SUMMARY

The volumes of broadband seismic data acquired and processed by the industry have grown rapidly. The spectral content of this new quality seismic is demonstrably superior to conventional seismic, both at the low and high frequency end of the spectrum. However, broadband seismic data will only deliver its full reservoir value if a quantitative interpretation is possible. Inversion to the impedance domain, assuming one has a good well-tie, is one of the main steps in quantitative interpretation.
Introduction

The volumes of broadband seismic data acquired and processed by the industry have grown rapidly. The spectral content of this new quality seismic is demonstrably superior to conventional seismic, both at the low and high frequency end of the spectrum. Broadband seismic data will deliver to its full potential if quantitative interpretation is optimized to benefit from the enhanced frequency content. Inversion to the impedance domain, assuming one has a good well-tie, is one of the main steps in quantitative interpretation.

We discuss the benefits of wider bandwidth on inversion in a Barents Sea 3D broadband survey over the recent Gohta and Alta discoveries that was acquired and processed in 2014. In order to demonstrate the advantages of increased bandwidth, the 3D broadband seismic data is inverted to impedance using its full bandwidth. Then using a bandpass filter, the seismic is reduced to a more conventional bandwidth and again inverted. A pre-requisite for a good inversion is a good well tie and wavelet. We show the impact of well tie on inversion using a number of estimated wavelets. Then, we demonstrate that the extra bandwidth can fill the low frequency gap further and this can push the use of broadband seismic data for reservoir characterization to its full potential.

Data Acquisition and Processing

The broadband, multi-client data was acquired in early summer of 2014. A conventional bandwidth source was used in flip-flop mode with 18.75m spacing and towed at a depth of 6m. The receiver spread used twelve 7km cables deployed with a linear slant from 18m at the front end to 28.5m at the far. A deep cable was preferred in order to minimize sea surface noise, while at the same time boosting the low frequency response of the receiver ghost (Williams and Pollatos, 2012). However, multiple attenuation is an important step in processing seismic data from the Barents Sea so the design also required preservation of the inline near offset. The front end depth of 18m allowed an inline near offset of 150m for all cables while the mild slant of 1.5m per km of offset allowed a deeper cable for increased low frequencies at the far offset.

An onboard fast track sequence including 2D SRME, de-ghosting and post stack time migration was completed one month after the last shot. The final PSTM sequence was delivered in December 2014 and is the dataset used for this inversion study. In this final sequence, receiver de-ghosting was applied after noise suppression and before 3D SRME. The data contained a significant level of seismic interference which was attenuated prior to de-ghosting. The very mild slant meant that notch diversity was not used for de-ghosting. Multiples are also strong in this area and the de-multiple sequence included 3D and 2D SRME plus Radon de-multiple both before and after PSTM. A full fold stack as well as 3 angle stacks, 0-10°, 10-20° and 20-30° were produced.

Inversion to Impedance

Simultaneous inversion of pre-stack seismic data, discussed by Hampson et al. (2005) and many others, is a method to invert directly from multiple seismic traces of different incident angle range to multiple elastic properties at the same time, for example to obtain reliable estimates of P- and S- wave velocity and density (we briefly explain this below). These elastic properties can then be used to predict the fluid and lithology properties of the subsurface of the earth.

Using the Fatti approximation (Fatti et al., 1994) to the Zoeppritz equation for the reflectivity of PP data, we have:

$$R_{PP} (\phi) = a_\rho u_{AI} + b_\rho u_{SI} + c_\rho u_{P}.$$  (1)

where the coefficients $a$, $b$ and $c$ are dependent on the angle of incident and $AI$, $SI$ and $\rho$ indicate acoustic impedance, shear impedance and density accordingly. By convolving both sides of equation 1 with a wavelet, one can effectively model the seismic data as:
This can then be formulated as a forward modelling problem:

\[ \mathbf{M} \mathbf{x} = \mathbf{s} \]  

where \( \mathbf{x} \) are the model parameters that we are trying to invert for e.g. impedance and density parameters, \( \mathbf{s} \) is the observed seismic traces, and \( \mathbf{M} \) is the forward modeling matrix that includes the wavelet. The objective function of this inverse problem is usually in the form of regularized least-squares such as:

\[
E = (\mathbf{M} \mathbf{x} - \mathbf{s})^T (\mathbf{M} \mathbf{x} - \mathbf{s}) + \lambda (\mathbf{x} - \mathbf{L})^T (\mathbf{x} - \mathbf{L}).
\]  

where \( \mathbf{L} \) is what is known as the low frequency background model (LFBM) from which we do not want the impedances to drift too far away, and \( \lambda \) is a positive coefficient balancing data fitting and model regularization. There are some immediate observations from this simple mathematical derivation:

1- One can either invert for acoustic impedance, using only the near angle stack, or invert for AI, SI and density using all angles simultaneously.
2- It is possible to model what we record as seismic data in the real world only if we have the wavelet (equation 2). This demonstrates the importance of wavelet estimation; a process often called a well tie.
3- Equation 4 shows how we can invert for impedence properties. The fundamental requirement is to have a wavelet. Also the LFBM is required to stabilize the inversion.
4- Broadband technology promises to rely less on the LFBM (interpreter driven and often subjective) and more on the seismic data itself, with the measured low frequencies filling the frequency gap.
5- Wavelet estimation for broadband seismic data needs special care to make sure all the spectral content of the data is captured properly.

**Data Example**

The Gohta field is in the Barents Sea, 35km north-west of the Snøhvit field. The water depth at the site is approximately 332 metres. In 1985 a dry hole was drilled right at the edge of the field, but a discovery was reported at Gotha in 2013. We took a seismic line from the broadband 3D volume over Gohta field which was recorded and processed in 2014 as described above. The objective is to analyse the benefits of broader bandwidth and better wavelet estimation.

Figure 1 compares the near angle stack volume with conventional and broad bandwidth and the corresponding spectra is shown highlighting the extra bandwidth in the broadband data. The conventional bandwidth data was obtained by bandpass filtering the broadband dataset.

**Figure 1 left:** conventional bandwidth (red spectrum) and **right:** broadband (blue spectrum) near angle stack.
The near angle stacks shown in figure 1 were used to invert for acoustic impedance. Associated with large contrast between the elastic properties of the carbonates and the overlying shales, a large step change in the seismic bandwidth is noted across the top carbonate interface. Time variant wavelets are therefore required in order to capture this change in frequency content. Another important factor is the phase which needs to be correctly estimated during well tie. In the following, we show a comparison between the inversion of conventional data with a single wavelet, and broadband data with a single wavelet, two depth dependent wavelets and a zero phase wavelet. The details behind the robust estimation of the wavelets for broadband data are beyond the scope of this paper and we refer to White and Naeini (2014) and Naeini (2014) for additional information.

Figure 2 shows the acoustic impedance section for the above mentioned 4 scenarios. The line displayed here crosses the 1985 dry hole, which was the only well we had available, and also intersects the Gohta field. The acoustic impedance log from the well is used to QC the inversion. We start with a comparison between inversions from conventional and broadband data. As the conventional data has narrower bandwidth, only one wavelet was used to compute the acoustic impedance in figure 2a whereas the broadband inversion in figure 2b uses two depth dependent wavelets as discussed above. When figure 2a. is compared with figure 2b, it can be observed that the extra bandwidth helps to achieve better delineation of the carbonate section and the intra-carbonate shale layering (black dotted lines). It may now be possible to track the base of the higher porosity, karstic carbonate layer in the Gotha field (white dotted lines).The conventional bandwidth inversion shows a LFBM overprint and subsequently causes the interpretation to be more ambiguous (e.g. areas shown with question marks).

Figures 2c and 2d show the acoustic impedance from the inversion of broadband data but by using only a single wavelet (2c) and a single zero phase wavelet (2d). Both figures show an undesirable overshoot at places, for example at the well location shown by the black arrow. And the zero phase wavelet causes some timing error too which may indicate there is still residual phase remnant in the data (as is often the case).
As mentioned in the previous section, one expects to rely less on the LFBM when inverting broadband seismic. This is based on the presence of additional low frequencies in the broadband data and means the inverted result is more reliable for interpretation, as is demonstrated in figure 2. To illustrate this further, we also show, in figure 3, the LFBMs used for inverting the conventional bandwidth and broadband seismic data. It can be clearly seen that the LFBM used for broadband data has much lower frequency content and therefore the inversion process is guided by the actual seismic data over a wider range.

![Figure 3 LFBM used in inversions](image)

**Conclusions**

For this dataset acquired over the Gohta field it was shown that the extra bandwidth has the potential to reduce the contribution of the LFBM to the inversion, and therefore reduce ambiguity in the interpretation. It was also demonstrated that one needs to capture the spectral behaviour of the seismic data when estimating the wavelet. This is more pronounced when we have broadband seismic data as it is important to capture the behaviour and sometimes abrupt cut-offs in the frequency spectrum at the low and high frequencies precisely.

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**References**


