Marine broadband seismic: Is the earth response helping the resolution revolution?

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Summary

Broadband seismic aims to provide a greater richness of both (a), robust low frequencies – ideal for deep structure imaging, and (b), high frequencies – which aid temporal resolution. However, the earth response will act as a frequency filter by attenuating high frequencies at a greater rate than low frequencies, a physical phenomenon described by the quality factor, Q. In this paper we consider effective attenuation, Q_{eff}, which is the inseparable combination of intrinsic attenuation, Q_{int}, and apparent attenuation, Q_{app}. This paper evaluates the changes in spectral content of broadband seismic versus conventional marine seismic through simple synthetic earth models. Results show that resolution of thin layers of sandstone (~50m) may not be resolved in broadband seismic where values of Q_{eff} are at typical values found in prospective basins such as the North Sea (Europe). In conclusion, this paper suggests that while broadband seismic is desirable, solving for the effects of effective attenuation, Q_{eff}, will be required to prevent a loss of resolution in some geological settings.

Introduction

Substantial moves have recently been made towards providing the industry with broadband marine seismic data. (Parkes and Hegna, 2011; Soubaras and Lafet, 2011). The aim is to remove the constraints imposed by the marine acquisition system in order to move towards the true earth response. Broadband seismic will provide a greater richness of both (a), robust low frequencies – ideal for deep structure imaging, and (b), high frequencies – which aid temporal resolution.

Comparisons of conventional and broadband reflectivity data in literature show the expected differences in amplitude spectra and these papers highlight the benefits of this broadband image. However, an in-house comparison between conventional and broadband seismic images (figure 1) from the Dutch Bank Basin (UK, North Sea) indicated variable results. The broadband image provides improved resolution in the Tertiary and Cretaceous sediments (green oval), however, at about the same two-way time, the Jurassic and Triassic section in the same image (red oval) is dominated by low frequencies. In this region, interpretation is better made on the 'conventional' image.

In this paper we evaluate the lack of resolution in parts of the broadband seismic and propose that it is a result of the earth's response, or more specifically, spatial variations in the effective attenuation, Q_{eff}.

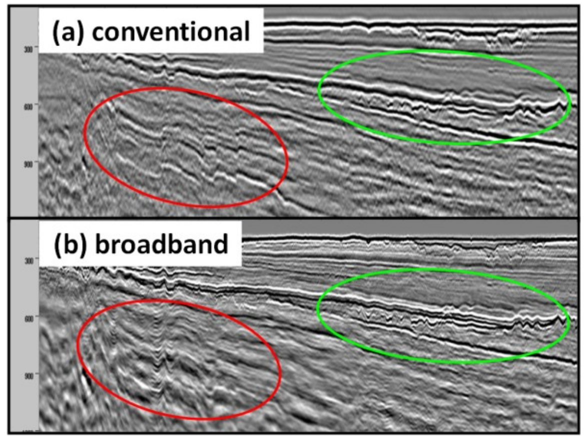

Figure 1. A sample 2D marine seismic section, (a) as a conventional image, and (b), as a broadband image. Image quality within the two highlighted regions are described in the text.

Theory

The exponential decay of seismic amplitude can be represented as a function of frequency by the relationship

$$A(f) = A_0(f)e^{-\alpha(f)z} . \quad (1)$$

$A_0(f)$ is the amplitude before propagation of the source wavefield and $A(f)$ is after propagation. For vertical incidence, z is depth and α contains all frequency dependent attenuation effects which can be expressed as

$$\alpha(f) = -\frac{\pi f}{Q_{eff}(f)V}, \quad (2)$$

where V is the phase velocity and Q_{eff} is the quality factor, given in the form considered most appropriate for seismic exploration: effective attenuation, Q_{eff}.

The quality factor is often considered as a singular term describing energy loss as a result of the propagation media; this is called intrinsic attenuation Q_{int}. Many authors provide intrinsic attenuation measurements (for example Gadallah and Fisher, 2005; Yilmaz, 2001), and Q_{int} values have been defined using expressions based on P-wave velocity (Li, 1993; Sheriff and Geldart, 1995), inferring a positive regression between the two. However, actual earth responses may suggest a negative regression with velocity (Hustedt and Clark, 1999). This can be considered due to attenuation linked to the propagation of seismic waves, such as scattering, transmission, mode conversion etc,

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which is called apparent attenuation Q_{app}. These two effects are combined to describe the complete attenuation to the seismic wave, called Q_{eff}, and is summarized as

$$\frac{1}{Q_{eff}} = \frac{1}{Q_{\mathrm{int}}} + \frac{1}{Q_{app}}. \qquad (3)$$

The amplitude decrease and the preferential loss of higher frequencies is only one part of the full picture, as the seismic wave changes phase during propagation. This is because velocity dispersion must occur in order for the signal to remain causative as it propagates through absorptive medium (Aki and Richards, 1980; Futterman, 1962). In this paper, however, we do not evaluate the effects of phase, as phase-only inverse-Q filters are common in the processing of both conventional and broadband seismic. Our aim here is to understand the apparent resolution challenges resulting in the relative changes to the frequency/power spectrum.

Model Studies

We evaluated a simple 1D model where we compare a broadband source wavelet, with a ‘flat’ frequency spectrum from 2 to 200 Hz (figure 2; green spectrum), versus a ‘conventional’ source wavelet (figure 2; red spectrum) which has ghost notches associated with a source depth of 7m and a receiver depth of 9m.

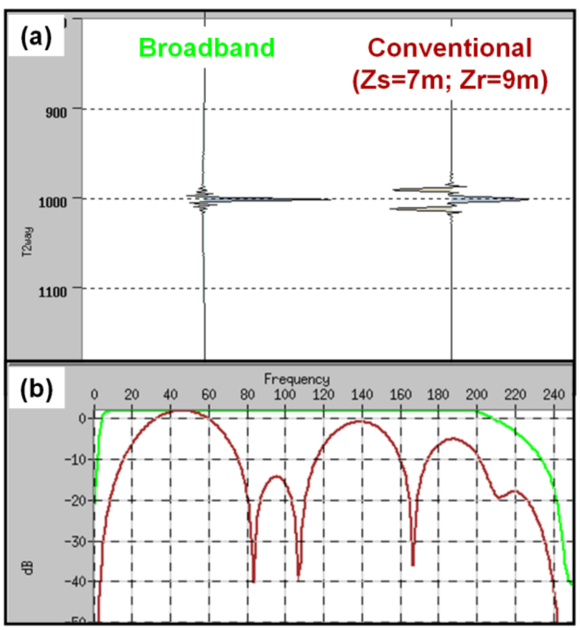

Figure 2. (a) Synthetic broadband and conventional marine (recorded) source wavelets used in the model studies described in the text; (b) associated frequency spectra.

These input source wavelets were then convolved with a synthetic earth model, where the seabed is at 1000 ms of two-way time and has a series of positive reflection coefficients thereafter. The earth model was given a constant value of effective attenuation, Q_{eff}. This was varied; however, we initially present results in this paper with a value of 110, which is a value considered common for the North Sea.

Figure 3(a) shows the broadband and conventional recordings derived from the synthetic model at 3000 ms of two-way time. The frequency response (figure 3(b)) indicates the dominance of lower frequencies in the broadband recording. Once the frequency responses are normalized, the useful bandwidth in the conventional recording appears much broader than in the broadband data.

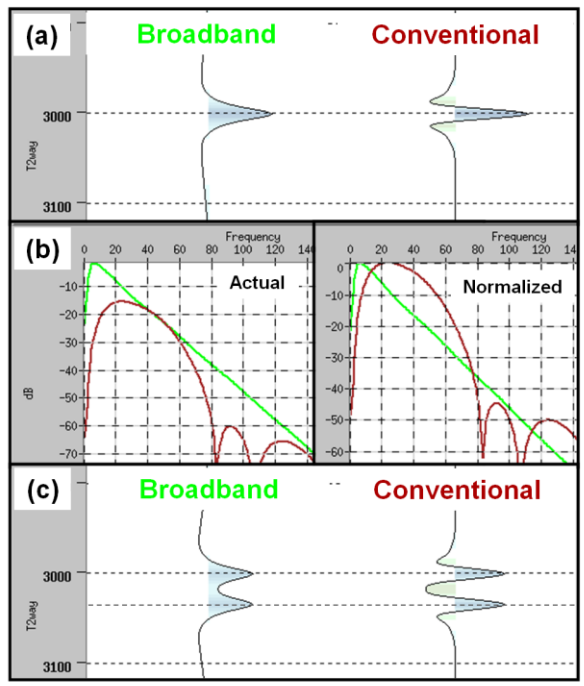

Figure 3. (a) synthetic time recordings at 3000 ms of two-way time (after propagation through an earth model with constant Q_{eff} = 110 – seabed at 1000 ms); (b) Actual and normalized frequency spectra; (c); time recordings – from a second earth model with a thin (~50m) sandstone layer beginning at 3000 ms of two-way time.

A second synthetic earth model was created to include thin rock layers. These rock layers represent about 50 m of sandstone, with a seismic velocity of 3000 m/s. At 3000 ms of two-way time, the broadband recording is only just about able to resolve the top and base of these layers (figure 3(c)). An incorrect interpretation may be made without careful

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attention to the gain levels and color scales used to display the image.

Figure 4(a) shows the broadband and conventional recordings derived from the synthetic model at 5000 ms of two-way time. At these depths the frequency response (figure 4(b)) suggests a pronounced dominance of lower frequencies in the broadband recording. At 5000 ms of two-way time, the 50 m sandstone layer cannot be resolved in the broadband recording (figure 4(c)). However, the same thickness of sandstone may be resolved in the conventional recording, as the normalized frequency spectrum indicates.

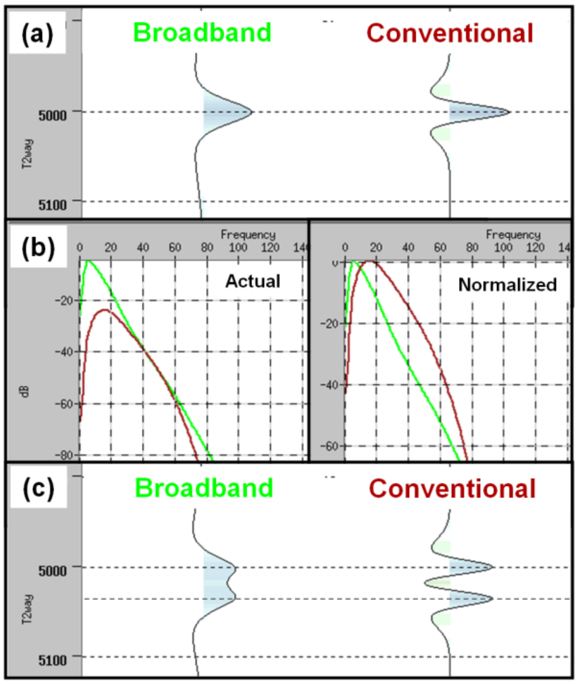

Figure 4. (a) synthetic time recordings at 5000 ms of two-way time (after propagation through an earth model with constant Q_{eff} = 110 – seabed at 1000 ms); (b) Actual and normalized frequency spectra; (c); time recordings – from a second earth model with a thin (~50m) sandstone layer beginning at 5000 ms of two-way time.

A final model was made in order to confirm the variations in resolution seen in the sample 2D seismic in figure 1. This model was created to simulate some of the geological features imaged in the seismic. This synthetic model, shown in figure 5, consists of a sample thin layer in the Tertiary section with an effective attenuation, Q_{eff} = 180, and a sample thin, highly faulted, layer in the Jurassic/Triassic section with an effective attenuation, Q_{eff} = 50. The seismic recordings from this model indicate the inability to truly resolve the Paleozoic horizons in the broadband image (figure 5(b)) – even though they are only imaged at 1000 ms of two-way time below the seabed.

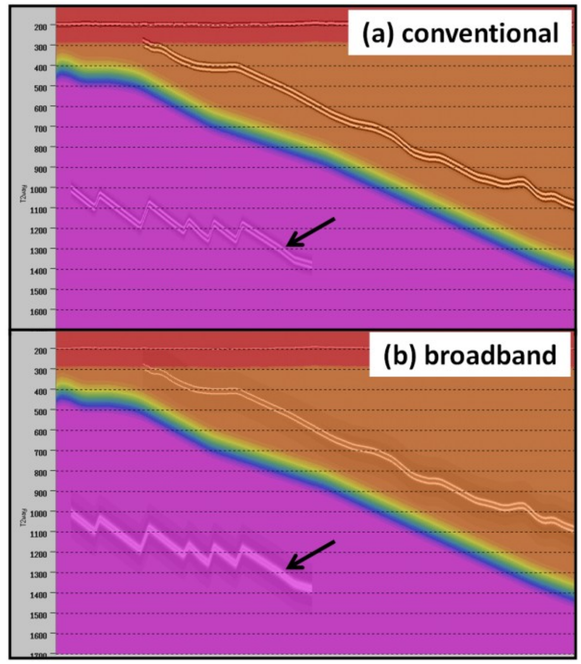

Figure 5. Seismic images of a synthetic model consisting of sample horizons in the Tertiary section (orange zone) which has an effective attenuation Q_{eff} = 180; and sample horizons in the Jurassic/Triassic section (purple zone), which has an effective attenuation Q_{eff} = 50. (a): Image with conventional seismic; (b): same image with broadband seismic. The arrow indicates the sample geological layer that in not resolved in the broadband seismic.

Conclusions

Broadband seismic enables us to move closer towards the ideal goal of imaging, which is to provide the true response of the earth. However, the effective attenuation of the earth response may hinder resolution in some geological settings. Figure 6 indicates the pronounced change in wavelet shape induced in broadband seismic recordings by the effective attenuation of the earth response, which is much less of a problem in conventional seismic recordings.

We believe the model studies described in this paper infer that a true broadband image can only be obtained after correctly inverting for the effects of effective attenuation, Q_{eff}, in the earth response. It is naïve to assume that 'broadband' acquisition alone will automatically lead to seismic images that are very broadband and focused. However, an important feature of broadband seismic is that more accurate measurements of the effective attenuation

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can be calculated from the data itself (Parkes and Hegna, 2011).

We can therefore, conclude that broadband seismic methodologies coupled with seismic processing techniques, which correctly determine and solve for the effects of effective attenuation, will move the industry towards the goal of images that are very broadband and focused. However, where severe attenuation has reduced the high frequency signal content to below the noise level, the effective attenuation may not be reversible without vigorous noise attenuation techniques.

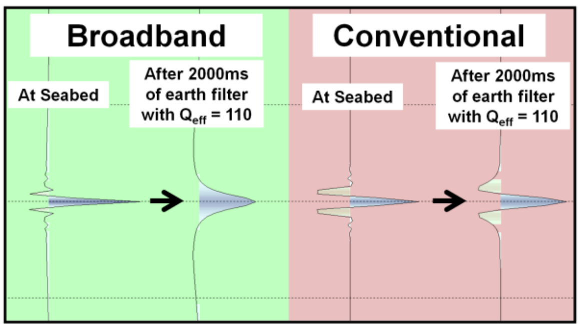

Figure 6. Synthetic seismic wavelets taken from two time locations in a 1D model. Note the change in wavelet shape for these 4ms wavelets. Note especially the differences between broadband and conventional seismic.

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EDITED REFERENCES

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