Enhanced imaging using bandwidth extending operators and pre-stack Q-inversion over the northwest European volcanic margin

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Summary

Extensive sequences of flood basalts dominate the northwest European Atlantic margin. The basalt flows absorb and scatter the higher frequencies present in any source wavelet through intrinsic and apparent seismic attenuation. Successful sub-basalt imaging therefore tends to focus on the generation of low frequencies in acquisition and retention in processing. Conversely, the Rosebank discovery in the Faroe-Shetland Basin of oil bearing sequences interbedded within the Basalt illustrates that high frequencies need to be recovered in order to delineate subtle stratigraphic plays. For this we require broad bandwidth, a robust approach to signal to noise improvement and accurate knowledge of the seismic quality factor (Q) to compensate for locally strong attenuation effects. We show that the required bandwidth can be obtained from conventionally acquired seismic data through the use of low and high frequency boosting operators and application of a horizon consistent Q field. The latter is derived using the pre-stack Q-inversion (PSQI) method to determine effective Q in defined intervals from the data itself. Through a combination of both techniques a substantial uplift in resolution is demonstrated for the highly prospective intra-basalt units with useable frequencies up to 50Hz.

Introduction

The vertical and lateral inhomogeneity of flood basalt flows along the northwest European Atlantic Margin results in the loss of temporal bandwidth and signal. All but the lowest frequency seismic energy penetrating the basalt becomes incoherent through a combination of anelastic (intrinsic) attenuation and elastic back-scattering (apparent attenuation). Sub-basalt imaging has therefore concentrated on the enhancement of low frequencies in the source amplitude spectra, usually by towing streamer cables deeper through constructive interference of the free surface ghost effect. The Rosebank discovery of oil bearing sands in the Flett formation interbedded within basaltic flows (Figure 1(b)) demonstrates the need to be able to delineate subtle stratigraphic features which conversely require higher frequencies.

The loss of higher frequencies can be compensated using inverse-Q filters, but requires knowledge of the seismic quality factor, effective Q (Q_{eff}), that accounts for both intrinsic and apparent attenuation in each interval of interest. In the absence of in-situ measurements from VSPs, it is desirable to determine Q_{eff} from surface seismic data directly. Here we describe the derivation of a spatially varying, interval consistent Q_{eff} field using the pre-stack Q inversion (PSQI) method from the data itself (Reine *et al*., 2012). This is applied to an existing 2D long offset seismic database in the Faroe-Shetland Basin close to the Rosebank discovery. In combination with bandwidth extension techniques we demonstrate a significant improvement in the temporal resolution of interbedded clastic sequences within the basalt.

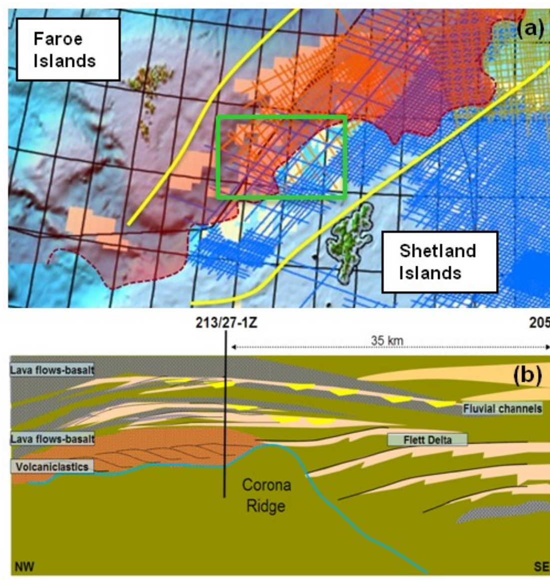

Figure 1: (a) Area of the PSQI study outlined in green and the extent of flood basalts along the northwest European Atlantic margin outlined in red. TGS' underlying 2D survey is shown with the region between the yellow lines recently reprocessed; (b) simplied cross section of the Rosebank discovery at the confluence of volcanic and sedimentary interaction from Duncan *et al*., (2009).

Bandwidth extension using low and high frequency boosting operators

The data set taken into the PSQI study forms part of a two year program commenced in 2010 to reprocess approximately 70,000 km of TGS' 2D seismic database from the Faroe-Shetland Basin in the south to the Barents Sea in the north crossing the volcanic margin (Figure 1(a)). These data were acquired with conventional acquisition parameters (typical gun volume ~ 4,600 cu in; source depth ~ 7 m; cable depth ~ 9 m). At the beginning of processing we apply operators that enhance both the low and high

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frequency components of a source wavelet amplitude spectra averaged from the data rather than utilizing a modeled signature. In this way we simulate the effect of deep towed acquisition but maintain a broad band response out to the first source/receiver ghost notch at ~ 80 Hz (Figure 2(a)) without compromising the resolution of overlying Eocene sediments.

Boosted noise is cancelled by a multi-domain approach in processing (e.g. Hardwick *et al*., 2010; Woodburn *et al*., 2011) and provides a cost effective alternative to new broadband acquisition in the area. Enhancement of the high frequencies should allow more accurate natural log spectral ratios to be estimated as part of any Q_{eff} compensation scheme relative to the flattened source amplitude spectra in Figure 2(a). We take the data with extended bandwidth into the PSQI method described in the next section.

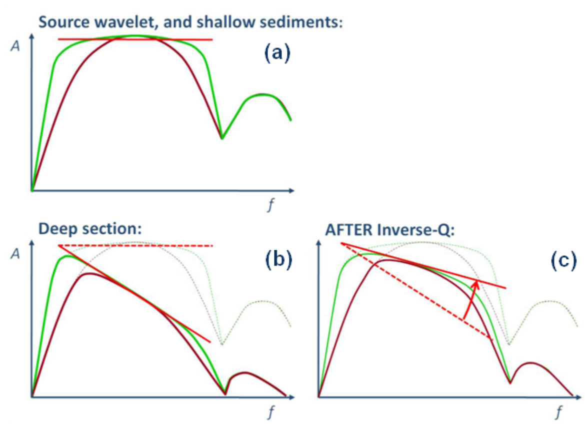

Figure 2: (a) Amplitude spectra of the source wavelet before propagation (red) and after application of low and high frequency boosting operators (green); (b) sub-basalt section after earth filtering effects and (c) after inverse-Q filtering

Pre-stack Q inversion (PSQI) method

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 a frequency dependent non-dimensional term that accounts for the inseparable combination of intrinsic attenuation (Q_{int}) and the propagating wave (Q_{app})

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

Crude estimates of Q_{eff} can be made by calculating the spectral ratio between a shallow reference and deep window on stacked data. The analysis however, should be performed pre-stack such that z in Equation (1) is the length of any given raypath connecting a source-receiver pair and becomes offset dependent. The PSQI method can determine Q_{eff} within defined intervals directly from CMP gathers following on from the Q versus offset (QVO) method (Dasgupta and Clark, 1998). Q_{eff} can be determined directly in the time-offset or tau-p domain where equivalent raypaths have the same constant slowness. The process is split into three parts:

- Tracking of key seismic reflection events in the domain of choice
- Transformation into the frequency domain via the *S*-transform using a variable time window
- Calculating the natural log spectral ratio surface and inversion for Q_{eff} through regression for the best fitting surface (Figure 3).

Advancements to the PSQI method for this study include the implementation of a 1-D ray tracer, improved tracking of events with a bandwidth constraint and the ability to use a time and space variant eta (η) field to account for anisotropic effects (Whittaker, 2011). With these improvements the method can be considered semi-automated and analogous to undertaking a velocity analysis.

Application to data in the Faroe-Shetland Basin

The data taken into the PSQI analysis needs to be sufficiently free of noise and multiple interference such that the key seismic reflections bounding the chosen intervals can be tracked out to far offsets. It is also of high importance that the pre-processing steps do not adversely affect the spectral content of the data. The input data set benefits from the bandwidth extension and multi-domain noise attenuation described earlier along with a robust demultiple sequence containing 2D SRME and hi-resolution Radon. As the low and high frequency boosting operators are applied globally this has no impact on the estimation. Each processing step was rigorously checked for its Q "friendliness" and analysis was undertaken in three intervals in both the time-offset and tau-p domains:

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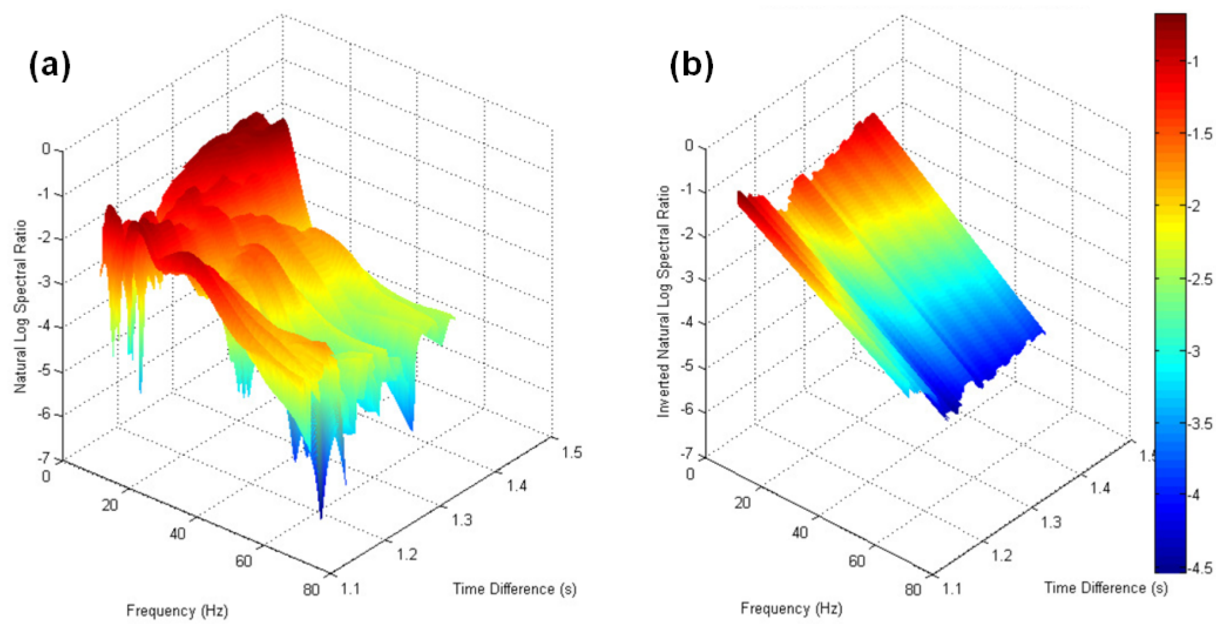

Figure 3: (a) The natural log spectral ratio surface for an example CMP in the seabed to top Balder interval. Spikes are caused by spectral interference effects. (b) The best fit surface to the data in (a).

- Seabed to top Balder formation above the basalt
- Balder formation to top Lamba formation including the basalt series and Flett formation
- Top Lamba to Vaila formation

Results

The Q_{eff} field derived from the time-offset domain analysis proved more consistent. The tau-*p* domain is more attractive for tracking reflection events as they do not cross but aliasing issues and transform artifacts require further consideration. A full statistical analysis was undertaken on the three intervals to remove spurious or anomalous values and the two sub-basalt intervals amalgamated. The derived Q_{eff} field is shown in Figure 4.

In the water bottom to Top Balder interval, Q_{eff} values fall within a range comparable to Tertiary sediments in the North Sea. The basalts thin and pinch out to the southeast, terminating against the flank of the Corona Ridge. As we move northwest onto the Faroe-Shetland escarpment the basalt thickens and becomes less heterogeneous. Not surprisingly, lower Q_{eff} values are obtained as it dominates the interval from top Balder to top Vaila used within the PSQI analysis. Low Q_{eff} values for the basalt here are comparable to VSP based measurements from the Brugdan I well further to the west. Figure 5 shows the application of the derived Q_{eff} field to the data, and within the Flett formation we observe a significant improvement in seismic resolution without compromising the sub- basalt image. Comparative amplitude spectra before and after application of the PSQI field show usable frequencies up to 50Hz within intra-basalt sequences (Figure 5(c)).

Conclusions

The PSQI method shows considerable promise as a method to determine Q_{eff} within defined intervals from surface seismic data in the absence of direct measurement from VSPs in a volcanic province. Through bandwidth extension and application of appropriate inverse-Q filtering, we show that frequencies of up to 50 Hz can be achieved in intra-basalt sediments using conventionally acquired data. Similar seismic attenuation studies need to be performed on modern broadband data acquired in the northwest European volcanic margin to determine whether they bring further uplift.

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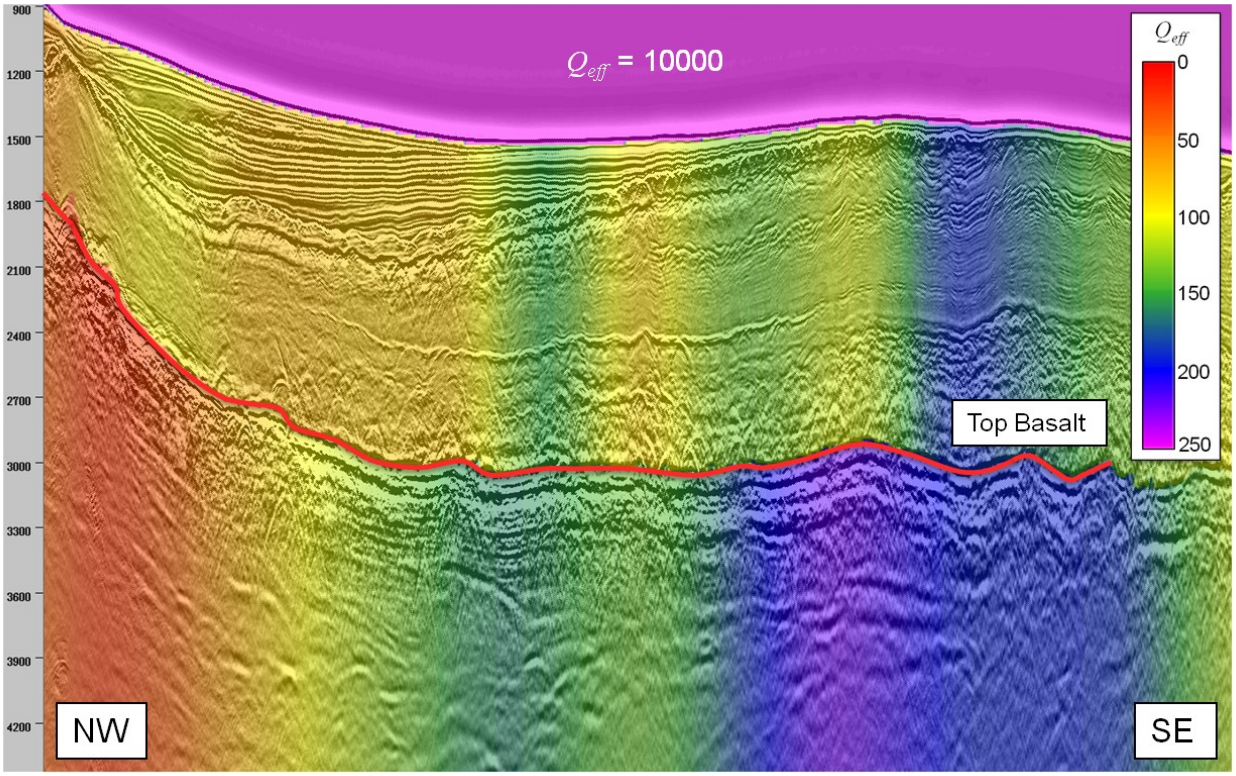

Figure 4: Q_{eff} field derived from surface seismic data. The water column is fixed with a constant Q_{eff} of 10,000. Q_{eff} values decrease in the second interval as the basalt thickens to the northwest onto the Faroe-Shetland escarpment.

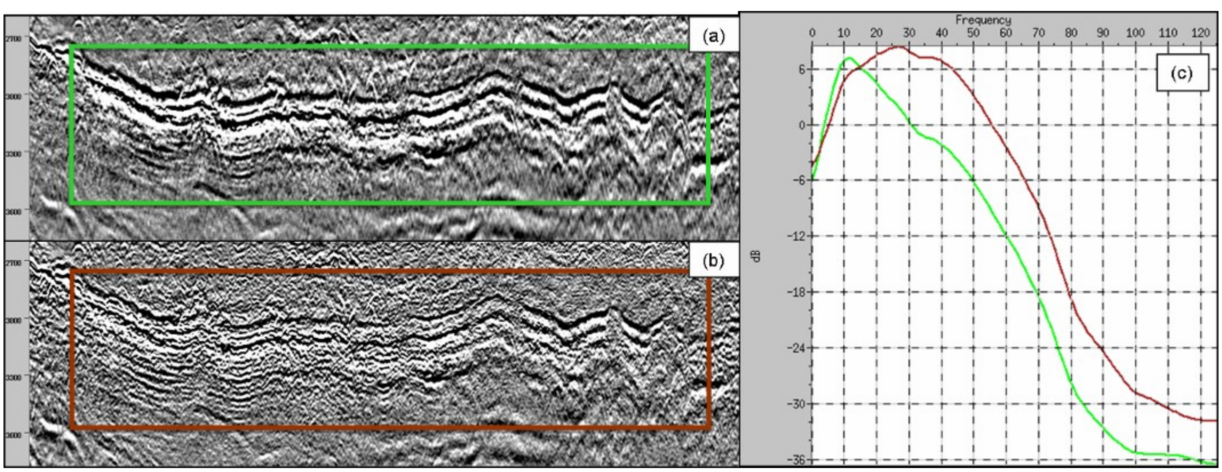

Figure 5: Zoom of stacked data focusing on the intra-basalt Flett formation before (a), and after (b), application of the Q_{eff} field shown in figure 4. Corresponding amplitude spectra are shown in (c).

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EDITED REFERENCES

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