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Improving Seismic Reservoir Characterization With Broadband Seismic

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Abstract

Broadband acquisition and processing technology has revolutionized seismic acquisition and interpretation. The revolution is not complete however, as we continue to explore how broadband can affect our efforts towards reservoir characterization. In particular, we see the ultimate benefits for reservoir properties with unprecedented bandwidth and accuracy through simultaneous AVO inversion. When performing inversion on broadband seismic data there are some particular properties that need to be considered in different steps of the process. Additionally, careful thought has to be given on how to use inversion QC's to indicate the value of broadband seismic in the inversion stage. We will show some results from our initial experiences in this area.

Introduction

In recent years, the benefits of broadband seismic have been argued and illustrated for seismic interpretation (e.g., Duval, 2012; Reiser et al., 2012; Wallick and Giroldi, 2013), impedance inversion, (e.g., Soubaras and Lafet, 2011; Wallick and Giroldi, 2013) and impedance inversion with subsequent reservoir characterization (e.g., Lafet et al., 2012; Reiser et al., 2012; Kneller et al., 2013). These benefits can be attributed to the wider spectrum of broadband seismic relative to conventional seismic. Enhanced high frequency content leads to a sharper wavelet and therefore higher resolution images. Enhanced low frequency content reduces wavelet sidelobes, may eliminate the need for a low frequency model from interpolated well logs, and results in better signal penetration (see also ten Kroode et al., 2013).

Figure 1 compares typical seismic spectra of conventional and broadband acquisition and processing and indicates the potential for this new technology. The impact on structural interpretation has already been demonstrated to be dramatic (e.g., Duval 2012). We expect no less from our inversions for reservoir characterization. The impact of the low frequencies in particular is illustrated in Figure 2 where a stacked sandstone model has been filtered to show the effects of the low frequencies below the band of traditional acquisition and processing. By adding low frequencies the impedance values converge towards the true profile.

Of critical importance to inversion processes is wavelet estimation. Broadband, with its extended low frequency range, demands longer wavelets and therefore longer wavelet design windows. Innovative techniques are necessary to estimate the low frequency components of these wavelets while retaining relevance to the reservoir in the high frequency band. These issues were recently addressed by Schakel

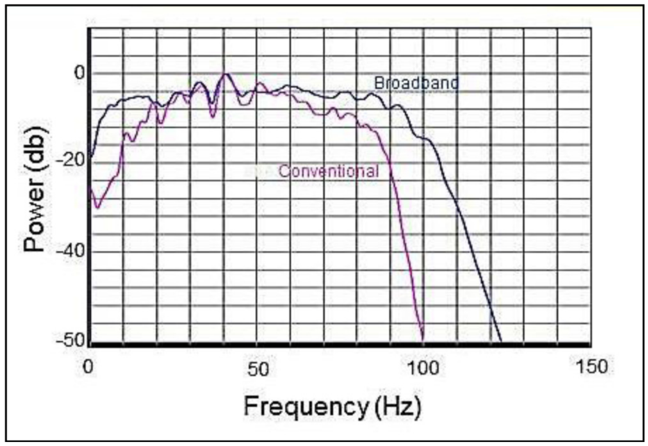

Figure 1—Comparison of conventional and broadband spectra

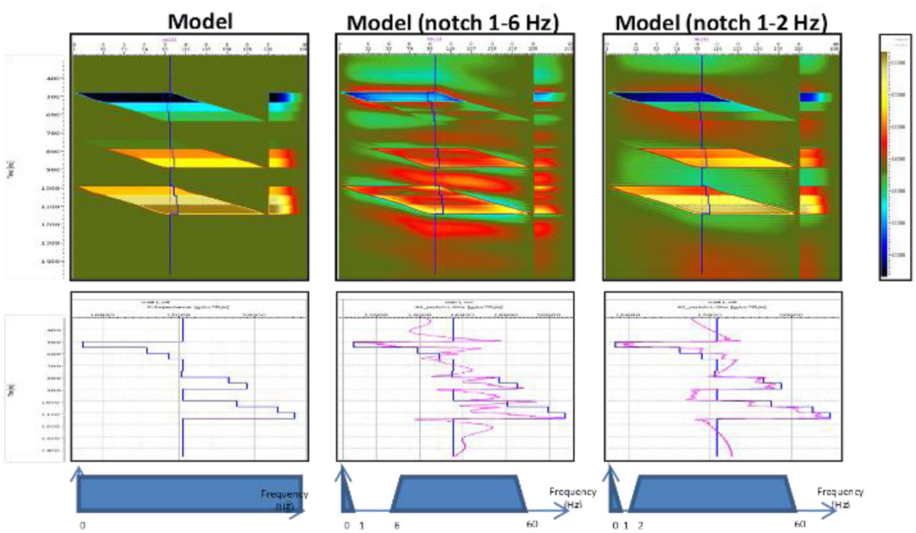

Figure 2—A stacked sandstone (impedance) sequence filtered to show the effects of the lowest frequencies recoverable from broadband

and Mesdag (2014). Seismic data was inverted using a low frequency model (0-2 Hz) derived from seismic velocities and a broadband wavelet constructed by merging both a high-frequency seismic-dominated wavelet and a low-frequency wavelet from a longer time window. Some results are shown in Figure 3. Note that the limits of the channel are much more confined and geologic-looking in the broadband inversion compared to the conventional. Lithofacies derived from inversions also showed more spatial heterogeneity as they are not constrained by low frequency models from logs.

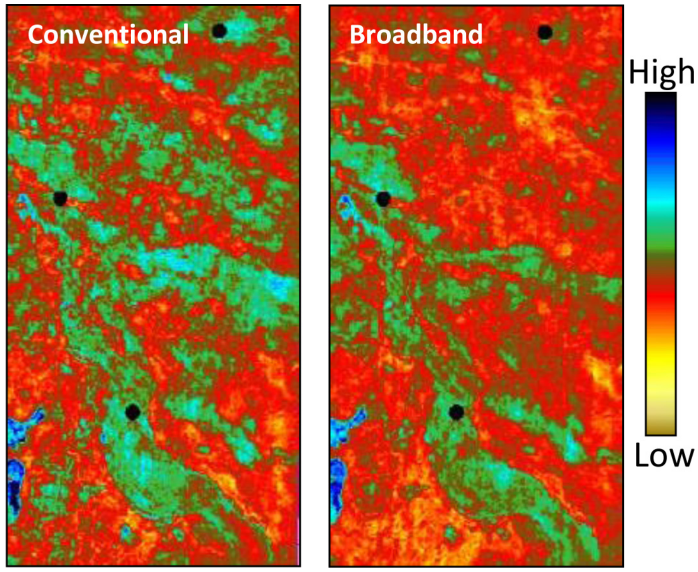

Figure 3—(from Schakel and Mesdag, 2014): Acoustic impedance inversion slice from conventional (left) and broadband (right). The sandstone channel is much better defined in the inversion of the broadband data.

In this paper several aspects of seismic inversion will be critically examined to show that careful thought has to be given on how to use inversion QC's to indicate the value of broadband seismic in the inversion stage.

Seismic inversion

For accurate reservoir characterization the seismic data needs to be converted to meaningful reservoir properties. An intermediate step towards reservoir properties is through elastic parameters. These elastic parameters are layer properties and are typically combinations of P-Velocity, S-Velocity and Density. Converting seismic data to elastic parameter data is called seismic inversion. There are several key components to seismic inversion:

- The wavelets
  Every seismic volume has its own wavelet. Processing takes great care to produce a zero phase wavelet. However residual corrections are commonly applied to it when inverting the seismic. Wavelets for seismic inversion need to be accurate both in amplitude and phase for all frequencies that are in the seismic data. Estimating wavelets for broadband inversion is more challenging than for conventional seismic inversion. It will be shown below how they can be estimated in current software packages.
- The low frequency trend or starting model
  In order to convert seismic data to layer properties the frequency band needs to be extended to zero Hertz on the lower end of the seismic spectrum. By nature of the physics this cannot come from the seismic data alone. So any inversion needs low frequency information to come from other sources. We will show that the requirements for the low frequency trend are a lot less demanding for broadband data. Consequently, the seismic inversion process is more driven by the data.
- The inversion engine
  Inversion algorithms use assumptions and constraints. These can positively or negatively affect the inversion results. For instance a popular constraint to use is the Gardner constraint. This constraint forces the density from inversion to follow the more stable P-Impedance. This is acceptable if the rock actually obeys the Gardner rule. At the same time this constraint can render the density useless as an independent parameter for reservoir characterization.

We will also discuss the effect of the sparsity constraint in the following sections

The Wavelets

Conventional seismic data typically has a low frequency cut off somewhere between 6 and 15 Hz. This cut off is dependent on the acquisition, the penetration of the seismic wave into the subsurface and the processing applied to the data. To capture these frequencies accurately in a wavelet the wavelet length needs to be between 60 ms (15 Hz) and 150 ms (6 Hz). The most accurate way to estimate a wavelet is by using well log information. For pre-stack seismic data you need P-Sonic, S-Sonic and Density well log curves. As a rule of thumb the time-equivalent extent of the curves, needs to exceed 2 to 3 times the wavelet length to achieve wavelet stability. Good quality well curves of sufficient length are not always available, but with good rock physics modeling it is generally possible to generate the necessary well log information.

On the other hand, for broadband seismic data, depending on the way they were acquired and processed the seismic low frequency cutoff is somewhere between 2.5 Hz and 4.5 Hz. This calls for wavelets that are in excess of 400 ms. Well curves that extend over a time interval of more than a full second are extremely rare. It is clear that well logs that are too short cannot entirely predict the necessary low frequency behavior of the seismic wavelets. To circumvent this limitation Schakel and Mesdag (2014) presented a two-step method to estimate broadband wavelets. In a first step the ‘best’ wavelet is estimated in a conventional manner and we will refer to it as ‘conventional wavelet’. In this process the wavelet length is made as long as the data will bear, i.e. the wavelet length is increased to the point where stability of the estimation process becomes an issue. In a second step the seismic amplitude spectrum is extracted using long time windows. The resulting smooth amplitude spectrum is colored by the well log amplitude spectrum and merged with the conventional wavelet phase spectrum. On the low frequency side of the spectrum, where the conventional wavelet phase is not defined, several hypotheses are tried out assuming smoothness of the phase spectrum in the seismic data. Every one of these hypothetical wavelets is carried through the inversion process. The inversions are carefully QC’ed and ranked to come up with a ‘best’ wavelet for broadband inversion. Examples of conventional and broadband wavelets estimated using well logs are shown in Figure 4.

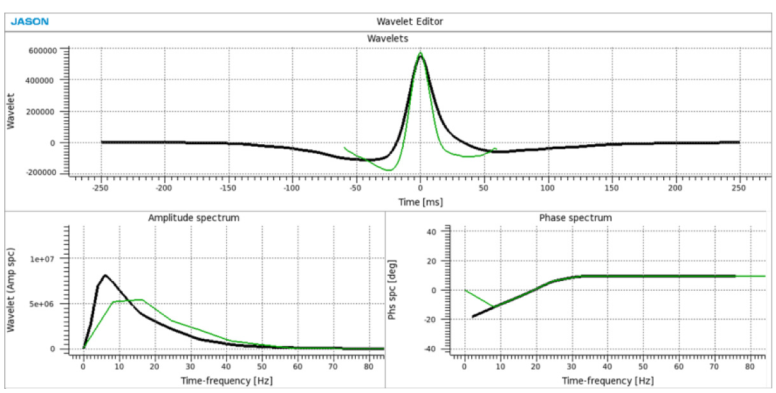

Figure 4—conventional (green) and broadband (black) wavelets

The low frequency trend or starting model

All inversions use a low frequency trend to replace the missing low frequencies in the seismic data. In addition some inversions use higher frequencies as a starting model. The low frequency trend is typically derived by horizon consistent interpolation and extrapolation of the well control. If the wells are poorly distributed, seismic velocities are used to control the lowest frequency band. The frequencies where the seismic velocities are to be trusted depend on their source. Typically, velocities from NMO or from migration are valid up to 2-3 Hz. Velocities from tomography and full waveform inversion can go a little higher. With conventional seismic data, where the missing frequencies are up to 6-15Hz there is a gap between where the seismic velocities are valid and where the seismic kicks in. To fill this gap you need to interpolate the well control. See Figure 5a.

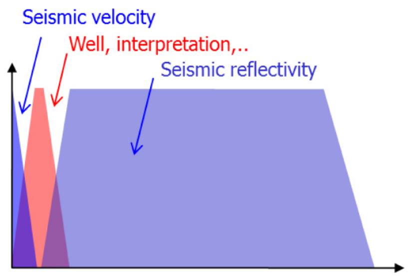

Figure 5a—Frequency coverage in conventional inversion

With broadband seismic data the gap between the seismic velocity information and the lowest seismic frequency is closed, at least if the seismic data go down to 2-3Hz (Figure 5b). For post stack PP inversion the low frequency trend is defined as P-Impedance. For pre-stack data you need three trends, P-Impedance, S-Impedance and Density or some other combination of Vp, Vs and Density. So the P-velocity model coming from processing needs to be transformed into P-Impedance, S-Impedance and Density for the frequencies that are valid in the velocity data. Typically the transformation is done with rock physics relationships and/or using well control as calibration points (e.g., Hak, 2015). For the ultra-low frequencies up to 3Hz the rock physics relationships are generally not too complicated and regional trends like Castagna's mudrock line or Gardner's rule can be used. It is always advised to validate the relationships and the trends used in the inversion by any available well control.

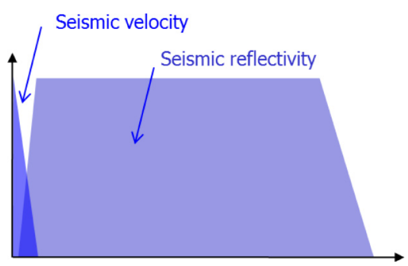

Figure 5b—Frequency coverage in broadband inversion

The inversion engine

Seismic inversion algorithms need an input model. At least for the missing seismic frequencies, but depending on the algorithm the input model may also be used as a starting model within the seismic frequency band.

Even if the algorithm only uses a specified maximum low frequency, some algorithms are able to fill the gap using sparsity assumptions. If the algorithm uses the input model up to a specified maximum frequency and a gap is left between it and the lowest frequency of the seismic data, some algorithms are still able to correctly predict the model. Figure 6 shows inversion results where we only use the low frequencies up to 2 Hz, while the seismic data extend down to 6 Hz. Even though there is a gap of 4 Hz, this is closed by the inversion algorithm. Of course this method only works for sparse models and will fail for instance for gradational transitions between layers.

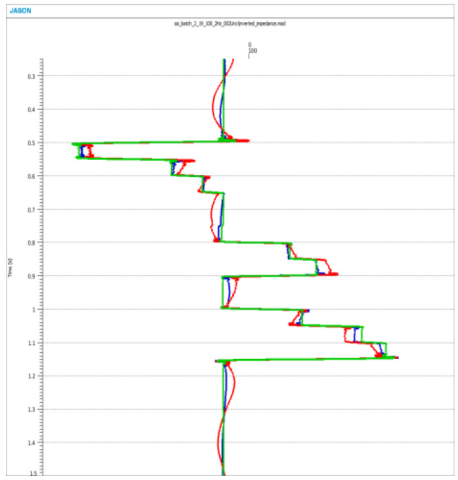

Figure 6—Sparse inversion of the layered sandstone impedance model from Figure 2. The sparsity is increasing from Red to blue to green.

The reason for bringing this up is that the power of broadband over conventional data sometimes is inferred using sparse synthetic models. Depending on the inversion algorithm, conclusions from sparse models need to be carefully scrutinized. So even the example shown in Figure 2 in the introduction should arguably not be used to prove the value of broadband data, unless the inversion algorithm is clearly stated. In fact, the inversion on synthetic models carried out with a sparsity-assumption algorithm would produce similar results for both 2-6 Hz and 1-2 Hz frequency-gap cases.

Inversion QC

In the literature we find many amazing examples of the quality of broadband seismic data over conventional seismic data. The inversion results are no less astonishing even if we ignore the cases where the conventional inversion may be biased by the low frequency model. Broadband inversions give a better match to blind control wells, geobodies are more clearly defined and lithology classification can be performed with less uncertainty.

However, away from well control the inversion QCs are always interpretive. You can find yourself arguing whether a detail is real or false: Is the one inversion result better or worse? In the introduction we suggested that the right hand panel of Figure 3 was the preferred result, but how do we fully prove that unless we have a blind well going through that feature? What is the value of a clearer image or reduced side lobes? In the end only the interpreter and the oil company can put value on the features that are seen in seismic inversions. The inversions need to go through the whole cycle of interpretation, drilling and production to prove their value.

An often used QC for inversion results is where the inversions are overlaid by a control well. Here too we must be careful to judge what we see, as most inversions use the well log information as a starting model in the inversion and most inversions use the low frequencies from the wells to fill the gap with the seismic data. So in fact a conventional inversion will generally look better when compared at the well control, as it is using more of the well information in the inverted result. An example is shown in Figure 7. Here the same high cut filtered (100 Hz) well log is overlain on the broadband and conventional inversion results. The 2-6 Hz frequency band comes from seismic in the broadband and from the well log in the conventional inversion. The uncertainty in the inversion in these frequencies would make the casual user incorrectly prefer the conventional inversion away from well control. In fact, the well control in broadband inversions gives a better estimate of the uncertainty for reservoir characterization. A more appropriate QC to compare broadband and conventional inversions is the match to blind control wells.

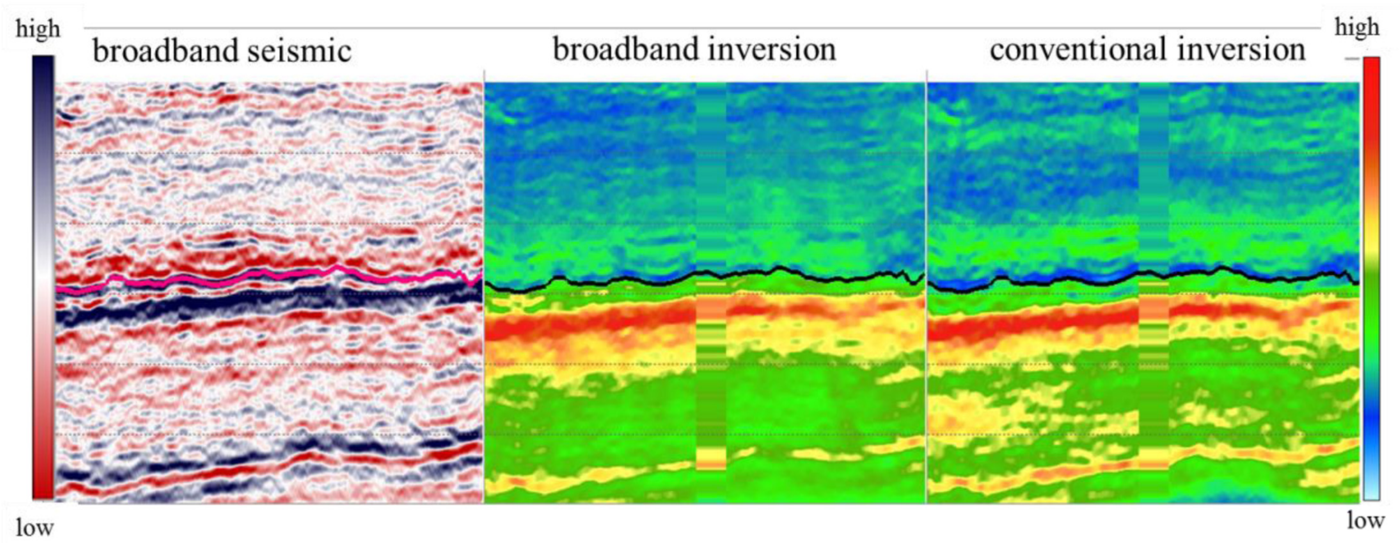

Figure 7—Broadband seismic and the broadband and conventional inversions with the P-Impedance well log in overlay.

Conclusions

Although the results of broadband seismic inversion can only be fully proven after the whole cycle of interpretation, drilling, and production, it delivers real value to the reservoir characterization. Of critical importance to broadband and all inversions is the estimation of the seismic wavelet(s). Variability in time, space and offset are all important and deserve our greatest attention.

An abundance of cases favor broadband data over conventional data, and this is also true for seismic inversion. Favoring one inversion result over the other by investigating their match at well control can be biased by the extent to which the control well is used as the starting model for inversion.

Acknowledgments

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