Advances in broadband quantitative interpretation

Cyrille Reiser and Tim Bird, PGS Reservoir Limited*

Summary

For almost 10 years now marine broadband seismic has provided the industry access to seismic data with a significant increase of seismic frequency bandwidth on both the low side of the frequency spectra and also on the high side. Seismic analysis and case studies in recent years using broadband seismic have revealed several benefits of broader seismic bandwidth for reservoir geoscientists - both for structural-stratigraphic interpretation and for quantitative seismic reservoir characterization and properties estimation. Pre-stack seismic inversion has been an excellent means to derive the full benefits and the value of acquired broadband pre-stack seismic for seismic reservoir characterisation and reservoir imaging.

This paper presents case studies of recent analysis at various stages of the exploration-production asset life as well as some potential pitfalls to be aware of when using pre-stack broadband seismic data for improved target delineation, estimation of reservoir properties and ultimately de-risking of a prospect or well positioning. A case study for a shallow reservoir in a frontier exploration setting will also demonstrate some recent developments in the integration of Full Waveform Inversion and imaging using multiples for an improved low frequency model and more reliable pre-stack seismic inversion.

Introduction

Getting the utmost seismic image of the subsurface is a key objective of many geoscientists. Until recently this objective has been limited by the acquisition and processing technology. On the acquisition side, with the advent of the towed dual-sensor streamer in 2007, new possibilities have been opened in removing the source and receiver ghosts at the acquisition stage. On the processing side, following “conventional” acquisition, various methodologies and workflows have been developed trying to remove or attenuate the notch (source and receiver).

These technologies are designed to offer a broader seismic bandwidth resulting in sharper seismic signal with significantly less side lobe artefacts (ten Kroode et al., 2013). The additional low frequencies from these solutions allow for an improved pre-stack inversion of seismic data for elastic attributes and should provide ultimately more reliable reservoir properties in 3D when combined with rock physics (Reiser et al., 2012, Whaley et al., 2013). In order to estimate these elastic properties, pre-stack or angles-stack seismic information is necessary. The full seismic stack image is an unreliable dataset which averages the seismic response across all offsets which makes it impossible to unravel a lithology response from a fluid effect. 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. The access to reliable pre-stack data is therefore crucial. In order to fully exploit the AVO behavior 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.

Some key post-migration issues to be aware of when dealing with broadband seismic data will be illustrated and QC steps emphasised, in particular phase stability, AVA/AVO integrity, wavelet extraction, and low frequency model requirements. Lessons and pitfalls of interpreting, characterising and quantifying using broadband data will be shared during the presentation.

Phase stability and its potential impact on seismic inversion results – a naïve experiment.

Estimation of the phase of the seismic data is a significant component of the quantitative seismic interpretation workflow. The most common method to estimate the phase of the seismic is by using well log information through a deterministic or Bayesian wavelet extraction.

A simple assessment of sensitivity of phase instability on AVO results the rotation of the phase of selected frequency bands (low and high bands on the angle sub-stacks). A -30° phase rotation was applied for all frequencies below 8 Hz and similarly for the over above 8 Hz. The results show that below 8 Hz 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 small time shifts of the events (Figure 1). A phase shift in the frequency domain results in a time shift in the time domain. For the ultra-low frequencies this implies a very large time/static shift as the wavelet is long. In this simple case the consequence is, close to a 10% error in estimating acoustic impedance being made with this phase rotation on the low frequencies. This in turn will lead to possible inaccuracy in the lithology and fluid prediction using the estimated elastic properties results from the seismic.

Wavelet estimation with broadband seismic data

Wavelet estimation is another key step in the quantitative interpretation workflow. With broadband data one of the main issues is in getting well log information over a long enough interval to capture the low frequency nature of the

broadband data. This becomes very challenging when the ultra-low frequency of the seismic is in the range of 3-4 Hz. This implies a wavelet period of about 300 ms on average, meaning that the well log information should be at least 600-700 ms long to capture the low frequency information adequately or to have a "BT" greater than 25, with B the bandwidth of the seismic data and the T the interval time window of the analysis (White, 2014). The main issue lies in the very sharp amplitude decay at low frequencies. Some practical approaches have been proposed by White (2014).
A pragmatic approach, especially when lacking long intervals of well log information, would be to use a statistical wavelet assuming a constant phase of the seismic data. Where suitable wells are available with a sufficient length of log record, phase corrections can be applied.
One of the other pragmatic approaches would be to perform a deterministic or Bayesian wavelet extraction on the same common bandwidth between the seismic and the well and to extrapolate the phase on the low frequency side taking into account White's (2014) comments.

A frequently asked question by many interpreters unfamiliar with the technical fundamentals of wavelet extraction is "Will the seismic to well tie be improved with broadband seismic data compared to conventional seismic data?". Figure 2 represents a well to seismic tie for four wells using conventional and broadband (dual-sensor streamer seismic) full stack seismic data. The wavelets for the conventional and broadband seismic data have been estimated using the inverse Fourier transform of the amplitude of their respective seismic. It can be considered that visually the well to seismic tie is very similar whereas the results of the relative inversion (Figure 3, representing the relative acoustic impedance) are very different. The broadband seismic inversion provides a far better image of the true geology than the conventional band-limited data, as significantly less side-lobe energy resulting in false events is inverted.

Seismically-derived Low Frequency Model

Low frequency model (LFM) 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. For decades seismic inversion for absolute elastic attributes required a significant amount of *a-priori* information to be introduced, as a Low Frequency Model (LFM), to fill the gap in the spectrum between 0Hz and the lowest available seismic frequency (typically around 8Hz). This made the whole workflow for elastic properties prediction using seismic and well information extremely dependent of the amount of "*a-priori*" input. The uncertainty or bias in these model inputs often led to results that were un-reliable and with low predictability in accuracy away from well-control. With pre-stack broadband data, building a low frequency model for seismic pre-stack inversion using richer ultra-low frequency information (<8Hz, down to 2-4 Hz) will lead to a significant improvement of predictability away from well control. The additional low frequency octaves from broadband seismic narrow or significantly attenuate the low frequency model "gap", reduce the need for well calibration and can even potentially enable absolute inversions "without" using or with minimal well information. The broader the seismic spectrum (specifically on the low side) , the less detailed ("high" frequency) the Low Frequency Model needs to be, leaving the possibility to rely more on the seismic data than a complicated and potentially biased LFM.

In frontier areas, such as the Barents Sea South East (northernmost part of Norway) where no nearby wells are available, seismic information has to be the main source of information for any prospectivity analysis. Some recent imaging technology developments (Whitmore et al., 2010) have allowed the use of the separated wavefield for imaging with multiples. This approach has been applied on recent broadband acquisition in this Barents Sea region (Rønholt et al., 2015). In this 3D survey area the reservoir, Jurassic in age, is very close to the sea surface (circa 700m). Processing using the multiples has allowed the full pre-stack imaging of the shallow reservoir which would have been impossible with only imaging with primaries as the near offsets/angles are not recorded (too shallow for recording any near offset information). In addition, to improve the velocity analysis, refraction based Full Waveform Inversion (FWI) was performed generating a high frequency velocity model (up to 18 Hz).

Thus, the combination of the Full Waveform Inversion up to 8-9 Hz results converted to impedance and the pre-stack seismic imaging above 8-9 Hz with multiples has allowed the filling of the frequency gap between the low frequency end of the seismic and 0 Hz, enabling the derivation of absolute elastic properties (Figure 4) without directly using any wells for the low frequency model building.

This type of integrated workflow of advanced velocity model (FWI) and broadband seismic should become more common and will enable pre-stack prospectivity analysis with limited well control allowing a significantly more confident de-risking of prospects and opportunities.

It is important to recall that the intrinsic requirement for these types of workflow to be used with confidence is dependent on the AVO pre-stack amplitude and phase reliability. Any assumptions and/or approximations made during the processing-imaging to retrieve unrecorded frequencies will have a serious impact on any prospectivity analysis.

Conclusions

Conventional towed streamer seismic data lacks ultra-low frequency amplitude information below 8-10 Hz, whereas acquired broadband seismic data typically contains pre-stack information with stable amplitude and phase behavior down to 3-4 Hz, meaning at least one octave of frequency gain on the low side of the frequency spectrum.

Having frequencies below 8 Hz brings significant benefits and value for the geoscientist in exploration and production settings. However this potential is critically dependent on having reliable and trustable seismic information across the frequencies bands and the offsets. This is important to bear in mind as more decisions will be based on richer broadband seismic information.

The benefits of robust and reliable broadband seismic data are that the subsequent workflows such as in the quantitative seismic interpretation become even more valuable tools to assist in de-risking prospects and in-field drilling. They can be used by reservoir geoscientists and engineers to better characterize and interpret their reservoirs away from limited well control.

Some aspects of the full quantitative interpretation workflow including wavelet extraction and phase estimation on the low frequency side are still under investigation. For instance, on the low frequency side, the well records are generally too short to evaluate and calibrate the seismic response. These two crucial steps have a significant impact on any of the qualitative and quantitative results that can be extracted from broadband seismic data, hence the need to have an acquisition system as robust as possible allowing less approximation and assumption during the rest of the sequence.

Advances in seismic imaging, provided by broader bandwidth seismic, offer the possibility to enable a far more reliable pre-stack qualitative and quantitative interpretation workflow leading to a significant improvement of our subsurface understanding.

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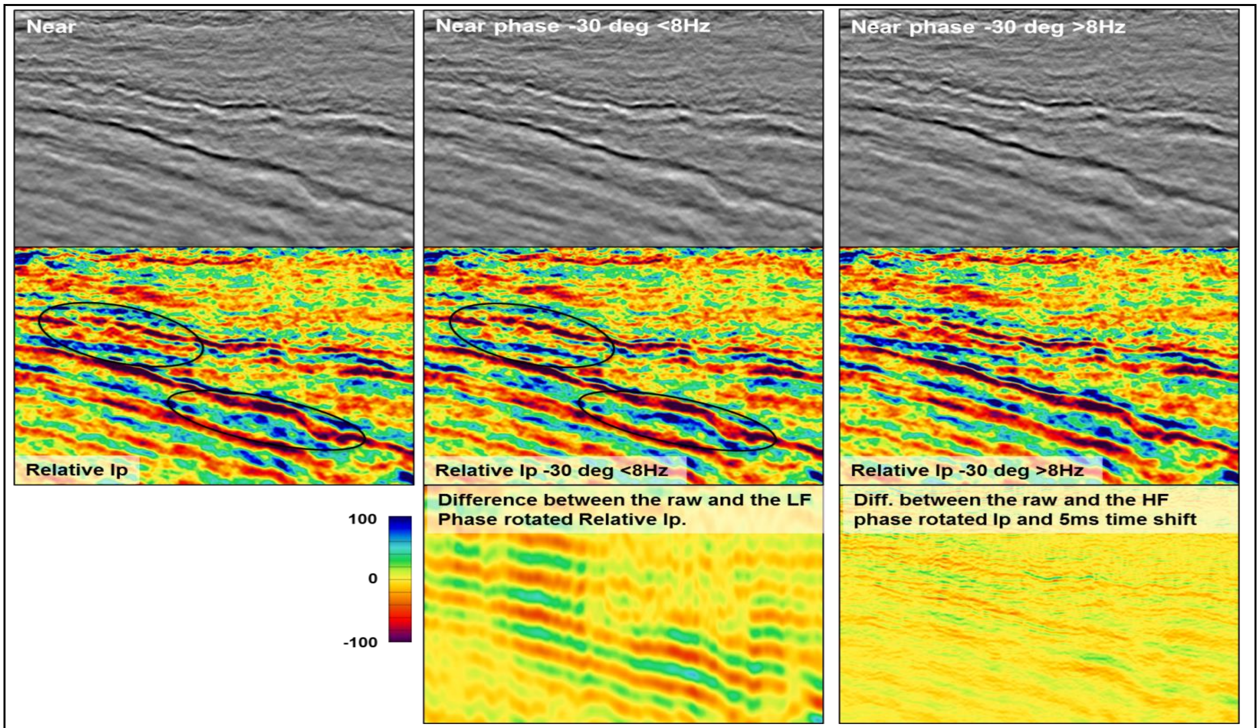

Figure 1: *Results of phase rotation (-30 deg) of low frequencies below 8 Hz (middle panel) and above 8 Hz (right panel). Below the near reflection stacks are the relative acoustic impedance inversion results (Relative Ip) for the different shifted frequency bands. A low frequency phase shift (in this 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, but which is not possible with low frequency phase rotation as this fundamentally changes the amplitude of the events.*

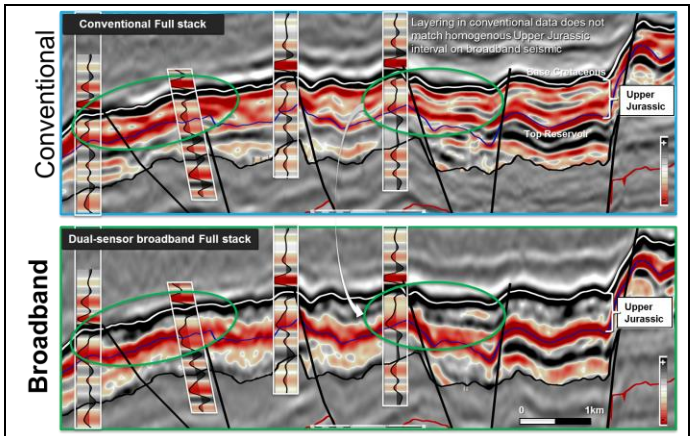

Figure 2: Conventional fullstack image with synthetics based on band-limited wavelet (upper image); 2012 acquired broadband with synthetics based on broadband wavelet (lower image)

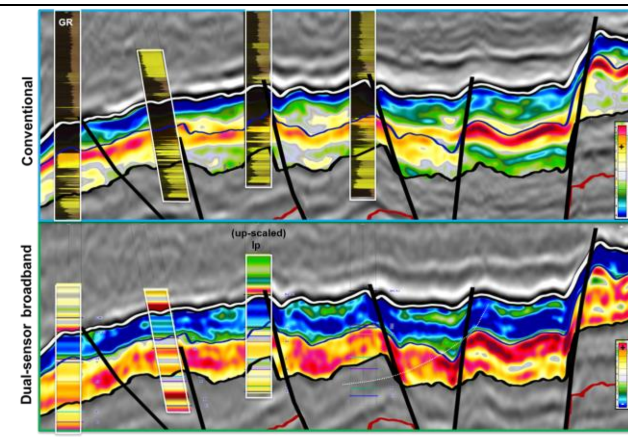

Figure 3: Relative pre-stack inversion results (acoustic impedance is displayed) from the band-limited/conventional seismic (upper image) and the 2012 acquired broadband relative impedance (lower image). The broadband relative acoustic impedance provides correct estimation of the shale thickness (blue layer – low acoustic impedance) observed at the well location and overall better match to the geology.

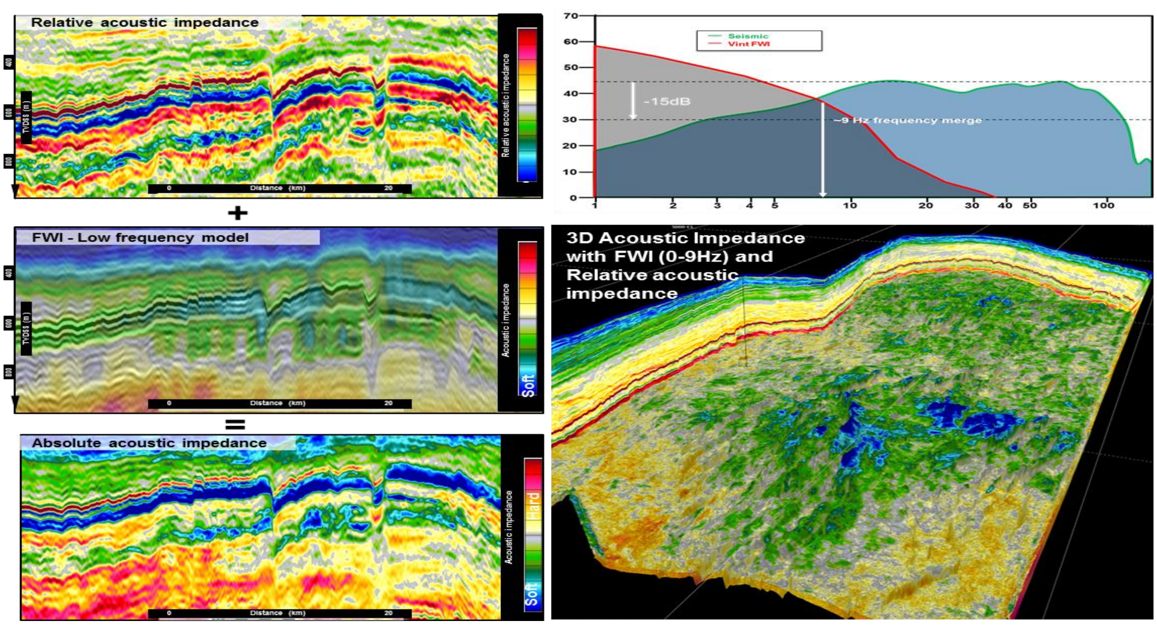

Figure 4: Absolute acoustic impedance (bottom left and right in 3D) obtained by merging scaled relative acoustic impedance (top left) with low frequency model derived from FWI compressional velocities.

EDITED REFERENCES

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