Improved signal processing for sub-basalt imaging

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Abstract: Sub-basalt imaging continues to provide a challenge within the West of Shetland region. Successful imaging is being achieved through the reprocessing of 2D reflection seismic data. These were acquired with conventional source array and streamer parameters and include key signal processing techniques. The first technique involves spectral processing to boost low-frequency signals at the early stages of processing. The second technique involves attenuating coherent and incoherent noise in all of the available ‘time-offset’ domains. Examples of the data after application of these techniques are presented and clear improvements over the original processing are demonstrated. As work on these reprocessing methods has progressed, the benefits of moving to a true broadband processing solution have become clear.

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The Faroe–Shetland Basin is bound to the SE by the West Shetland Platform and to the NW by the Fugloy Ridge. Voluminous Palaeogene intrusive and extrusive igneous material is found within the basin in the form of continental flood basalts, hyaloclastites, sill and dyke complexes, igneous centres, mafic magmatic underplating and the deposition of regional tuff horizons associated with the opening of the proto North Atlantic Ocean (Naylor et al. 1999; Lundin & Doré 2005). The Corona Ridge approximates the limit of extrusive volcanic units which gradually thicken to the NW, exceeding 6 km onshore Faroe Islands (White et al. 2003). These volcanic units, present as heterogeneous high-velocity layers, continue to provide a challenge for seismic imaging of the prospective sedimentary units beneath. Lower-frequency energy in the source wavelet is more likely to penetrate through the basalt than higher frequencies as it is less attenuated by intrinsic absorption, and less scattered by the heterogeneity of the basalt reflectors (Ziolkowski et al. 2003). A solution to providing improved images beneath basalt flows is therefore to generate, retain and enhance as much low-frequency energy as possible.

Various methods of generating low-frequency signal have been proposed and employed in the last 10 years. While accepting that carefully parameterized acquisition can be used to provide a greater richness in low-frequency signal, Gallagher & Dromgoole (2007) and Hardwick et al. (2010) conclude the sub-basalt image is primarily dependent on the careful retention and enhancement of low-frequency signal at all stages of the processing.

In 2010 TGS began a program to reprocess 70 000 km of its 2D seismic database across the NW European Atlantic Margin, including 20 000 km from the West of Shetland region. These long-offset data were acquired with conventional acquisition parameters (typical gun volume c. 0.075 m³, or 4600 cubic inches; source depth c. 7 m; cable depth c. 9 m). The solution to providing successful sub-basalt imaging for these data is down to careful signal processing. The key signal processing techniques are described in the following sections.

Spectral processing: low-frequency boost

After conversion to zero-phase at the beginning of data processing, the recorded source wavelet is manipulated in order to enhance the signal at the low-frequency end of the amplitude spectrum. The low-frequency components of the wavelet are edited and shaped to generate a target wavelet and appropriate zero-phase matching operators, one operator for each vintage of seismic acquisition.

An example input wavelet, low-frequency boosting operator and output wavelet is shown in Figure 1. The amplitude spectrum of the operator (brown line) indicates a maximum boost of c. 12 dB. This maximum boost is centred in the 3–7 Hz frequency band where signal levels drop off rapidly in the input spectrum (green line), thus providing the greatest uplift where it is most required. The operator also provides a smooth increase in the 7 Hz to peak frequency range to approximately simulate a deep towed source array. This apparent spectral shaping is in alignment with some key findings made in an evaluation on the spectral output of marine airgun arrays by Parkes & Hegna (2011).

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Fig. 1. Spectral analyses of a sample input zero-phase wavelet (green line), the low-frequency boosting operator (brown line) and the output wavelet (orange line). The red shaded region indicates the 3–7 Hz band where the operator provides maximum boost. The yellow shaded region indicates the 7 Hz to peak frequency band where the operator boost simulates a deeper towed source.

Fig. 2. Example stack section (a) before and (b) after application of the low-frequency boosting operator, with accompanying normalized spectral analyses (spectra calculated from data within the green and red boxes). Red spectra represent data before boost; green spectra after boost.
They suggest there are inherent restrictions imposed on the low-frequency signal. Their assessment indicates an almost fixed decay in signal levels between c. 3 and 7 Hz irrespective of airgun array size, design and tow depth. Rather, modifications to source arrays will alter the low-frequency content from c. 7 Hz to 30–40 Hz.

A similar concept for low-frequency spectral manipulation was proposed by Masoomzadeh et al. (2006) using spectral whitening before the final

![Normalized spectral analyses of source wavelets derived from six separate common p-planes. Each common p-trace represents a unique emergence angle; the values are provided in the display.](image1)

![Example NMO-corrected CMP after several key pre-migration processing stages: (a) after SRME multiple attenuation; (b) after noise attenuation in the shot and receiver domains; (c) after radon multiple attenuation; (d) final pre-processed gather – ready for pre-stack migration. Maximum offset = 10 km. Green dashed lines indicate top and base of basalt layer.](image2)
stack. Moving to a pre-stack application is important, and the decision to apply the boosting operator at the beginning of the data processing sequence is considered key for the following two reasons. Firstly, as the boosting operator does not discriminate between signal and noise, the poor signal-to-noise ratio common at low frequencies is not improved after the simple process of applying the operator (see the red lines in Fig. 1). However, by applying the operator at the start of processing, the noise component assumes its true prominence relative to the flattened signal amplitude spectrum. This in turn enables the full suite of signal enhancing components in the processing sequence to

Fig. 5. Example stack image after several key pre-migration processing stages: (a) after SRME multiple attenuation; (b) after noise attenuation in the shot and receiver domains; (c) after radon multiple attenuation; (d) final pre-processed gather – ready for pre-stack migration.

Fig. 6. Example processing flow used to reprocess 2D seismic data in the West of Shetland region. The flow chart indicates the position of the noise attenuation stages (blue boxes). The blue arrows indicate the pre-migration processing stages applied to the sample gather and stack section displayed in Figures 4 and 5, respectively.
be tested for optimal application to the boosted low-frequency data. Secondly, seismic horizons related to the intra- and sub-basalt geology are more easily identified in low-frequency enhanced data displayed as stack images, gathers and in semblance plots. In consequence, more accurate sub-basalt velocity models can be produced throughout the processing sequence. Since many pre-migration demultiple and noise attenuation processes are guided by the primary velocity function, these algorithms can be applied to greater effect.

Figure 2 displays the results of applying the low-frequency operator to the ‘raw’ zero-phased data. The accompanying spectral analyses show the frequency content of tertiary sediments overlying the basalt are not compromised by this process. Furthermore, application of a single boosting operator does not affect the natural attenuation of higher frequencies through the basalt.

Some concerns have been raised regarding the stability of a single operator applied to pre-stack data. These concerns arise from the knowledge that the ghost function varies with angle of incidence. The question arises, therefore, as to how representative of the full dataset is the input wavelet, which only represents energy travelling at
As a test source wavelets were derived from the raw data transformed to plane-wave \( (p) \) domain, such that each wavelet represents a unique emergence angle. Figure 3 displays the frequency spectra of the six wavelets extracted across a range of common \( p \)-planes. As expected, the position of the first non-zero notch in the spectra moves to higher frequencies as the angle of propagation from the vertical increases. However, the frequency content below 40 Hz exhibited consistent character across all of the common \( p \)-values tested. This test suggests that a single operator convolved with the full dataset (which shapes the spectra below 40 Hz) remains a robust approach. Furthermore, it is equally valid as a method for both 2D and 3D seismic datasets.

**Multi-domain noise attenuation**

Several noise-attenuating processes were performed in all of the available ‘time-offset’ domains. Noise attenuation techniques were applied in four different domains, namely the shot, receiver, common mid-point (CMP) and common offset domains, to enhance low-frequency sub-basalt primary signal and minimize both coherent and incoherent noise. CMP gathers (Fig. 4) and stack images (Fig. 5) show the significant improvements made by the shot and receiver noise attenuation applied after surface-related multiple elimination (SRME), and the subsequent improvements made by the CMP and offset noise attenuation after Radon demultiple. Figure 6 provides a processing flow diagram for the reprocessing of 2D data from...
the West of Shetlands. Techniques employed in each of the four domains (shown as the blue boxes in Fig. 6) include: coherent noise attenuation using a time and space variant $f\times x$ apparent velocity dip filter; several iterations of an algorithm which decomposes data into frequency bands and identifies and attenuates anomalous amplitudes within those bands based on time-variant thresholds; and multiple passes of time- and space-variant $f\times x$ deconvolution, regularly operating only below the top or base basalt horizons.

**Imaging results**

An example reprocessed time image (Fig. 7b) trans-ecting many of the major intra-basinal highs and sub-basins in the Faroe–Shetland Basin shows a dramatic improvement over the original version (Fig. 7a). The greatest improvements are demonstrated in the previously poorly imaged Mesozoic and Palaeozoic structure. This is provided without compromising the frequency content of the post-basalt Tertiary section.

**Further work: pushing for broadband seismic from conventional streamer acquisition**

The oil industry is increasingly recognizing the benefits of broadband data. Broadband seismic provides a greater richness of both robust low frequencies, ideal for sub-basalt imaging and inversion stability, and high frequencies, which aid temporal resolution. Suggested acquisition-based solutions include variable-depth streamer or

![Figure 9](image_url)
slanting cable to tackle the receiver-side ghosting (Soubaras & Dowle 2010), and dual-sensor streamers combined with random-depth sources (Carlson et al. 2007; Tenghamn et al. 2007). Following the success of the methods described earlier in this paper the technique has been expanded upon to provide a processing-based broadband solution. This is highly cost effective for two reasons: it does not require any extra acquisition effort and it is applicable to the existing legacy data library acquired by conventional flat cables.

Delivering increased bandwidth (i.e. broadband) data for exploration and production (E&P) purposes has numerous advantages. However, two major factors serve to significantly reduce the useful bandwidth of the source wavelet. The first is the interference between the source pulse and reflections from the water surface (‘ghosts’) and the second is the fact that the Earth acts as a filter which preferentially attenuates high frequencies in the source wavefield as it travels through the Earth. In order to obtain truly ‘broadband’ seismic images, both factors need to be addressed. These have both been dealt with by substituting the low-frequency boosting described earlier for the following two steps.

**Step 1: Broadband spectral processing**

To suppress the effects of the source and receiver ghosts, the low-frequency boosting described earlier is replaced with a multi-dimensional deconvolution applied in the plane-wave ($p$) domain. In this domain each trace represents a common emergence angle, making it the preferred domain for de-ghosting. Using a stochastic search for the best set of parameters, a semi-deterministic stage of de-ghosting operations is applied. This is complemented by a statistical stage including a carefully designed deconvolution operation, averaging over a large number of common-slowness traces in order to address the remaining spectral defects including residual ghosts, side lobes and bubble effect. This full de-ghosting regime applied to 2D legacy data works towards replicating the benefits of broadband acquisition and processing.

**Step 2: Effectively solve for the Earth’s attenuation**

The result of the Earth’s attenuation is a preferential loss of higher frequencies during wave propagation, which induces a ‘tilt’ in the spectral content of deeper horizons.

This attenuation is commonly expressed as effective Q, which is a combination of the intrinsic attenuation, describing energy loss due to the propagation media, and apparent attenuation describing attenuation due to scattering, transmission, mode conversion, etc. An important feature of broadening the spectrum in step 1 is that more accurate measurements of the effective Q can be calculated from the data itself. The attenuation caused by the Earth’s filter can therefore be determined and solved for on the pre-stack data. This is beneficial for deeper targets as the apparent tilt in the spectrum is minimized.

Any process that seeks to broaden the spectrum must take care to enhance the signal and not the noise. In order to maximize the whitening of the useful signal, the two steps are complemented by the multi-domain noise attenuation processes described earlier.

In the context of sub-basalt imaging, the benefit of this broadband processing technique is to provide substantial enhancement of the low-frequency signal. A further benefit is provided for imaging of intra-basalt prospects where the improved low and high frequencies combine to yield superior temporal resolution. Figure 8 provides a comparison of a portion of 2D seismic with and without our broadband processing applied. Clear benefits of higher resolution within the intrusive volcanics can be seen along with a richness of lower-frequency energy below this sequence. Figure 9 provides a comparison of a different portion of the same 2D seismic line, demonstrating the benefits of broadband seismic data in the shallower Eocene sediments.

**Conclusions**

Significant improvements in imaging intra- and sub-basalt geology through the reprocessing of seismic data covering the West of Shetland region is demonstrated. The two signal processing approaches key to providing these improvements are the application of a single low-frequency boosting operator at the beginning of the processing sequence, and the application of several noise attenuating processes performed in the various ‘time-offset’ domains. Our new broadband processing technique provides a greater richness of both robust low frequencies, ideal for sub-basalt imaging, and high frequencies, which aid temporal resolution of intra-basalt prospects.

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