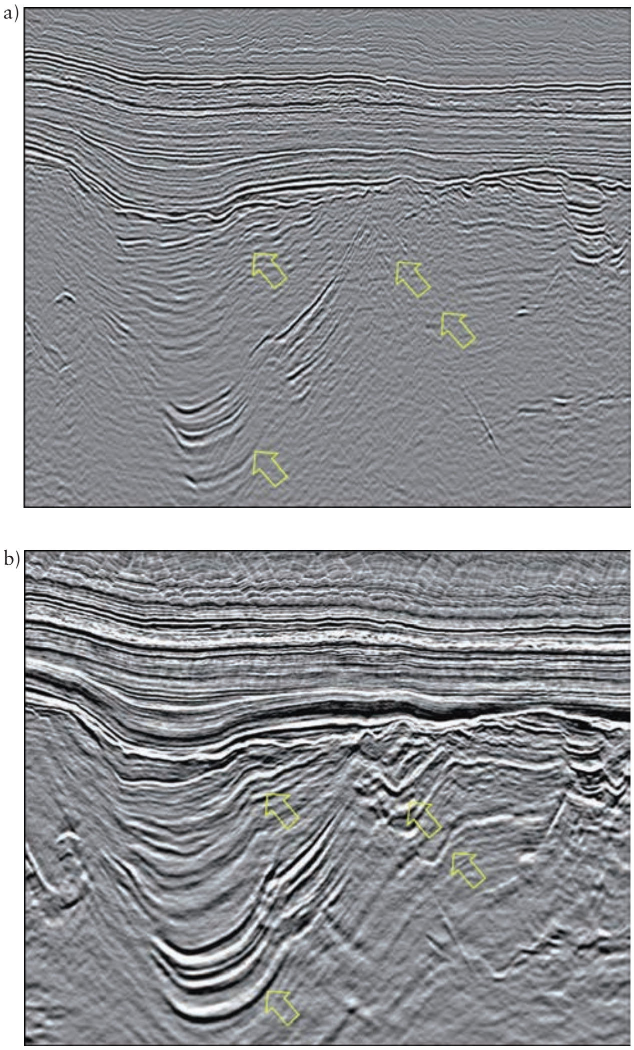

Figure 5 *a) This narrow-bandwidth vintage PSTM result is typical of the previous generation of seismic images in the CNS and is contaminated by residual multiple. b) The latest PSDM result benefiting from dual-azimuth coverage, new broadband acquisition and the new depth imaging workflow provides greatly improved images of the structures below the BCU.*

The upper Cretaceous chalk interval also presents many challenges for achieving stable velocities with reflection tomography. Complex thin layers, large vertical velocity contrasts and the reduced offset range of reflection events within high-velocity layers all make inversion difficult. Despite these challenges, multi-layer tomography was successful in producing a spatially stable velocity field with regional trends which were geologically consistent. Analysis of the regional velocity profile (Figure 4) shows how these trends retain their geologic consistency over a distance of 250 km and how they relate to the main basin features, fields and discoveries along the arbitrary line, such as Andrew, Montrose, Madoes and Fram. This

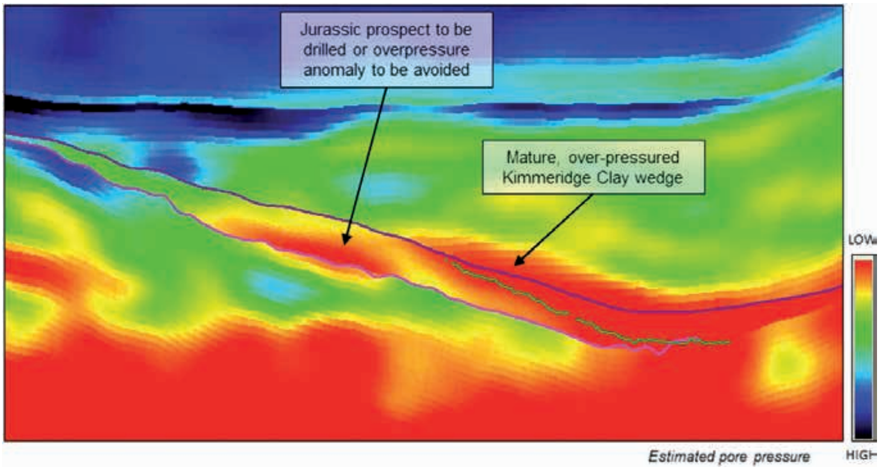

***Figure 6** Example of pore pressure prediction section from seismic velocities in the Central North Sea.*

geological consistency is also observed in the deeper section below the BCU where conventional methods often fail to deliver spatially stable results due to poor or sparse RMO information.

In addition to geologically consistent regional trends the final model also retains fine details that we would expect to achieve with smaller, reservoir-focused PSDM projects. The stable velocities improved the imaging of the pre-Cretaceous section, which was further enhanced by the bandwidth extension from GWE. Comparison of final stack images highlights the clear benefits of the latest dataset (Figure 5).

The benefits of stable velocity coverage over such a large area extend beyond improvements to the seismic images themselves. Products derived from seismic and seismic velocities, such as 'quick-look' regional seismic AVO attributes and pore pressure predictions (Figure 6) provide a way to rapidly spot areas of interest and flag them for more detailed investigation.

Conclusion

We have demonstrated how the latest advances in processing technology can breathe new life into vintage data. Despite covering 35,000 km^2 with a consistent and unique dataset, quality has not been compromised. In particular, multi-layer tomography and shallow channel modelling have been used to successfully generate a mega-scale PSDM dataset in the Central North Sea with geologically consistent regional trends. We have also shown that this regional model retains the resolution and accurate well ties we have come to expect from smaller field-focused PSDM projects but with a greater degree of stability and geological plausibility. This 'simpler' regional model, when combined with ghost wavefield elimination, yields significantly improved seismic images of the pre-Cretaceous, leading to an improved understanding of Jurassic and older reservoirs in the area.

As new and improved technologies become available, continued evolution and refinement of data and models enable operators within a mature basin, such as the North Sea, to maximise hydrocarbon recovery. The creation of this PSDM super-dataset sets a new quality standard in North Sea seismic. This will enable reliable identification and exploitation of any remaining opportunities within this mature area.

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