Increasing resolution in the North Sea

Phil Hayes[1]*, Luke Twigger[1], Krzysztof Ubik[1], Thomas Latter[1], Chris Purcell[1], Bingmu Xiao[1] and Andrew Ratcliffe[1] explore improvements in resolution that have been demonstrated on two multi-client surveys in the North Sea.

Introduction

Recent step changes in seismic processing and imaging technology have delivered dramatic improvements in resolution, velocity model building and multiple attenuation. This article will explore improvements in resolution that have been demonstrated on two multi-client surveys in the North Sea: Cornerstone and Northern Viking Graben (NVG). Extending full-waveform inversion (FWI) to include absorption effects as well as velocity has delivered improved imaging, higher resolution and more reliable AVO products for the NVG survey, and this will now be applied to the reprocessed Cornerstone data. Both surveys cover more than 35,000 km^2 each, so application of high-resolution processing sequences to these two data sets will deliver advanced high-resolution data over two large areas of the North Sea.

The NVG survey was acquired using BroadSeis variable-depth streamers in conjunction with a broadband source to maximize the bandwidth. However, new developments in broadband processing, including ghost wavefield elimination (GWE) and bandwidth extension, can be extended to the reprocessing of conventionally-acquired data sets, which can now be uplifted to deliver data of almost similar quality to modern broadband data by mitigating many of the limitations of traditional acquisition. This is demonstrated by the reprocessing of the Cornerstone project in the Central North Sea. Although this survey was recently reprocessed in depth using multi-layer tomography, the rapid improvements in GWE, multiple and noise attenuation, velocity modelling and imaging in the last few years mean that it can still benefit from being reprocessed again.

Modern processing techniques ensure compliance with amplitude versus offset (AVO) analysis, and AVO attributes are used for QC purposes during the processing flow to ensure that the final data sets can be used directly for reservoir characterization. The AVO attribute maps for Cornerstone shown later in this article have already delivered impressive high-resolution images of the Forties field.

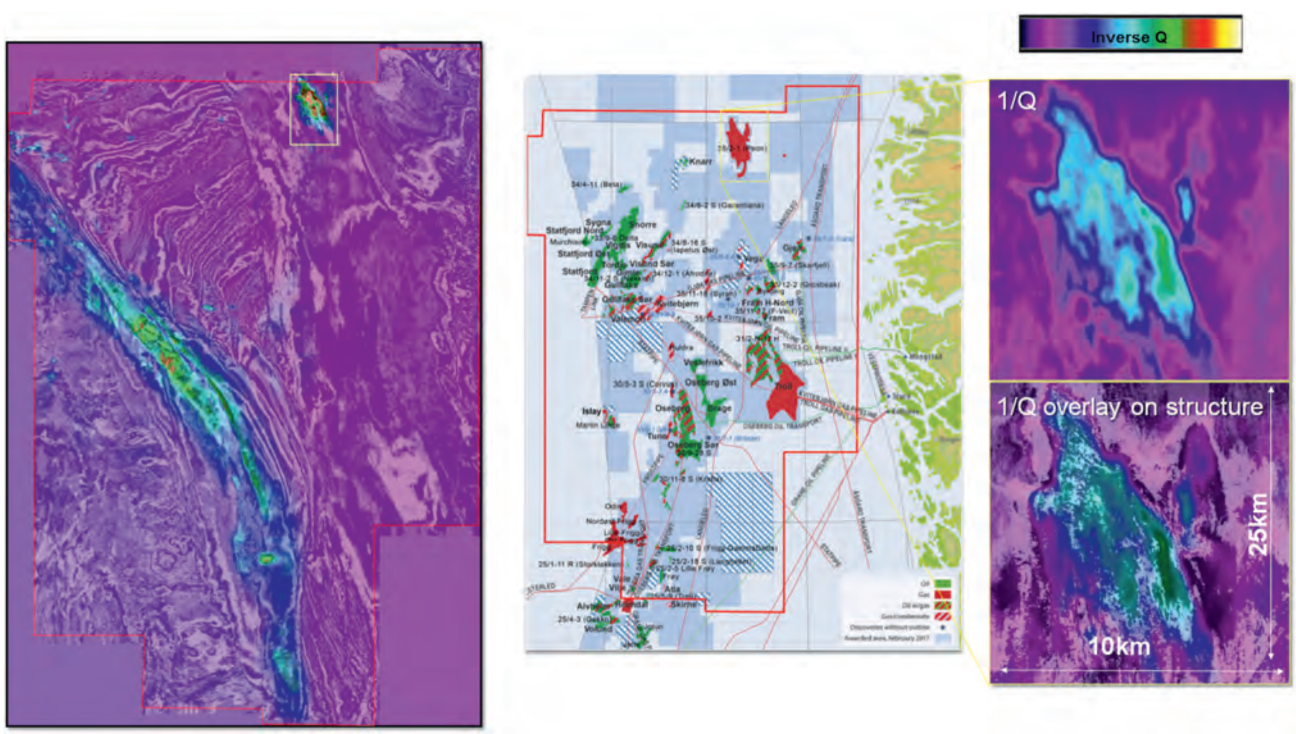

Figure 1 Depth slice over the entire 35,400 km^2 Northern Viking Graben multi-client survey with Q overlay derived from Q-FWI and zoom over the Peon gas field. Q-FWI clearly defines the edges of the gas fields and other anomalies in the region, providing regional coverage with local detail (Xiao et al., 2018)..

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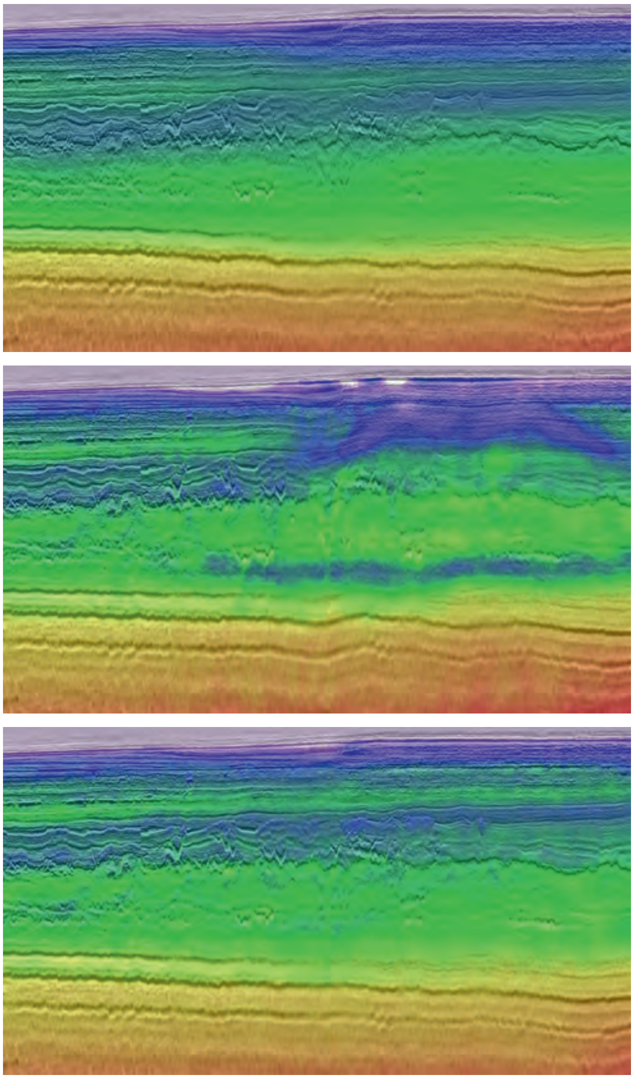

Figure 2 This example from the Northern Viking Graben compares the input velocity model (top), conventional FWI velocity result (middle) and Q-FWI velocity result (bottom). This clearly shows that the inclusion of near-surface Q anomalies in the FWI has a significant impact and improves the resulting velocity model and image, especially the deeper events below the anomaly.

Northern Viking Graben

The Norwegian North Sea is a mature hydrocarbon province, with major oil and gas fields such as Troll, Oseberg, Gullfaks, Snorre and Statfjord having been in production for decades. However, recent discoveries such as Johan Sverdrup show that there are still discoveries to be made in this area. Previous exploration in this area focused mainly on the Jurassic sandstones, along with the chalk reservoirs in the Ekofisk field, and Paleogene sand reservoirs of the Frigg field (Mann-Kalil, 2015). More recently, particularly after the discovery of the Cara oilfield, attention has been directed towards the Cretaceous sands, whose hydrocarbon potential was demonstrated more than 30 years ago with the Agat discoveries.

Deposition of Cretaceous reservoir sediments in the North Sea was strongly influenced by the basin topography created by Jurassic rifting. The availability of new high-resolution broadband data allows a more accurate approach to the mapping of petroleum systems and understanding new play models. Potential reservoir sandstones within the Cretaceous are much easier to identify and the risk of mapping isolated sand bodies is reduced. The Agat field is made up of two complex small discoveries in stratigraphically trapped sandstones, but the extent of these is difficult to map with conventional seismic data. Modern reservoir characterization techniques are also a significant tool for exploration in these areas.

This area contains many areas of gas leakage, which cause both velocity anomalies and areas of amplitude dimming owing to the absorption effect of the gas. In some cases, these areas are large enough to become gas fields such as Peon, while, in others, they are just small pockets which represent a shallow hazard to drilling. In all cases, it is desirable to both identify these areas and incorporate them into the model building so that they can be properly accounted for. Amplitude dimming caused by absorption anomalies is a serious impediment to accurate AVO analysis and therefore requires compensation. Q-FWI, where FWI is used to invert jointly for visco-acoustic (Q) phase and amplitude effects alongside velocity, is an important new tool for identifying these anomalies. Figure 1 shows the results of the Q-FWI-derived Q field over the entire 35,000 km^2 Northern Viking Graben survey

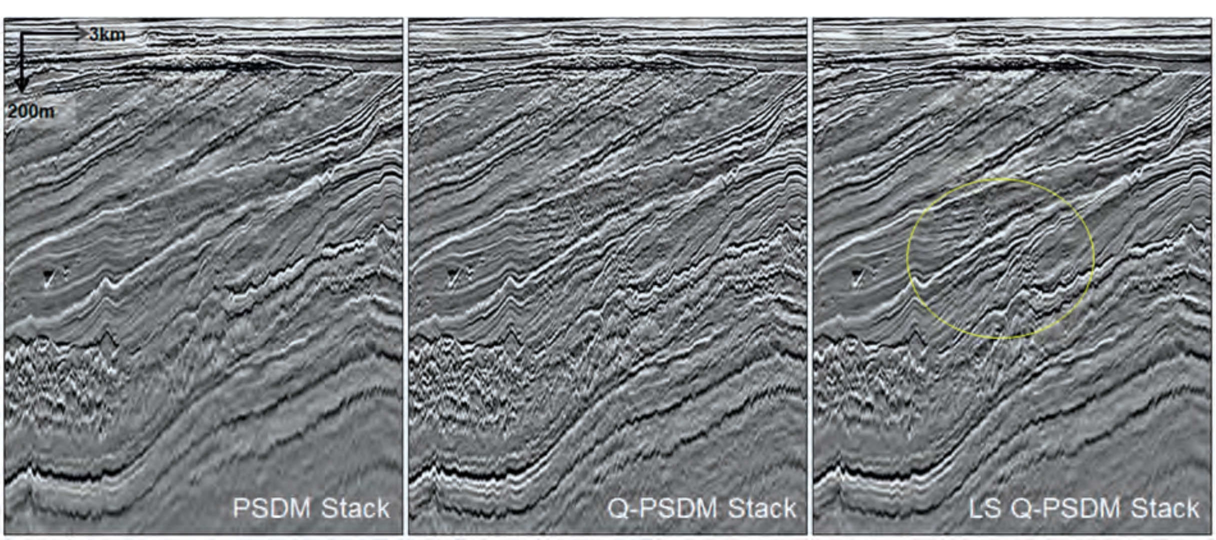

Figure 3 Comparison of data below the Peon gas field, showing the improved resolution and amplitudes achieved by Q-PSDM, but at the expense of boosting noise. LS Q-PSDM retains the resolution and amplitude enhancements without the additional noise.

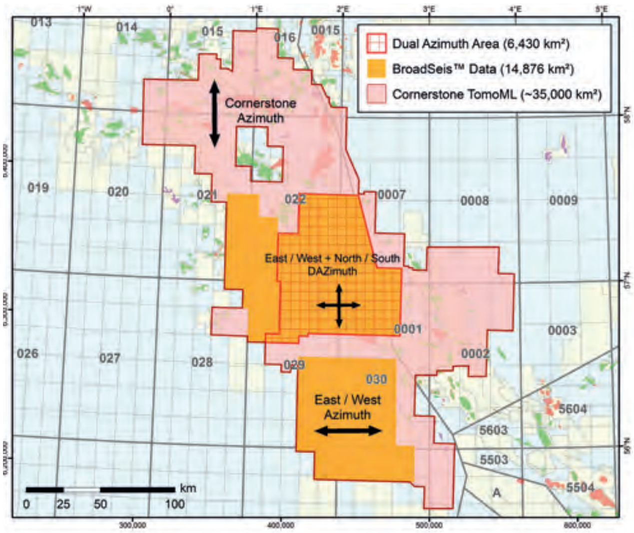

Figure 4 Map showing the location of the Cornerstone survey.

area. The high degree of spatial resolution achieved honours the structural boundaries and, notably, captures strength changes within the anomalies. Previous methods of deriving a Q model, such as Q-tomography, inherently struggle in the near-surface, where energy becomes post-critical at very short offsets. Q-FWI was successful over all gas bodies of varying sizes and scales, from field size to small-scale point gas features, as well as the different overburden in the Norwegian trench, the major NW-SE feature crossing the survey.

The inclusion of Q in the FWI helps to mitigate erroneous velocities being derived from FWI owing to cross talk between the Q and velocity attributes. Figure 2 shows the improvement in the velocity model, and hence the avoidance of artificial pull-ups and push-downs, obtained by correctly accounting for Q. The result shows good conformance with the seismic structure and geology.

Inclusion of Q in the migration algorithm successfully corrected local phase dispersion and amplitude loss below these anomalies, but also caused some increase in the noise level beneath these anomalies. However, when least-squares Q prestack depth migration (LS-Q PSDM) was applied these problems were mitigated, with amplitude compensation and resolution enhancement achieved without boosting noise levels (Latter et al., 2018). Figure 3 shows that, not only are the main reflectors more coherent, but finer-scale events were imaged as well. So far, LS Q-PSDM has only been applied to targeted areas of the NVG survey, but where it has been applied, significant uplifts in continuity and resolution below shallow gas anomalies have been observed.

Cornerstone evolution reprocessing

The Central North Sea has many of the same features as the Northern Viking Graben, although, in addition, it contains some salt features and, farther to the south, a high-pressure, high-temperature (HPHT) area. However, the prospective intervals are similar, with hydrocarbons encountered within the Upper Jurassic sandstones, Cretaceous chalks and Lower Tertiary submarine fan systems. Due to the maturity of the basin, advances in technology have continuously allowed new play models to be explored and new discoveries to be made, many from upgrading the seismic data available.

The Cornerstone data set comprises a selection of surveys which represent a range of different vintages of seismic acquisition technology, and combine to form a contiguous area of 35,000 km^2 (Figure 4). Some of these surveys were acquired with conventional source and streamer configurations, while others used a broadband variable-depth streamer acquisition design (Soubaras, 2010). The most recent surveys were acquired in an east-west direction, orthogonal to, and in places overlying, the conventional data, enabling the use of dual-azimuth processing and imaging in these areas.

Wavelet processing

One of the key limitations of legacy seismic processing is the limited bandwidth of the data. Source and receiver ghost energy naturally limits the bandwidth; generally producing a peak at around 30 Hz. Removal of the ghosts yields a sharper broadband wavelet and has the effect of reducing sidelobe energy. The resulting wavelet makes the data easier to interpret and improves the resolution of small-scale features such as fault planes and thin beds that, at legacy bandwidth, would be masked by sidelobe interference, making events difficult to identify and interpret.

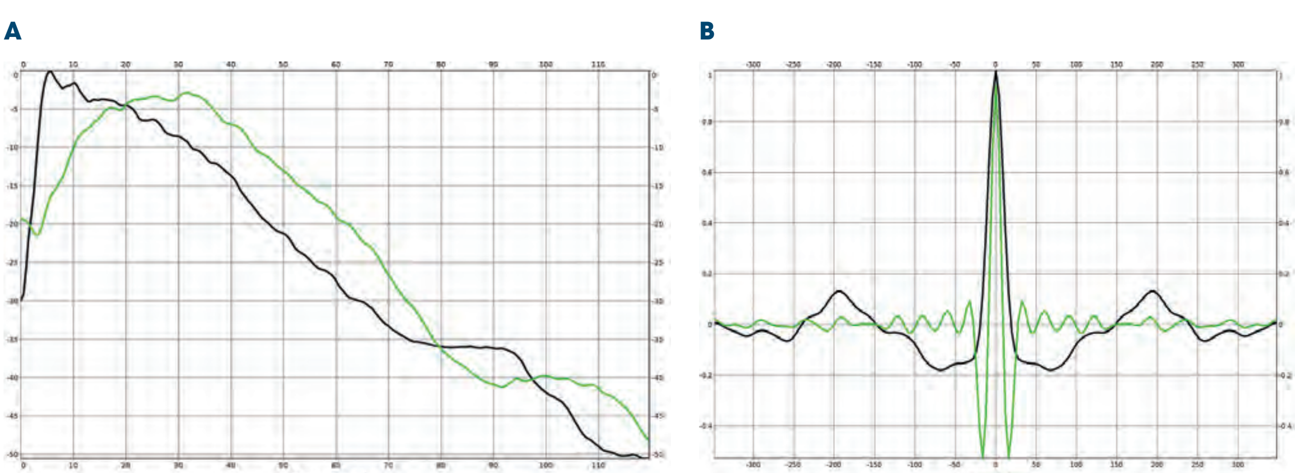

Figure 5 (a) Amplitude spectra of legacy (green) and reprocessed (black) seismic data show the shift in peak frequency to around 5 Hz, which leads to clear improvements in any inversion-derived products. (b) Wavelet extraction from legacy and reprocessed data shows that the reprocessed volume contains a much sharper wavelet with reduced sidelobe energy, which in turn produces a clearer and more focused seismic image.

Although the previous reprocessing of the Cornerstone data included an early form of GWE and bandwidth extension, these techniques have evolved rapidly since then. By starting from the original field data and applying the latest designature and deghosting techniques, significantly improved wavelets were obtained in the current reprocessing.

Near-field hydrophone (NFH) recordings are generated in marine acquisition in order to QC the energy source. Recently acquired surveys use these shot-by-shot measurements to improve estimation of the source response, and so improve debubbling and zero phasing (Ziolkowski et al., 1982). In much of the work on Cornerstone, these operators were used to generate a global wavelet for each survey, as the quality of the NFH recordings was variable and not suitable for shot-by-shot use. For more recent acquisitions, where the NFH recordings are more reliable and designed for use in designature and deghosting, shot-by-shot 3D designature was applied.

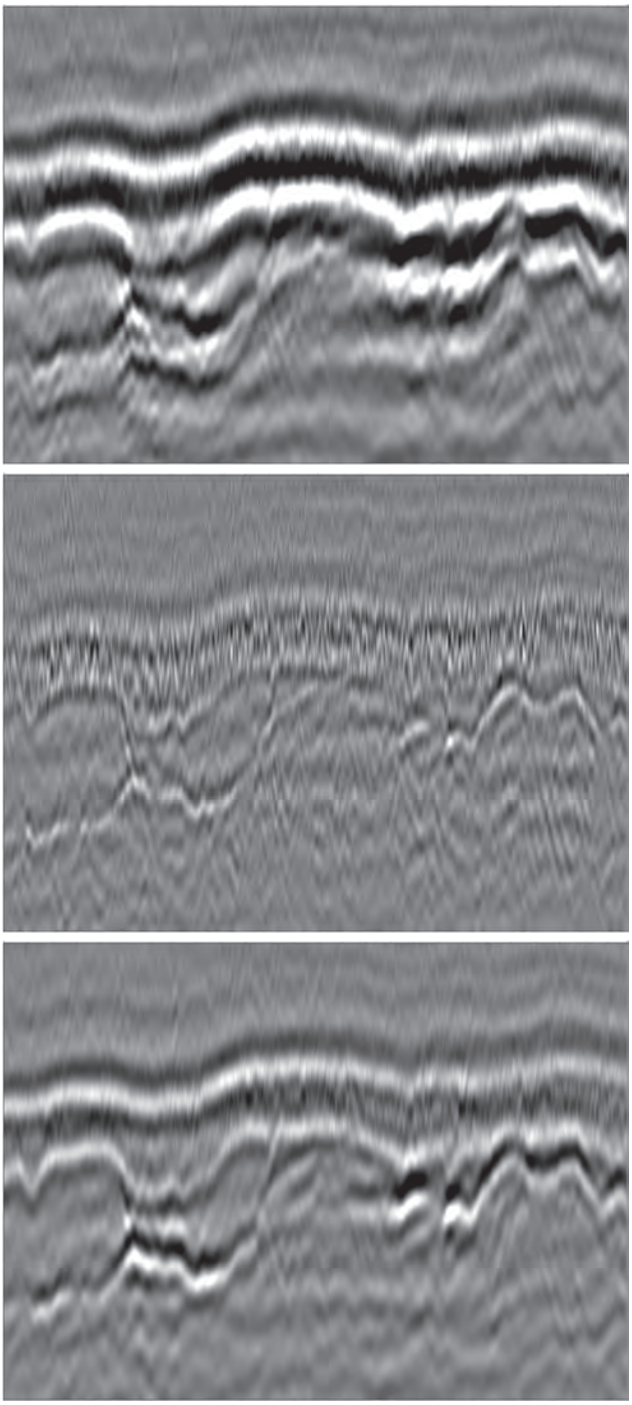

Figure 6 PSDM full-offset stack: 2-8 Hz filter panels comparing legacy with pre-demultiple (top), legacy demultiple (middle) and reprocessing result (bottom) showing the damage to the lowest frequencies in the legacy processing, while the reprocessing delivers a clear improvement in the continuity and clarity of the data.

The amplitude spectra and wavelets shown in Figure 5 compare legacy and reprocessed data. The constructive interference of the source and receiver ghost wavefields creates a 6 dB boost, to produce a peak frequency of 30 Hz which is not a true property of the Earth (Poole, 2013). Removal of the ghosts and recovery of the low frequencies move the peak frequency to 5 Hz. The linear decay observed is a result of the attenuation of higher frequencies caused by the Earth's absorption (Q) that can be compensated with Q migration, as in the NVG survey. The diagnostic wavelets extracted from the reprocessed data show a significant reduction in sidelobe energy and increased low-frequency character compared to the legacy data. Analysis of phase and timing shifts between the reprocessed seismic data and the available well data in the area indicated that a good match was achieved after the new designature and deghosting, with an overall mean phase difference of less than 10° across the survey area.

Multiple attenuation

Water-layer generated multiples are a known problem in the Central North Sea. These tend to have a periodicity of around 100 ms and obscure the primary reflections. Historically, data sets in this area were typically processed using a shot and receiver pass of Tau-P domain gap deconvolution to attenuate these short-period multiples. However, this long-established demultiple technique has recently been shown to harm primary reflections which may have a similar period to the targeted multiples, especially at low frequencies (see Figure 6).

A key improvement resulting from the reprocessing was the removal of the use of predictive deconvolution techniques and the employment instead of model- and inversion-based techniques such as model-based water-layer demultiple (MWD). In shallow water settings, with water depths of around 100 m and shallower, the 3D Surface-Related Multiple Elimination (3D SRME) approach cannot be reliably applied, owing to the fact that the limited near offsets do not provide the sufficiently reliable recording of the seabed reflection needed to produce a good-quality model. Other techniques, such as model-based water-layer demultiple, are therefore required for the short-period multiples, followed by a 3D SRME technique for the longer-period multiples.

3D recursive model-based water-layer demultiple (MWD)

In recent years, methods for MWD, in both 2D and 3D, have been developed (Wang et al., 2011). MWD uses a Green's function of the water bottom convolved with the recorded seismic data in order to produce a multiple model. This means that the quality of the model is not as dependent on the recording of the seabed and requires less adaption to the input seismic.

We used a 3D recursive implementation of MWD which correctly predicts the amplitude of the water bottom peg-leg

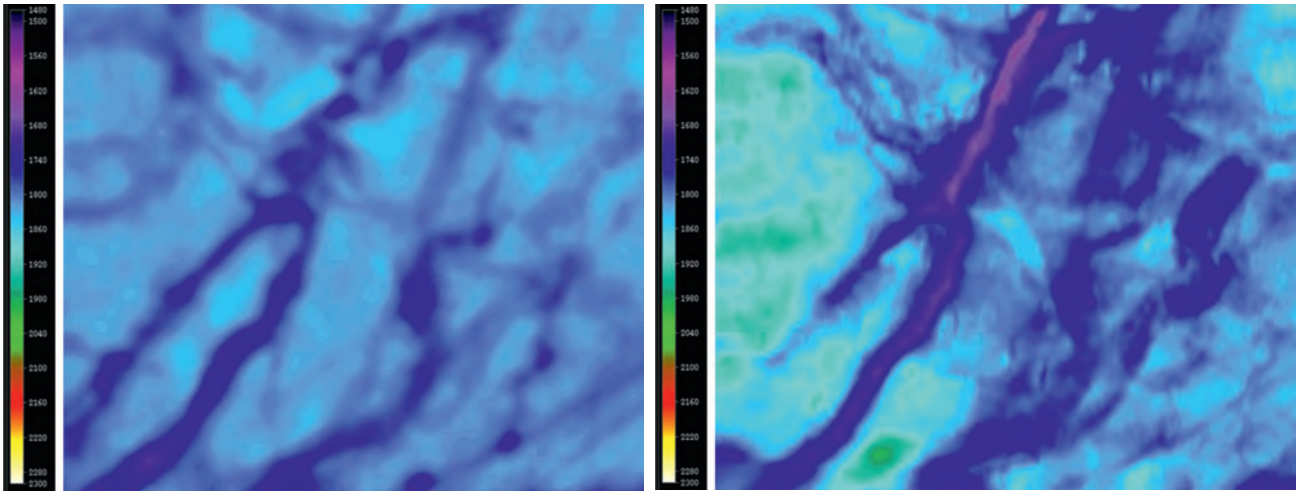

Figure 7 200 m depth slice through the input legacy velocity model (left) and FWI velocity model (right), which shows the significant uplift in definition and clarity achieved by FWI.

multiples, whose amplitudes are not fully resolved when using a non-recursive method (Cooper et al., 2015). This resulted in a water-layer multiple model which was so accurate in the low frequencies (<12 Hz) that it required minimal adaption to the input data set, and even in the remaining bandwidth required only a small amount of time and phase adaption to safely remove the water-layer generated multiples.

Wave-equation deconvolution

Wave-equation deconvolution is an emerging data-driven short-period demultiple technology based on the principles of Pica et al. (2005). The approach uses least-squares inversion to derive an image of the multiple generators that are responsible for generating upgoing multiples, using the downgoing wavefield. The resulting image is used to predict multiples, which are then subtracted from the input data. As well as addressing water-bottom multiples, the approach is proving effective at attenuating short-period peg-leg multiples relating to reflectors in the shallow section. By their very nature, the kinematics of short-period multiples can be strongly out of the 2D plane. This approach therefore uses a multi-sail line 3D implementation to complement the MWD solution. This technique has been applied in addition to the MWD, and both models were jointly subtracted from the input seismic.

Any remaining longer-period surface-related multiple events that had not been addressed by the earlier demultiple methods were modelled and adaptively subtracted using 3D SRME (Verschuur et al., 1992).

An example of combined demultiple results on a 2-8 Hz filter panel is shown in Figure 6 (bottom) compared to the legacy and the input data. The legacy image (middle) shows a lack of continuity in events caused primarily by the predictive deconvolution. The bottom image from the latest reprocessing does not suffer from this issue.

Velocity model building: full-waveform inversion

One of the many reasons for reprocessing the Cornerstone survey was to use the more inversion-based velocity model updating techniques now commercially available. In earlier work, the main tool used for velocity model construction and updating was multi-layer non-linear slope tomography (Guillaume et al., 2012), combined with calibration of available well data.

The key improvement required from the new model-building was to clarify the near surface and associated anomalies. These cannot be successfully resolved by tomographic-based solutions, since in shallow water areas, conventionally acquired towed-streamer data does not record a sufficient offset range at shallow horizons to be able to pick the residual moveout (RMO) required for a tomography-based update. Any inaccuracies in the shallow section cause imaging distortion in deeper structures.

For the reprocessing, the initial model was based on legacy models and available well data from across the survey area. In order to handle the adverse effects of glacial channels present in the quaternary section, the legacy processing used a dip-constrained tomographic approach based on limited RMO picking combined with tomographic inversion (Guillaume et al., 2012; Guillaume et al., 2013). For approximately the first 2000 m of the subsurface, FWI was used in the model-building of the reprocessing. This uses recorded and modelled waveforms to derive a high-resolution (compared to a standard tomography-based update) velocity model of the near surface, which typically has enough detail to be used for shallow hazard identification. FWI does not rely on any assumptions regarding structure or any requirement for RMO picks and is therefore a much more effective and reliable tool. The source wavelet and the initial velocity model are two key requirements for a successful FWI update. Figure 7 shows examples of a depth slice at 200 m through the velocity model with and without the application of the FWI update, this shows a good correlation of the velocity anomalies with the seismic structure. Work is continuing to extend the inversion to include Q.

Amplitude versus offset (AVO) and reservoir QC

The use of a reservoir-focused processing and imaging flow has contributed to a significant uplift in overall image quality, reliable reservoir properties and quantitative interpretation (QI) attributes, confirmed by reservoir-focused QC products at intermediate stages throughout the processing sequence.

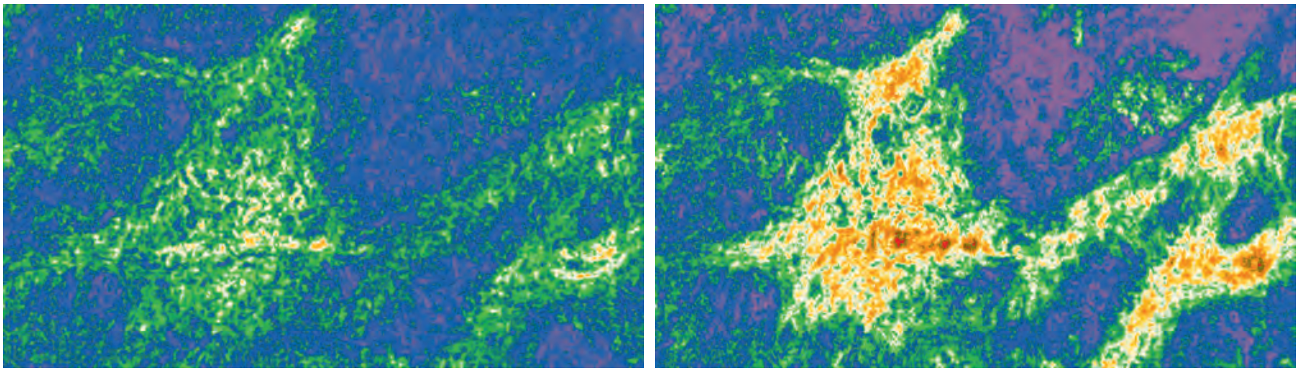

Figure 8 Amplitude extraction through far-offset stacks: Legacy (left) and reprocessing (right) showing the improved clarity of the field outline compared to the legacy processing.

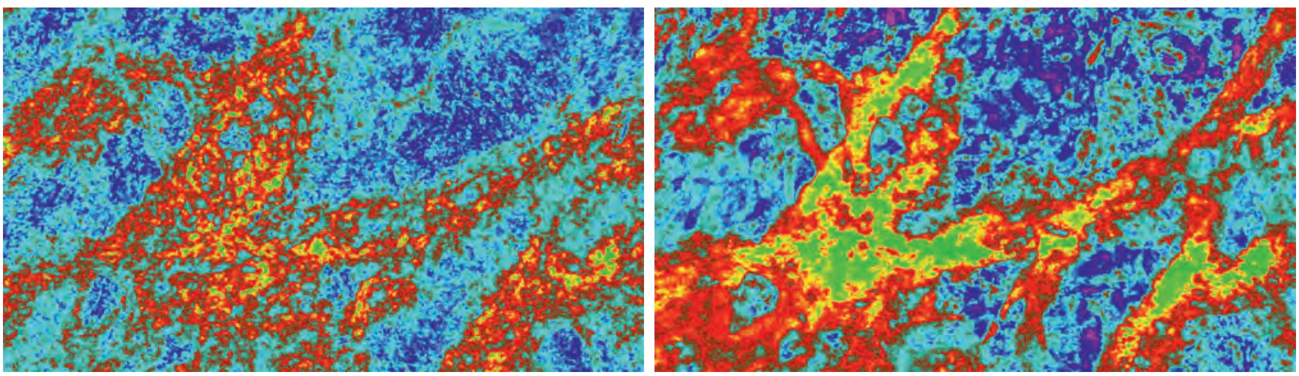

Figure 9 VP/VS ratio: Legacy (left) and reprocessing (right). The reprocessing shows a clear step-change improvement in the definition of lithology compared to the legacy processing around the Forties formation.

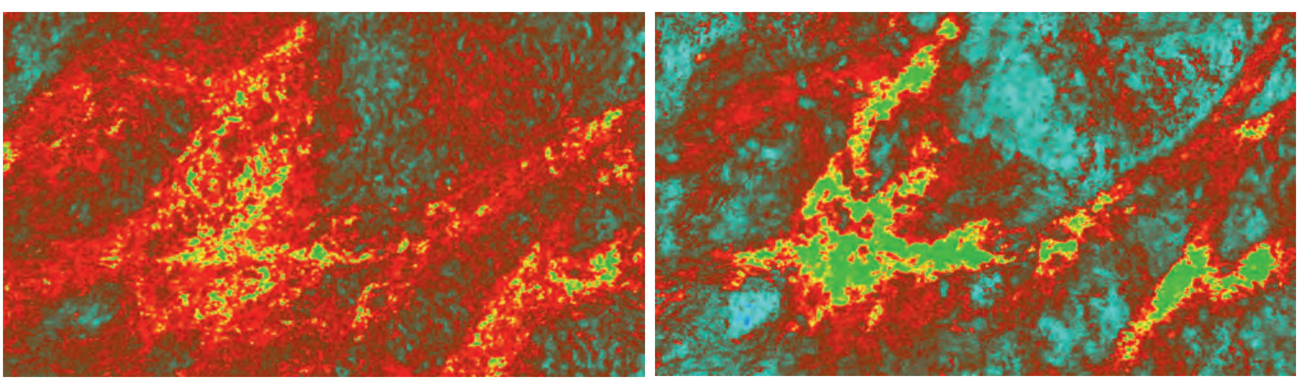

Figure 10 Lambda Rho: Legacy (left) and reprocessing (right) shows an improvement in the definition and clarity of the map compared to the legacy processing. Some small-scale features are more visible in the reprocessing compared to the legacy.

The amplitude extraction shown in Figure 8 enables easier identification of smaller-scale features that are not as clear in the legacy processing. An additional benefit of the reprocessing is that the maximum usable angle range of the stacks has been increased compared to the legacy data.

Quantitative AVO QC products can be tailor-made to highlight specific reservoir characteristics. The examples above make use of VP/VS ratio (which distinguishes different lithologies, such as channel sands and background mudstone, as shown in Figure 9) and Lambda Rho (used as a fluid indicator attribute, as shown in Figure 10). The VP/VS ratio was calculated using a linearized Bayesian inversion based on pre-stack data. Zero-phase statistical wavelets are derived for each angle-stack and used in the pre-stack inversion process. No stratigraphic constraint is imposed and the inversion is run on the native seismic sampling grid in time (JafarGandomi et al., 2015).

It is becoming standard practice to use reservoir-focused AVO QC attributes, generated after each key processing stage, to ensure that the seismic data will be compliant with any requirements for later reservoir characterization work. On this project, these AVO QC attributes were also used to ensure that AVO features, identified from the legacy data, were improved as a result of the reprocessing.

The uplifts in the signal processing and demultiple processing translated into clear improvement in the AVO QC products such as the VP/VS ratio and the Lambda Rho attributes. The amplitude extractions across key horizons also show improved definition compared to the legacy processing. These attributes show improved continuity of the AVO responses along with the identification of smaller-scale features that are not visible in the legacy processing examples.

Conclusion

The latest processing and imaging techniques have been used to provide high-quality seismic volumes in two challenging areas of the North Sea, delivering clearer and higher-resolution images than have been seen before. Q-FWI produces high-resolution models of both velocity and attenuation, as well as improving structural imaging. By incorporating accurate Q compensation in the imaging, data is delivered that is more reliable for AVO and reservoir characterization.

Application of the latest available processing and imaging technologies to the reprocessing of Cornerstone has significantly improved the signal processing, resulting in a sharp wavelet containing minimal sidelobe energy, with good phase and timing alignment to well data in the area. The quality and bandwidth of the data has been brought up to a similar standard to newly-acquired data. A cascaded sequence of the latest model-based demultiple techniques using mild adaptive subtraction ensured that primary reflections were unaffected by the demultiple processing, while removing as much of the multiple energy as possible. This provides a significant improvement over the previous processing. Further improvements are expected as the whole survey is imaged through the latest Q-FWI and Q-PSDM sequences, which are expected to provide the definitive seismic data volume for the area.

Incorporating reservoir-focused AVO QC and calibration within the processing ensures the preservation of the true amplitude response of the Earth, corroborated by the use of well data. These AVO attribute QC products also deliver early insight into the lithologies and facies of the area. Improved AVO will enable better understanding of the geology and hence deliver significant improvements in the ability to maximize exploitation of the remaining hydrocarbons in these mature basins.

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