Reservoir property estimation using only dual-sensor seismic data – a case study from the West of Shetlands, UKCS

Cyrille Reiser[1*], Tim Bird[1] and Matthew Whaley[1] **describe the data analysis of dual-sensor 3D seismic from the West of Shetlands area that focuses on wavelet extraction and low frequency phase stability.**

Marine broadband towed streamer seismic analysis and case studies in recent years have revealed several benefits of extended seismic bandwidth for the reservoir geoscientist – both for structural and quantitative seismic interpretation. Since 2007, dual-sensor towed streamer seismic technology (Tenghamn et al., 2007) has provided industry-wide access to seismic data with a significantly broader range of low and high frequencies. Benefits on the interpretation side include improved vertical resolution, enhanced geological texture, cleaner event continuity and character, sharper fault plane truncations and improved seismic-to-well correlations. The key benefit for quantitative seismic interpretation (QI) is a significant reduction of the low frequency model requirement and this allows seismic inversion to be derived from the seismic data rather than from a model extrapolation of *a priori* information. In addition, the quality and prediction of the reservoir properties derived from seismic data, without well log information, has significantly improved – resulting in the potential de-risking of prospects and discoveries.

This paper describes the data analysis of dual-sensor 3D seismic from the West of Shetlands area and specifically focuses on wavelet extraction and low frequency phase stability. The study explores the relevance of these aspects to the inversion and investigates the estimation of reservoir properties, including porosity prediction, without the direct use of well information. The match of results from seismic only inversion to 'blind wells' demonstrates the potential of dual-sensor pre-stack data to reliably estimate elastic and reservoir properties in an exploration setting.

Estimating reliable absolute reservoir properties away from wells has been a continuous challenge for reservoir geoscientists. Where it can be achieved, the value of the information can be significant in de-risking an opportunity and/or better characterising a prospect. In addition, in appraisal, development and reservoir optimisation, any reliable elastic information extracted from seismic data can potentially assist in optimising a well location and its trajectory for maximum recovery.

Within a well, absolute properties can be measured from wireline data at very high frequencies (kilohertz) but seismic data by its band-limited nature generally lacks the fidelity needed to estimate and quantify rock properties to well log precision (Figure 1). A combination of both well log and seismic measurements is therefore routinely used to accurately and reliably compute the lateral distribution of reservoir properties.

The advent of the dual-sensor towed streamer system in 2007 (Tenghamn et al., 2007 and Hegna et al., 2012) introduced seismic data with much broader bandwidth, potentially reducing the need for well log information in the low-frequency model for seismic inversion. The dual-sensor streamer consists of co-located particle velocity and pressure sensors allowing it to be towed much deeper than conventional streamers as unwanted ghost reflection effects are eliminated. This design enables more low-frequency energy to be recorded with improved signal-to-noise characteristics, while additional higher frequencies are preserved for increased vertical resolution. Furthermore, the combination of dual-sensor recording with time and depth distributed source systems for source ghost elimination (Hegna et al., 2012) results in seismic data of maximum bandwidth and fidelity.

Extended signal bandwidth has been demonstrated to result in sharper seismic signals with significantly reduced side lobe artefacts affecting the seismic image. This provides the best vertical resolution (ten Kroode et al., 2013) and improves the interpretability of a clearer non-distorted seismic image. The benefits of reliable broadband seismic data have been described (Reiser et al., 2012, Michel, 2012, Whaley et al., 2013) for the complete workflow of quantitative seismic interpretation and structural interpretation. These include low-frequency model building (LFM), elastic property estimation, depth conversion and pre-stack wavelet extraction.

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The full seismic stack image is an unreliable dataset from which to extract information regarding lithology and fluid behaviour because the stack process averages the seismic response across all offsets. AVO lithology and fluid effects are therefore combined and distorted. When extracting rock property and lithology information from seismic data, most of the fluid information is contained in the far offsets. Access to reliable pre-stack data is therefore crucial. To fully exploit the AVO behaviour of the data across the full offset range it is important to ensure that amplitude and phase have been measured and preserved reliably from near to far offsets and over the full signal bandwidth.

A case study from the West of Shetlands is described to demonstrate the value of high fidelity broadband seismic data for improved delineation and estimation of reservoir properties and the de-risking of prospects. This reservoir characterisation workflow is performed based on seismic information only and without using well information as hard calibration points. Well data is subsequently used to validate the results.

The impact of low frequency content on seismic inversion accuracy

Low frequency information is required for the computation of absolute elastic properties. If more low frequency information is available from the seismic data, the need for well log or other *a priori* information to complete the LFM is reduced. However, before using these additional seismic low frequencies it is essential to ensure that the information provided by the seismic data at the lowest frequency end is reliable.

Pre-stack simultaneous seismic inversion, a key component of QI, converts angle-dependent pre-stack seismic data from units of reflection amplitude to units of elastic attributes such as acoustic impedance, shear impedance and Vp/Vs. The results can be quantitatively integrated with statistical rock physics analysis and stochastic modelling workflows for lithology and fluid prediction. Conventionally a LFM is built by low-pass filtering well log measurements, incorporating smooth seismic velocity data and spatial extrapolation to fill the gap at the ultra-low frequency end of the spectrum (below the bandwidth of seismic data). By combining the LFM with the simultaneous pre-stack relative seismic inversion a prediction of absolute elastic properties (with the full bandwidth of information down to 0 Hz) can be derived from 3D spatial information in the seismic data.

Figure 1 represents the effect of varying the amount of LFM used and the corresponding relative seismic elastic attributes needed to obtain the absolute measurement. For example, if the bandwidth of the seismic data used is between 10 and 50 Hz (column c) then the LFM needed will be the complement 0-10 Hz spectrum (column b) to obtain the desired absolute acoustic impedance (column a). If a dataset has a broader bandwidth (column e or g) the amount of LFM needed is relatively small (column d or f) meaning that a relative seismic inversion of dataset e and g would result in elastic properties close to the absolute properties.

Figure 1 illustrates that if column f and g are considered, for instance, with a seismic data bandwidth of 2 to 50 Hz, the necessary low frequency model is very small as it only needs to fill the gap between 0 and 2 Hz. This can generally be achieved by using pre-stack time or depth seismic velocity information. Nowadays, full waveform inversion can deliver a low frequency component significantly higher than 2 Hz (Baeten et al, 2013) benefiting the seismic inversion.

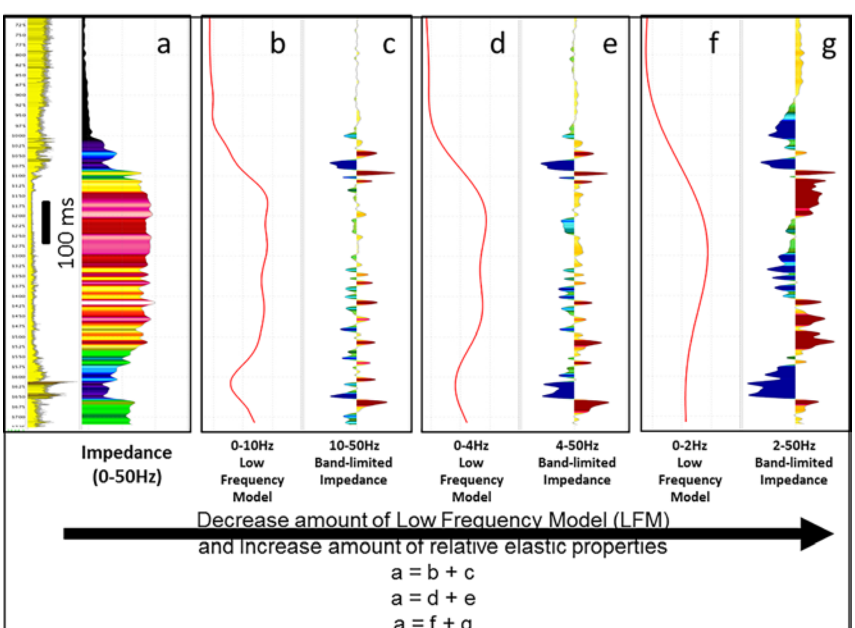

Figure 1 *Illustration of the importance of the low frequency information contained in the seismic signal by means of well log filtering.*

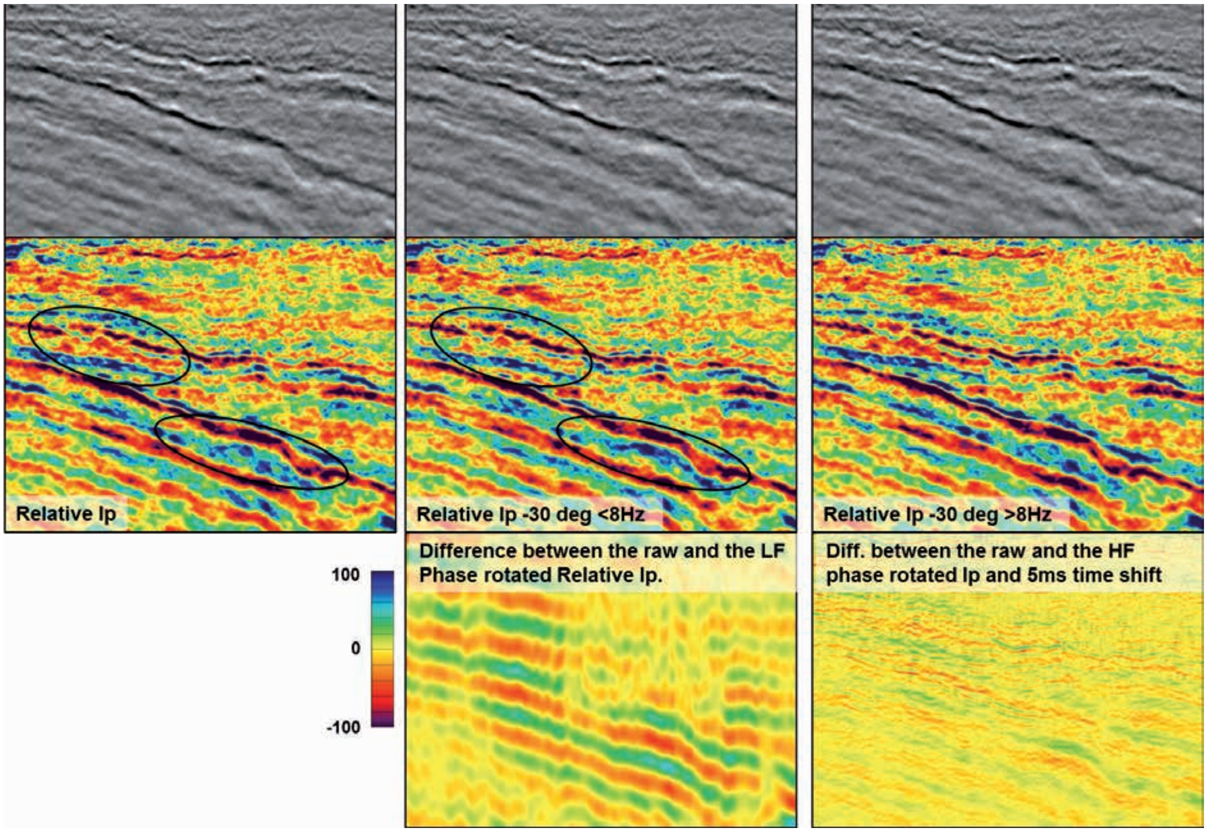

Figure 2 Results of phase rotation (-30 deg) of low frequencies (below 8 Hz) and above 8 Hz (right panel). Below the near reflection stacks are the relative acoustic impedance inversion results (Relative Ip) for the different frequency bands. A low frequency phase shift (in this case below 8 Hz) changes the amplitude response (seen in the difference panel), whereas high frequency phase rotation (above 8 Hz) presents visually as a simple time shift. A time shift correction has been applied to the data before the differencing as this is something that can be easily corrected after the phase rotation, however this is not possible with low frequency phase rotation as this fundamentally changes the amplitude of the events.

The impact of pre-stack fidelity and reliability on inversion quality

It is instructive to examine one of the critical aspects of pre-stack quantitative seismic inversion: the importance of phase stability and its impact on the inversion results.

To assess and understand the impact of any phase problem relating to the low frequency content of the seismic data, an analysis has been conducted by performing a phase rotation of dual-sensor broadband seismic data by -30° for all frequencies below 8 Hz. This has been compared with a phase rotation by the same amount (i.e. -30°) of all frequencies above 8 Hz (Figure 2). The original and the two phase rotated datasets (low and high side of the spectra) were then inverted and difference plots generated.

Visual examination of the difference between the initial data and the two phase rotated relative inversion results can be summarized as follows: below 8Hz the impact is mainly evident as large amplitude changes in the estimated acoustic impedance values, whereas the phase rotation for the frequencies above 8 Hz appears more as a small time shift of the events. As Figure 3 illustrates, a phase shift in the frequency domain results in a time shift in the time domain and that for the ultra-low frequencies this implies a very large time/static shift as the wavelet is long.

In an attempt to further quantify the difference between low and high frequency phase errors, the same experiment was repeated with acoustic impedance values from well log data. The acoustic impedance log was again phase rotated by -30° above 8 Hz in one case and below 8 Hz in the other case. The resulting phase-rotated logs were cross-plotted against the true response (Figure 4). Similar to the findings for the seismic data the degree of correlation between the phase-rotated log and the true acoustic response shows that the correlation is poorer when a phase rotation is introduced to the very low frequencies, whereas the correlation is still good for the case where a phase error is only applied to the high frequencies. This result confirms the importance of ensuring phase accuracy for the very low frequencies in any broadband seismic dataset when performing quantitative interpretation and reservoir properties prediction.

The importance of the ultra-low frequencies for pre-stack analysis in the context of broadband seismic data can be further illustrated by the simple comparison between the intercept and gradient on Figure 5. The dual-sensor dataset in this example contained meaningful amplitudes down to around

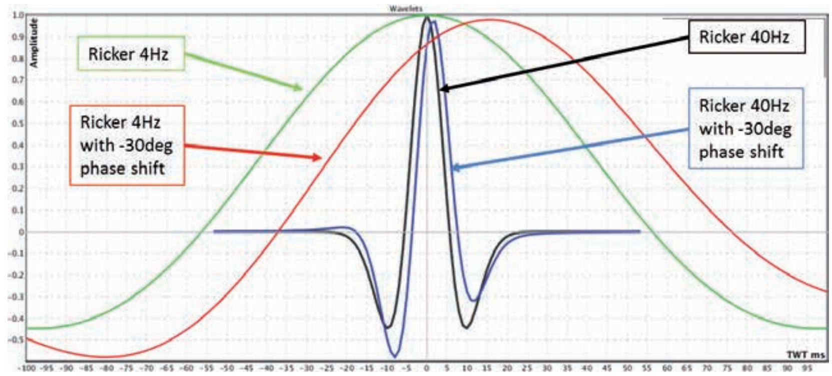

Figure 3 *Simple comparison of time series of low and high-frequency wavelets with and without -30 degree phase shift. For high frequencies, in this case a simple Ricker wavelet with central frequency of 40 Hz (black wavelet), a phase shift from zero to -30 degrees (blue wavelet) results in negligible change in the amplitude of the main peak (more in the side lobes) and a very small effective time shift (<2 ms); whereas for a low frequency wavelet (Ricker with 4 Hz central frequency, bandwidth approximately 2-8 Hz, green wavelet) the same phase shift results in a large apparent time shift of over 16 ms (red wavelet).*

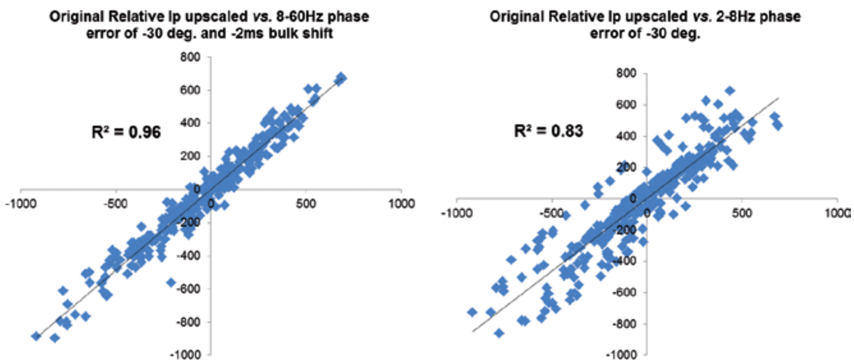

Figure 4 *Results of the phase rotation (-30 deg) of upscaled well logs: left side for rotation of high frequencies (above 8 Hz); right side for low frequencies (below 8 Hz).*

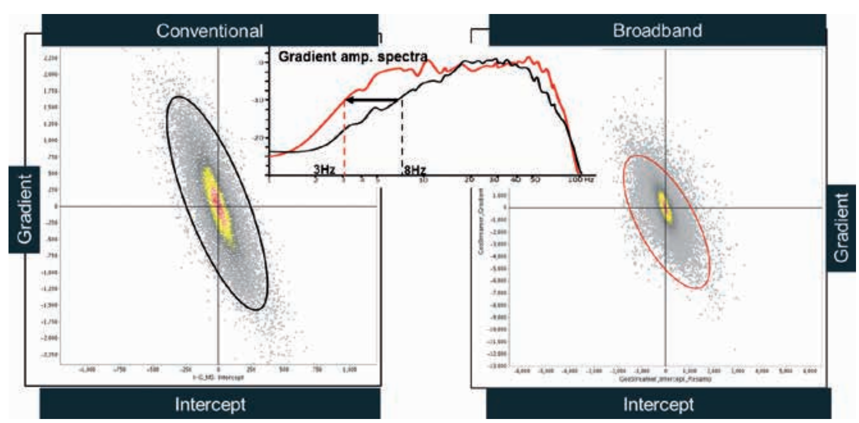

Figure 5 *Intercept and gradient calculation from 2 co-located seismic datasets: a conventional and broadband dual-sensor seismic dataset. The intercept and gradient have been estimated using the Shuey 2-term approximation with identical angle ranges for both datasets. Both cross-plots have been displayed with the same aspect ratio (~2.2) between the intercept and the gradient.*

3 Hz, whereas the conventional seismic data only contained useful amplitude information down to around 8 Hz. The upper limit was more or less identical for both datasets. Although absolute intercept and gradient values are different for both datasets (the cross-plots have been displayed with the same aspect ratio (~2.2), a more stable and constrained gradient estimate is evident in the seismic data rich in low frequencies.

Improved far angle stack bandwidth with dual-sensor recording

Finally let us consider how the bandwidth extension of deep-tow dual-sensor data affects the different offsets or angle sub-stacks after high-frequency attenuation due to longer travel paths in the sub-surface. For a moderate depth, the amplitude spectrum for the near angle stack of a typical conventional seismic dataset can be expected to be between 8 and 60 Hz, whereas the equivalent broadband seismic data will generally be between 3 and 60 Hz. This represents a bandwidth extension of 9%. In the equivalent far angle stack the conventional seismic data contains frequencies between 8 and 30 Hz, while the dual-sensor deep-tow data contains frequencies down to 3 Hz. In percentage terms, this represents a 17% bandwidth increase. Translating this into octaves, the broadband data contains 2 more octaves bandwidth than the conventional data for both the near and the far stack.

Shear-wave information is mainly contained in the far offset data and it is the additional bandwidth recorded for the far stacks that particularly benefits Vp/Vs estimates.

This fact explains why the gradient attribute is generally found to be more robust when dual-sensor deep-tow seismic data is used compared to conventional data.

Using the described analysis we are able to make the following general observations:

- Building a LFM for seismic pre-stack inversion using richer low frequency information provided by dual-sensor deep-tow data will reduce the need for well information and can potentially lead to improved predictability away from well control.
- Errors and uncertainties in the phase and amplitude behaviour of, in particular, the ultra-low frequencies (below 8 Hz) will lead to inaccurate estimation of elastic properties and therefore reduce the confidence in the accuracy of computed reservoir properties.
- Far offset seismic data benefit most from the additional low frequency content provided by deep-tow dual-sensor data, improving the overall stability of AVO attributes such as shear wave impedance and Vp/Vs.

The benefits of broader bandwidth data are illustrated using a case study from the West of Shetland. The main objective of this case study is to estimate reservoir properties such as acoustic impedance, Vp/Vs ratio and porosity using only the seismic data i.e. without integrating well information into the inversion process.

Case study – West of Shetland

The area of interest

The Faroe-Shetland Basin (FSB) is located offshore north of the UK mainland (Figure 6) on the Atlantic Margin stretching from the west of Ireland to Norway. The water depth in the FSB region is up to 2000 m and the sediment fill can be more than 5-km thick. The FSB is a Jurassic-Cretaceous-Paleocene rift basin and is the geological continuation of the faulted-block and graben province of the Møre Basin offshore Norway. Paleocene aged basaltic lava and hyaloclastite flows cover the majority of the basin impeding imaging and interpretation of the older sequences. Reservoir provenance and quality is a major source of uncertainty along this margin and there is a need for high-quality seismic data to properly image the geology and the trapping mechanisms for delineation of hydrocarbon accumulations beneath the volcanics.

Workflow and main results

Most of the published examples of broadband seismic inversion to date have focused on the computation of relative elastic properties and these have already provided significant improvements in terms of reservoir understanding (Reiser 2012a,b,c; Michel, 2012; Duval, 2012 and 2013; Kneller, 2013; Bird, 2014; Geisslinger, 2014; Bouloudas, 2015). The objective here is to further investigate the high fidelity of dual-sensor seismic data (acquired in partnership by PGS and TGS) by deriving estimations of absolute elastic attributes and benchmarking these results against available well data from the public domain. Well data was only used to validate the results at the end of the process.

Typical inputs to low-frequency model building may include upscaled (low frequency) well logs, seismic horizons with associated stratigraphic conformability constraints, rock physics models and velocity models. Significant QC

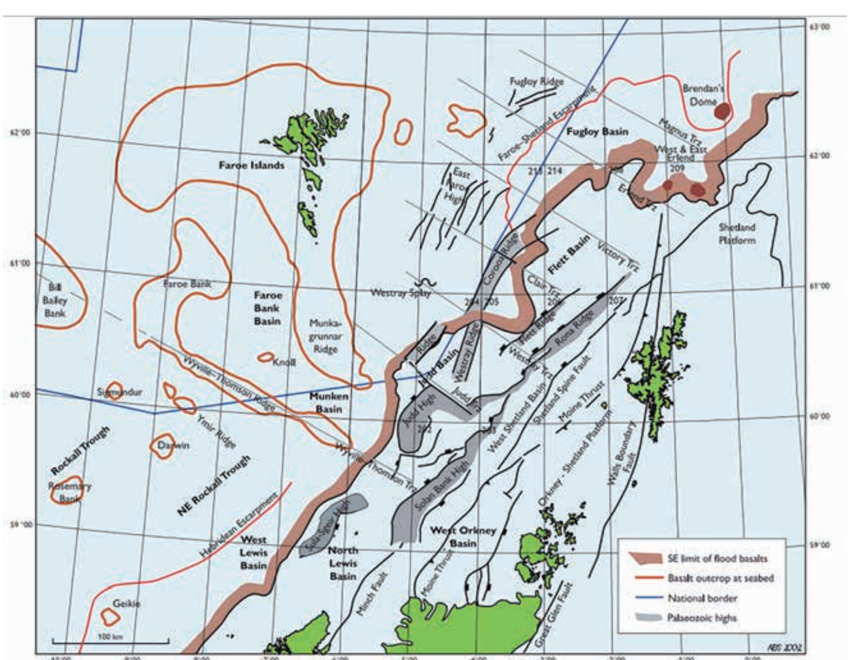

Figure 6 Location map of the area of interest showing the main structural elements and the survey location (A.B. Sorensen., 2003).

and interpretation of pre-stack seismic data is part of the early seismic inversion workflow. Rock physics models can be used to define variation away from well control if desired. Note the emphasis upon establishing low-frequency trends. The aim with the LFM is to create a stratigraphically and structurally accurate framework to spatially extrapolate calibrated low frequency impedance information over large distances away from available well locations. This will provide background information for the absolute estimation of elastic properties. The main drawback in the past has been that the seismic data used was significantly band-limited, therefore the frequency gap (below seismic bandwidth) was substantial, and consequently a considerable amount of *a priori* information was needed to fill the gap. This conventional workflow made the prediction of the background model highly dependent on the quality and quantity of the input assumptions.

In the present case study, the seismic data have a broad bandwidth from 3 Hz to 60-70 Hz at the reservoir level, with good signal-to-noise-ratio for the various angle stacks (Figure 7). Encouraged by the initial quality of the pre-stack data, the goal was to perform a simultaneous pre-stack seismic inversion of the data for absolute elastic properties without using the available well information for building the low frequency model. Instead the wells were only used for the wavelet amplitude scaling to the seismic data, as the overall relationship of background amplitude to impedance was needed. Apart from this, the wells are not used as *a priori* information in the inversion process.

As context for the broadband results, a re-processed conventional 3D seismic survey is available covering the same area. To show the bandwidth difference between the dual-sensor deep-tow data and the conventional seismic data, signal-to-noise ratios of angle stacks have been produced. Since the far angle stacks contain the important shear information, the signal-to-noise ratio for the far angles is displayed alongside the frequency decomposition in the octave domain. The far angle stacks were produced using angles between 35° and 45° for both datasets. As Figure 7 shows, the dual-sensor deep-tow data contains usable low frequencies down to 3 Hz (over the full bandwidth) with significantly better signal-to-noise ratios than the conventional data.

As a consequence of the observed richness in low frequencies in the broadband data, seismic velocities were used as the only input for the low-frequency model building. For this, the seismic velocity was multiplied by a constant density value (average reservoir density encountered in the area is taken from regional knowledge to generate an impedance

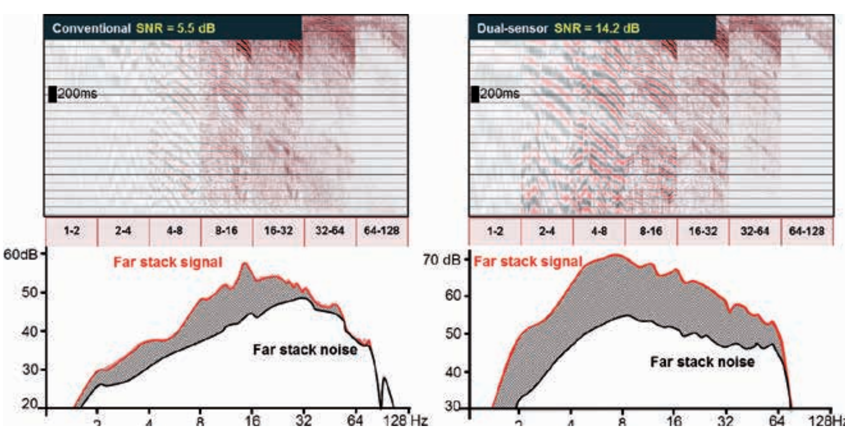

Figure 7 *Seismic decomposition into octave frequency bands (upper panels) for the far angle stack for the conventional (left) and the dual-sensor streamer (right). Bottom panels represent corresponding signal/noise analysis for the conventional and broadband datasets.*

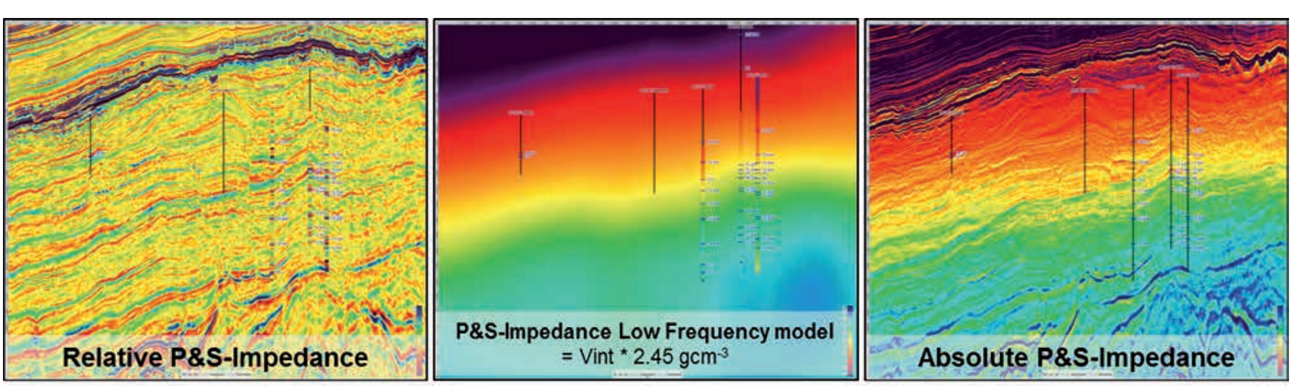

Figure 8 *Workflow for deriving absolute elastic properties by integration of a pre-stack relative simultaneous inversion. A low-frequency background model was used which was derived from an interval velocity field combined with constant density information. All the wells represented are used as blind wells only.*

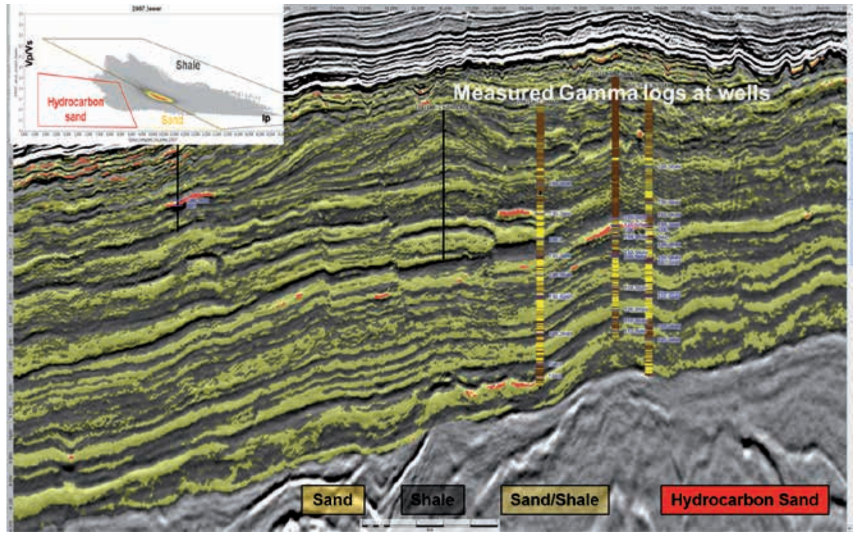

Figure 9 *Arbitrary line going through the acquired broadband seismic data showing the lithology-fluid classification based on the pre-stack inversion. A lithology-fluid classification has been performed using the polygons presented in Figure 10. The wells display the measured gamma logs as a QC of the lithology classification.*

volume). In addition a density trend could have been used, but for simplicity a single value was deemed sufficient to validate the overall workflow. The employed workflow was simple and is illustrated in Figure 8.

Within the study area of the survey a number of discoveries including the Tornado (gas with oil rim) and Suilven (gas condensate) fields are located in addition to some recent dry wells, including those drilled into the Onslow and Handcross prospects.

To gain insight into the reservoir properties (e.g. lithology-fluid and porosity), inversion for both acoustic impedance (Ip) and shear impedance (Is) is required, which allows the calculation of the Vp/Vs ratio. Inverting for just acoustic impedance is less informative and this will not demonstrate that the data is AVO compliant. Instead the real benefit of lithology and fluid prediction and seismic reservoir characterisation comes from the simultaneous use of both acoustic impedance and the Vp/Vs ratio (or equivalents, e.g. Lambda-Rho, Mu-Rho). The reliable estimation of both attributes indicates AVO stability throughout the full pre-stack analysis. After pre-stack simultaneous inversion, the 3D volumes can be further characterised into lithology and fluid classes such as shale, sandstone, hydrocarbons and brine by using acoustic impedance over Vp/Vs cross-plot.

In Figure 9 simple polygons in the cross-plot domain (top left handside) have been used to discriminate between lithologies and fluids. Reliable lithology-fluid classification would not have been possible if the Vp/Vs ratio had not been used because in the acoustic impedance domain a significant overlap exists between the hydrocarbon-bearing sandstone reservoir and the surrounding shale. This has subsequently been verified by rock physics analysis (Figure 10) where the ellipses correspond to the elastic property response of the well end-member (sand in this case) at the well location at some certain depth. The only background knowledge required here was an expected soft sand response for the target depth, relative to the shale background. This kind of general knowledge could be determined from regional studies in a frontier context.

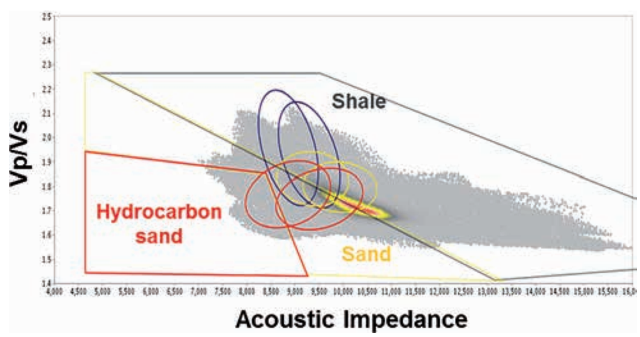

Figure 10 *Comparison between the rock physics analysis (ellipses) and the results of the absolute pre-stack seismic inversion using the workflow illustrated in Figure 7. The ellipses are statistical distributions derived from the rock physics and were not used in the lithology-fluid classification (post-mortem analysis), but do validate the implemented workflow.*

A good match (*a posteriori*) between the seismically estimated lithology-fluid volume and the volume fractions from the well logs (Figure 9) can be observed across the random line going through the Tornado discovery (left hand side) and the Suilven Field (right hand side).

Once the robust prediction of sandstone and shale distribution has been established without any direct well input, the relationship between P-impedance and sandstone porosity (Figure 11) can be used to derive porosity predictions directly from pre-stack seismic inversion data.

This simple linear relationship has been applied directly to the estimated sandstone volume (and associated impedance) results to derive a 3D porosity volume (Figure 12). The match between the porosity estimated from pre-stack broadband seismic data followed by lithology-fluid classifi-

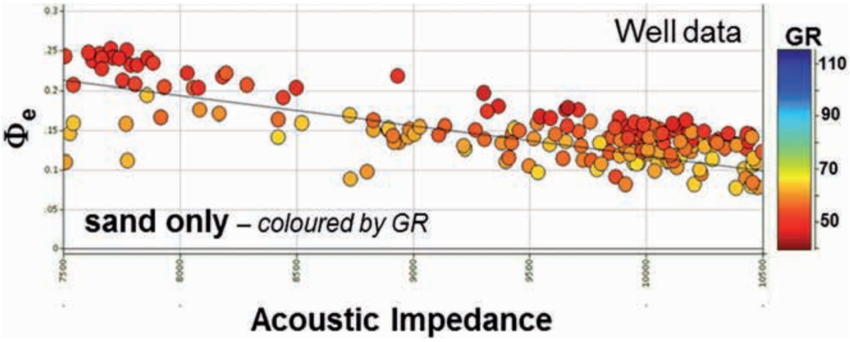

***Figure 11** Relationship at well locations between acoustic impedance and porosity in the sand intervals.*

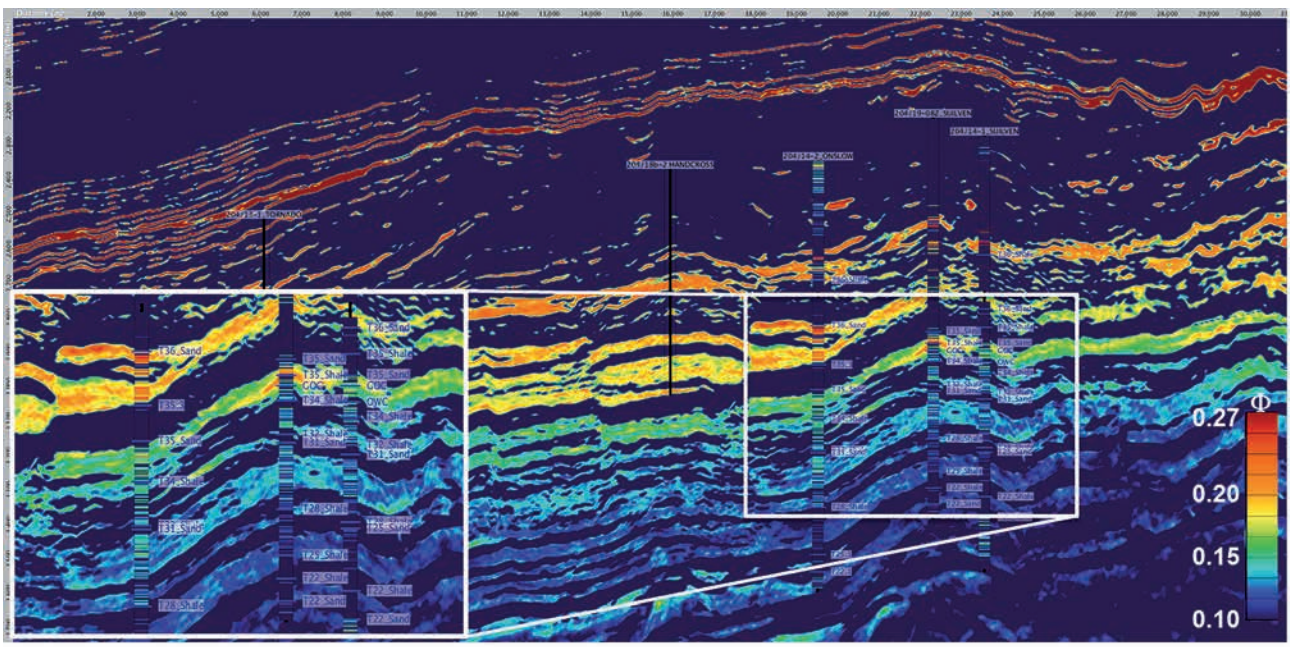

***Figure 12** An arbitrary line through the acquired broadband seismic data showing the estimated porosity, based on the pre-stack inversion. The wells are displaying the petrophysical porosity logs as a QC of the estimation.*

cation is in very good agreement with the porosity observed in the wells (even though no well information was used in the pre-stack simultaneous inversion.)

Summary

Conventional towed streamer seismic data lacks ultra-low frequency amplitude information below 7- 10 Hz, whereas dual-sensor deep-tow seismic data typically contains pre-stack information with stable amplitude and phase behaviour down to 3 Hz.

Accurate and reliable low-frequency information as provided by dual-sensor broadband data enables use of AVO information for elastic and reservoir property estimation. This includes lithology-fluid distribution and porosity estimates without the need to use any available well information for building the required low frequency model. In this way broadband seismic inversion offers significant opportunity to reliably de-risk interpretation of prospects and decrease uncertainties about geological characteristics of assets, with the strong proviso that, as explained above, the low-frequency information must be reliable (as they have been shown to be in this case).

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