Lows and highs: using low frequencies and improved velocity tools to image complex ridges and basement highs in the Faroe-Shetland Basin

Anthony Hardwick,[1*] Tom Travis,[1] Simon Stokes[1] and Matthew Hart[1] describe three seismic reprocessing strategies in the time domain for two regional long offset 2D surveys in the Faroe-Shetland Basin which combine to provide a dramatic improvement in the interpretability of the sub-basalt image in the dataset.

In January 2010 TGS completed the reprocessing of two regional long offset 2D multi-client seismic surveys in the Faroe-Shetland Basin (FSB). This reprocessing forms part of TGS' ongoing Atlantic Margin Revival (AMR) project that extends from the FSB area to the western Barents Sea. The reprocessed surveys, FSB 1999 and FSB 2000, lie in the far northwestern part of the UK continental shelf and extend into Faroese territory with a total line length of 9779 km (Figure 1). Extensively thick sequences of basalt dominate the northwestern flank of both survey areas. The principal objective was to improve imaging of the prospective Palaeocene clastic sediments interbedded within the basaltic flows and the potentially prospective Mesozoic and Palaeozoic section concealed beneath by adopting new strategies in the reprocessing campaign.

Here we describe three seismic data processing approaches in the time domain. These in combination provide a dramatic improvement in the interpretability of the sub-basalt image on the reprocessed datasets which were acquired with a source and streamer configuration typical of most surveys conducted in the West of Shetland region at that time. These are (1) the enhancement of recorded low frequencies through spectral manipulation, (2) noise attenuation in several domains to maximize the signal-to-noise ratio, and (3) an interpretation-led method we term 'full sequence migration multi-velocity analysis', which adopts a strategy analogous to that used in pre-stack depth migration for updating velocity models in areas of complex structure.

This third approach, which is described in the most detail, is seen to be the key to improving the structural interpretability of concealed Mesozoic and Palaeozoic structures and is demonstrated with examples over the highly prospective Corona Ridge. The improved time migration velocity field was used to constrain the initial pass of hybrid gridded tomography and produced a much improved depth image.

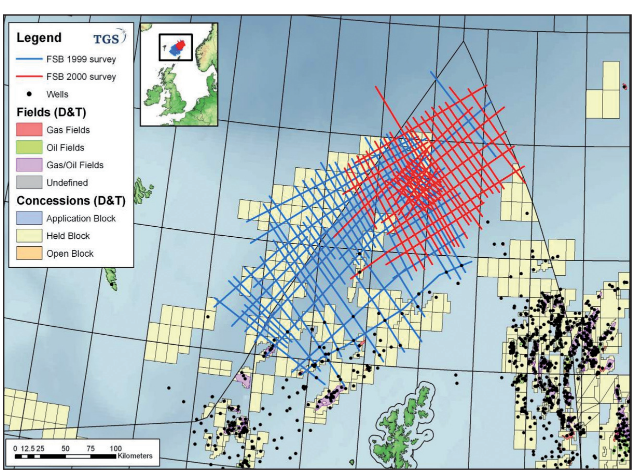

Figure 1 Location map of the FSB 1999 and FSB 2000 surveys in the far northwestern UKCS crossing into Faroese territory.

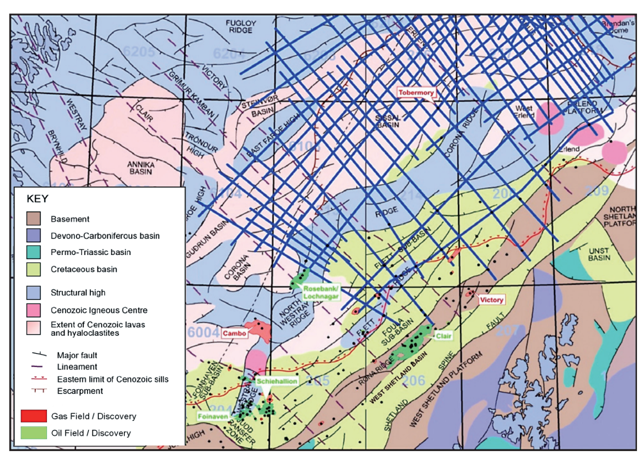

Figure 2 Tectonic elements map of the Faroe-Shetland Basin modified from Moy (2010) showing the FSB 1999/2000 2D survey lines in dark blue, wells in black and oil/gas discoveries.

[1] *TGS, Graylaw House, 21-21A Goldington Road, Bedford MK40 3JY, UK.*

[*] *Corresponding author, E-mail: anthony.hardwick@tgsnopec.com*

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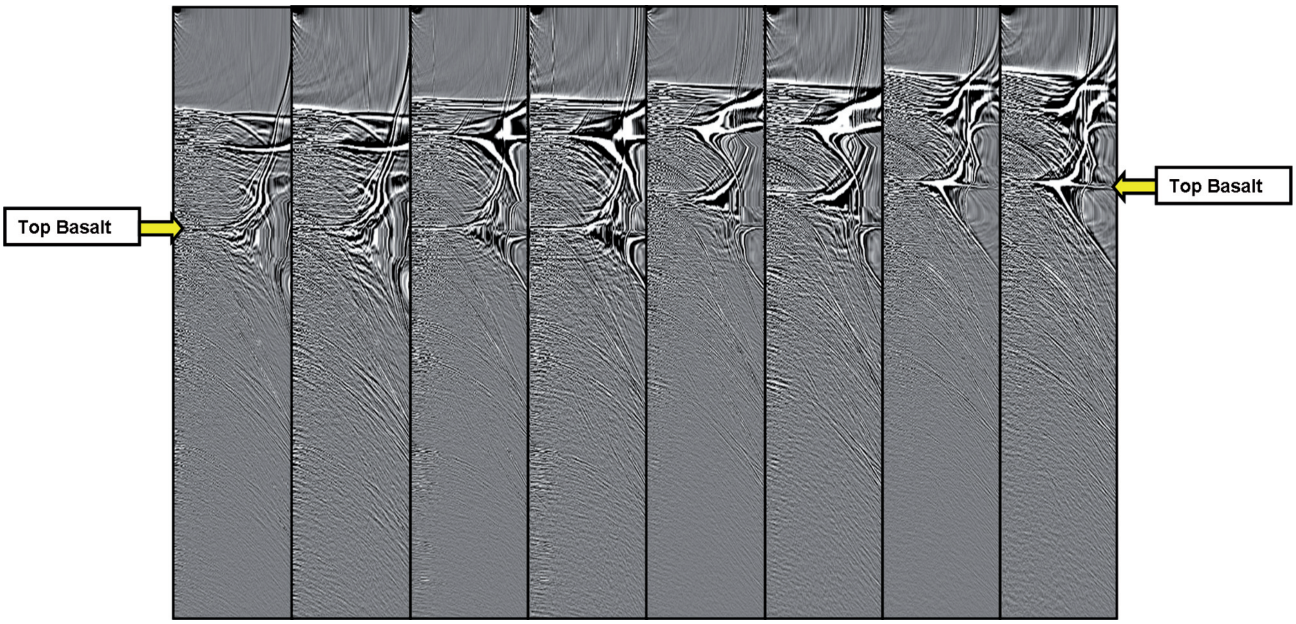

Figure 3 *Selected shot gathers sampling the extensive Palaeogene flood basalts in the northwestern part of the FSB 1999 survey area. Gathers are shown side-by-side before and after application of the low frequency boosting operator.*

The resultant reprocessed images in time and depth now allow the meaningful interpretation and correlation of units in the prospective sub-basalt interval.

Structural framework of the FSB 1999/2000 area

The Faroe-Shetland Basin, bounded to the southeast by the West Shetland Platform and to the northwest by the Fugloy Ridge, has experienced numerous phases of rifting since the end of the Caledonian orogeny in the early Devonian until continental break-up in the early Eocene. During the rift events, the principal direction of extension was orientated northwest-southeast creating a pattern of northeast-southwest trending faults. This orientation is considered to be inherited from the reactivation of the pre-existing Caledonian structural trend that dominates the northwestern Atlantic margin of Europe, continuing into the adjacent Møre and Vøring Basins to the northeast. The faults delineate a series of sub-basins separated by intra-basinal ridges or highs such as the Rona, Flett, Corona Ridges, and the East Faroe High (Figure 2). Rumph et al. (1993) identified a suite of northwest-southeast trending lineaments from potential field data segmenting and offsetting the intra-basinal features such as the Clair and Victory 'transfer zones'. Moy (2010), from the interpretation of 3D seismic data, found these rift-oblique lineaments are unlikely to exist as basin-wide tectonic features within the Faroe-Shetland Basin. From analogues elsewhere along the northeast Atlantic margin the basin segmenting structures are related to intra-rift processes (i.e., accommodation zones) and/or may be related to deeper underlying heterogeneity of the crust.

The earliest period of rifting is thought to have occurred following the collapse of the Caledonian orogeny in the late Palaeozoic to Mesozoic (Dean et al., 1999). This led to the deposition of the Devono-Carboniferous red-bed sequences of the Clair Group. The Clair oil field lies immediately to the southeast of the FSB survey on the Rona Ridge complex hosted in a fractured Devonian sandstone reservoir. Evidence of Jurassic rifting in the Faroe-Shetland Basin is particularly tentative. Doré et al. (1997) observed that the general expression of Jurassic extension in northwest Europe is given by a

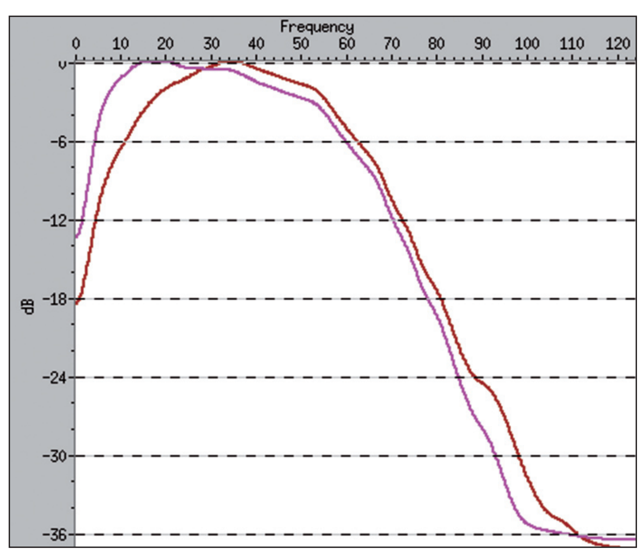

Figure 4 *Amplitude spectrum of the shot gathers shown in Figure 3 in a window below top basalt; the pink line shows the enhanced low frequency content after application of the matching operator and brown line without.*

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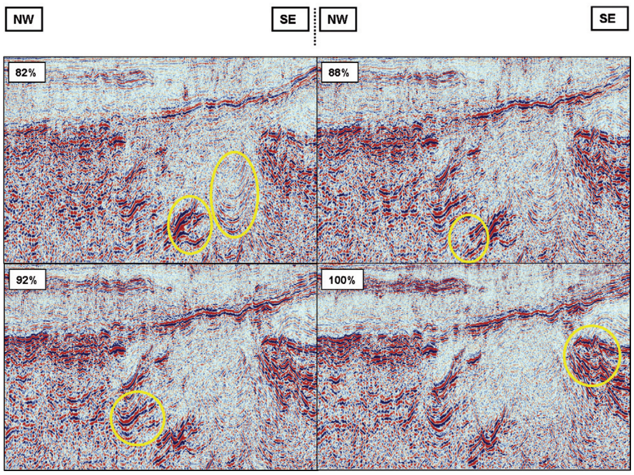

Figure 5 *Zoom of selected full sequence migration multi-velocity analysis panels across the northern Corona Ridge with the percentage velocity variation relative to the initial 100% function annotated. Examples of preferred images are ringed.*

north-south trending pattern of rifts, such as in the North Sea and the Halten Terrace offshore mid-Norway. Understanding of this period in the Faroe-Shetland Basin is problematic due the widespread mid-Jurassic unconformity and later overprinting by Cretaceous and Tertiary activity. Examples of north-south and north-northeast to south-southwest basinal faults are limited although mapped from 3D seismic data over the Corona Ridge (Dean et al., 1999). Reflective packages below the Upper Cretaceous may represent remnants of a Jurassic rift system. The Corona ridge system contains the Lochnager discovery in upper Jurassic sandstones on the southern edge of the FSB survey area (Figure 2).

Rifting and subsidence reached a peak in the Cretaceous but was variable in relation to timing and location within the basin, coinciding with a period of rising eustatic sea levels, drowning most palaeohighs. Palaeocene rifting in the southwestern part of the Faroe-Shetland Basin may have occurred from the observation of Dean et al. (1999) that some of the Cretaceous normal faults appear to have been reactivated during this period. Evidence for this is probably concealed beneath the thick Palaeogene flood basalts in the northwestern part of the basin (Moy and Imber, 2009). Voluminous Palaeogene intrusive and extrusive igneous material is found within the basin in the form of continental flood basalts, sill and dyke complexes, igneous centres, magmatic underplating, and the deposition of regional tuff horizons associated with the opening of the proto North Atlantic Ocean (White and McKenzie, 1989; Naylor et al., 1999; Lundin and Doré, 2005). The Corona Ridge approximates the limit of extrusive volcanic units which gradually thicken to the northwest, exceeding 6 km onshore Faroe Islands (White et al., 2003). Post-rift thermal subsidence has occurred from the Eocene to present, resulting in the deposition of the mid-Eocene

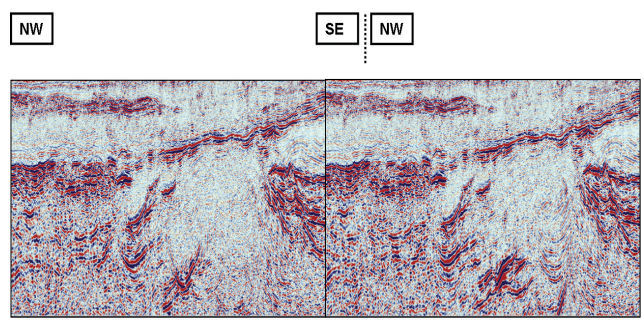

Figure 6 *Initial 2D Kirchhoff pre-stack time migration image from the initial (100%) reference function (left) and updated image (right) after re-migrating and stacking with the derived full sequence migration multi-velocity analysis function.*

Survey	Year	Array Size (in^3)	Maximum Offset (m)	Cable Depth (m)	Gun Depth (m)
OF94	1994	5280	6050	10	6
OF95	1995	6000	6150	9	6
AMG96	1996	4736	4600/6100	11	9
FSB99	**1999**	**4258**	**8072**	**9**	**7**
GFA99	1999	4986	11550	14	10
ST0107	2001	5525	12150	15	10
ST0112	2001	7610[a]	12150	15	15
iSIMM	2002	10170[b]	12000	18	18
ST0308 (3D)	2003	5260[b]	6 × 7950	20	15

Table 1 *Comparison of acquisition parameters modified from Gallagher and Dromgoole (2007) showing the general trend over time to deeper towed cables and sources, larger source arrays and long offsets. [a] = BLAST' : extra large source; [b] = Bubble tuned array.*

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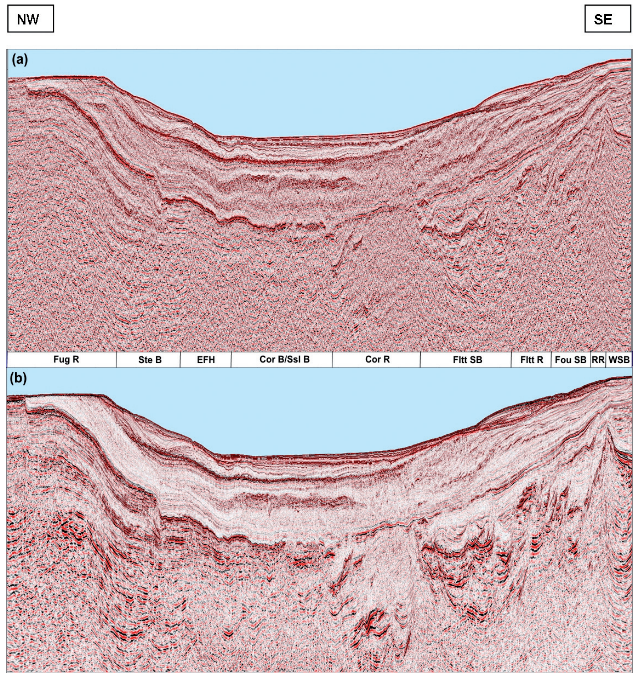

Figure 7 Comparison of the final time migrated section across the Faroe-Shetland Basin. (a) Original and (b) reprocessed FSB 1999 time image. Annotated above the reprocessed image are features which can be related to the major intra-basinal highs and basins shown in Figure 2: Fug R = Fugloy Ridge; Ste B = Steinvør Basin; EFH = East Faroe High; Cor B/Ssl B = Corona/Sissal Basin; Cor R = Corona Ridge; Fltt SB = Flett Sub-Basin; Fltt R = Flett Ridge; Fou SB = Foula Sub-Basin; RR = Rona Ridge; WSB = West Shetland Basin.

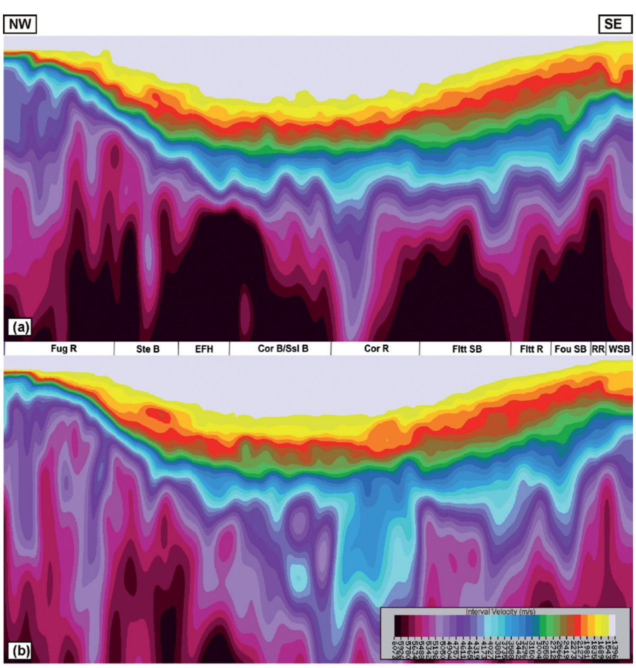

Figure 8 Final time migration interval velocity fields (a) derived from the original processing and (b) from reprocessing with the inclusion of full sequence migration multi-velocity analysis. A significant reduction of velocity is observed in the vicinity of the Corona Ridge. Annotated features refer to those described in Figure 7.

fan system in the central part of the basin, interrupted by episodic periods of northwest-southeast directed compression and the growth of large-scale Cenozoic anticlines (e.g., Davies et al., 2004).

Sub-basalt challenges in acquisition and processing

Imaging beneath thick basalt flows remains a challenge along the northwest European Atlantic Margin although many of the issues are now well understood. The strongly reflective top of the basalt and rugose nature of the flows scatter much of the incident P-wave energy whilst interbed multiples generated within the basalt layers and surface multiples mask weaker sub-basalt reflections with similar moveout. The high velocity basalt layer absorbs and scatters the higher frequencies present in the source wavelet, not only limiting the effective resolution of the sub-basalt image, but large velocity discontinuities at top and base basalt interface result in significant ray-path distortion and multi-pathing. The key to improved imaging is therefore to generate and retain as much low frequency energy as possible in processing (e.g., Ziolkowski et al., 2001). Subsequently, more recent acquisition has seen the towing of cables and sources at increasingly greater depths using very large sources (Table 1), concentrating more of the available energy into the low frequency end of the amplitude spectrum through constructive interference of the free surface ghost. Bubble-tuned (de-tuned) arrays (e.g., White et al., 2002) can be used to provide greater penetration, however Gallagher and Dromgoole (2007) observed little was gained over conventional peak-tuned source arrays in a comparison test in the Faroe Shetland Basin.

Whilst accepting a deep towed streamer and source is beneficial, Gallagher and Dromgoole (2007) conclude that the sub-basalt image is primarily dependent on the processing sequence. From the reprocessing of vintage data with a shallower towed configuration similar to the FSB 1999 and 2000 surveys, a significant improvement to the sub-basalt image is made through the processing of low frequencies only, iterative velocity analysis, and cascaded demultiple schemes. Surface-related multiple attenuation (SRME) for example will not attenuate the intra-basalt multiples, nor P-S wave conversions at the top basalt boundary. A combination of SRME and Radon-based filters need to be applied in an iterative manner. Multiple attenuation techniques such as parabolic Radon filtering are sensitive to the amount of velocity discrimination between the primary events in the sub-basalt sequence and the intra-basalt multiple trend. As such Radon filtering should only be applied when sub-basalt energy can be identified and its velocity picked with reasonable confidence. We adopt this demultiple strategy along with the three approaches described in the next sections.

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Sub-basalt imaging with vintage datasets

Enhancement of low frequency energy
Energy passing through the basalt is strongly attenuated at frequencies above ~ 30 Hz. At an early stage of processing we manipulate the source wavelet to recover as much energy as possible in the low frequency end of the amplitude spectrum. After applying operators to debubble and zero phase the shot gathers, a wavelet is statistically derived representing the averaged source amplitude spectrum for the FSB 1999 and 2000 datasets. The low frequency components of the wavelet are edited to generate a zero phase equivalent 'target wavelet' and matching operator. Figure 3 shows the effect of applying this operator to shot gathers and Figure 4 the amplitude spectra before and after application in a time window beneath the top basalt horizon. This demonstrates a much broader response at the low end. An unsurprising consequence of applying the matching operator is the boosting of swell and other low frequency acquisition noise alongside low frequency, low amplitude primary signal. Rather than being counter-productive, the noise becomes easier to discriminate and remove using frequency-amplitude threshold-based techniques.

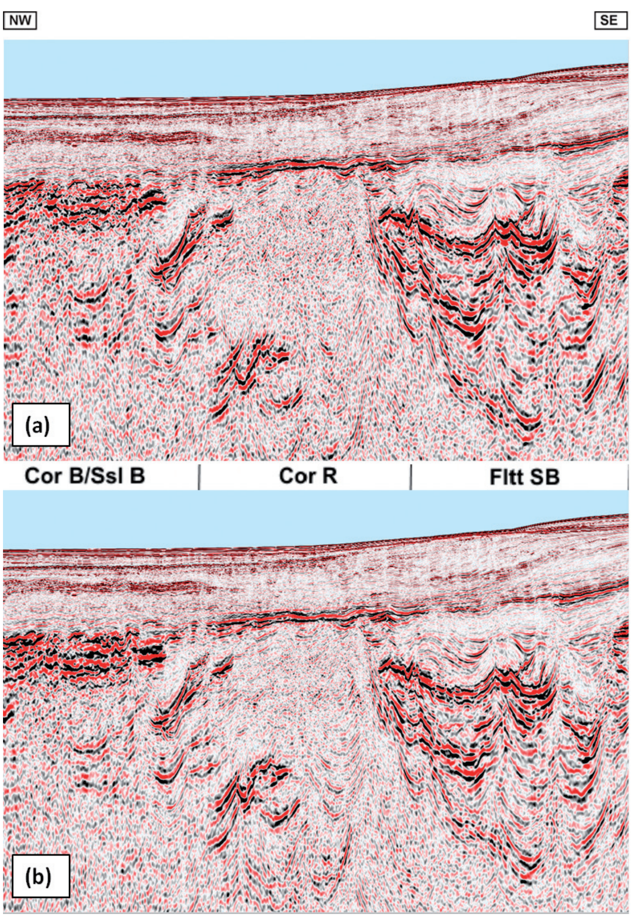

Figure 9 Initial (iteration 0) pre-stack Kirchhoff depth migration image obtained from (a) velocities derived from the original time processing and (b) from the reprocessing with reference to Figure 10(a). The input dataset in both examples is identical. Annotated features refer to those given in Figure 7.

Multi-domain noise attenuation
Every opportunity is taken to de-noise the data in several domains. Multiple passes of noise attenuation were performed in the shot, receiver, common mid-point (CMP), common offset, and common channel domains to enhance weak low frequency sub-basalt primary returns and minimize both coherent and incoherent noise. The noise attenuation methods include several iterations of a technique which decomposes the data into frequency bands and identifies and attenuates anomalous amplitudes within those bands based on time-variant thresholds. This is followed by F-X deconvolution and time/space variant dip filtering guided by primary stacking velocities. Unlike deep towed source and streamer configurations where high frequencies are irrecoverably lost due to destructive interference of the source-receiver ghost, the shallower towed configuration of the FSB surveys produces a receiver ghost notch centred at ~ 82 Hz. By minimizing the effects of scattering through this approach, the high frequency content of the overlying Tertiary section is not affected.

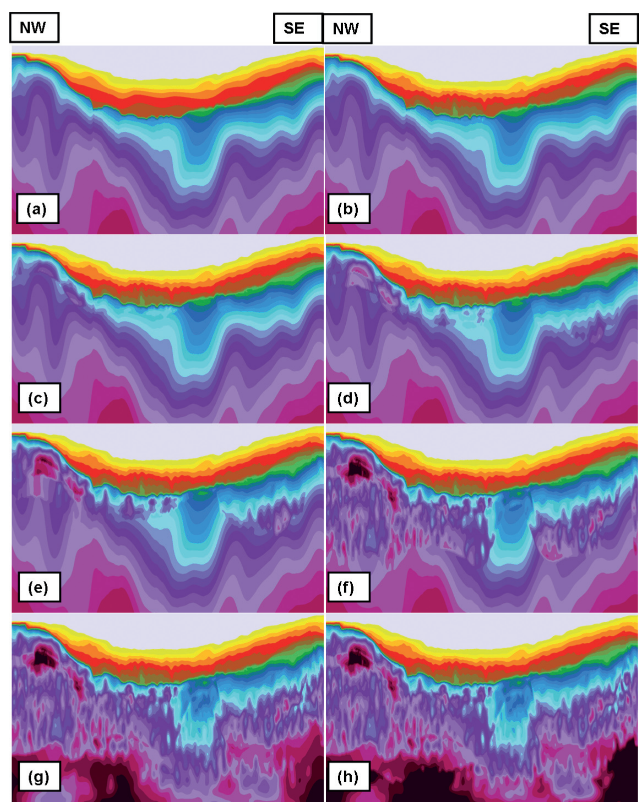

Figure 10 Tomographic updates: (a) iteration 0 – reference model derived from full sequence migration multi-velocity analysis stacking velocities; (b) update through Tertiary; (c) update to Flett formation and top Palaeocene; (d) update to Lamba formation; (e) update to Vaila formation; (f) update to Sullom formation; (g) update to Top Triassic; (h) final update for late Mesozoic and Palaeozoic.

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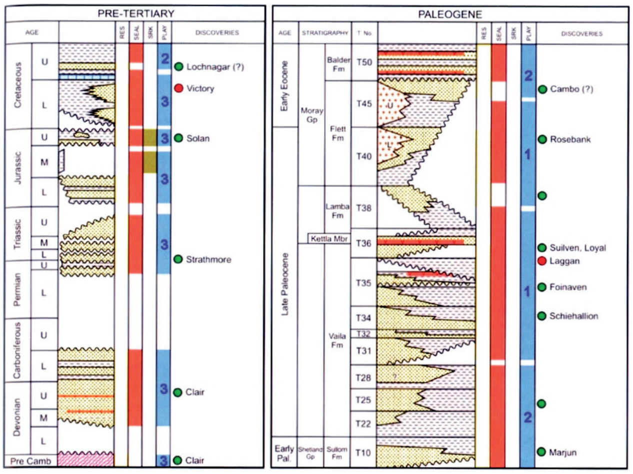

Figure 11 Stratigraphic column of the Faroe-Shetland Basin petroleum system from Beswetherick et al. (2009).

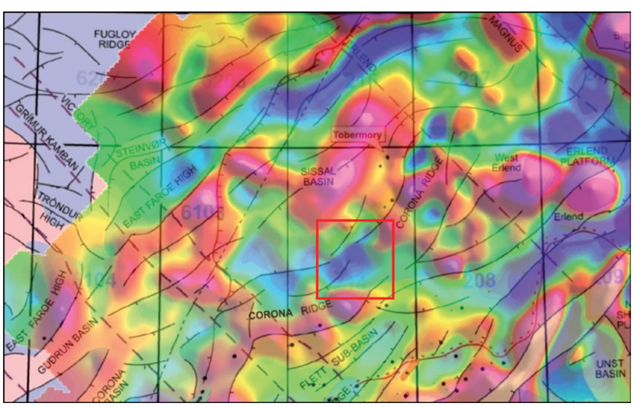

Figure 12 Bouguer gravity anomaly with a 50 km high pass residual filter applied overlain on the tectonic elements from Moy (2010) shown in Figure 2. The gravity data were acquired in conjunction with the FSB 1999/2000 seismic surveys. The area highlighted in red refers to the general area around the Corona Ridge shown in previous 2D time and depth examples.

Full sequence migration multi-velocity analysis

After spectral manipulation, noise attenuation, SRME, and predictive deconvolution in the tau-p domain to remove intra-basalt multiples, we apply a time domain approach analogous to interpretation-driven subsalt wave equation migration (WEM) scans in depth (Wang *et al*., 2006). At greater travel times and beneath the top basalt reflector, interpretation of seismic velocity, based upon semblance maxima and gather flattening is problematic due to relatively weak primary returns and structural complexity. For this reason, an easier velocity analysis may be made by interpretation of images derived from stacking velocities based on a percentage of an approximate input function, commonly referred to as 'multi-velocity' stacks.

Increased computing speed now allows the quick, full pre-stack Kirchhoff time migration of data to produce a suite of migrated images using migration velocities initially derived from selected percentages of the best set of stacking velocities. We term this 'full sequence migration multi-velocity analysis' as these images have an almost complete pre-stack sequence applied and post-stack signal-to-noise enhancement to improve their interpretability. Velocity-based demultiple is performed immediately before migration to effectively remove residual multiple for each migrated velocity panel using the corresponding percentage velocity function. We generate a suite of up to 15 pre-stack migrated panels using Radon demultiple and migration velocities scaled typically within the 60–140% range, which are interpreted using the multi-velocity picking tool within TGS' PRIMA software. Picks on the migrated panels are related to gathers and semblances interactively. The data are then re-migrated with the updated migration velocity field and further iterations are performed if necessary.

Figure 5 shows selected panels from full sequence migration multi-velocity analysis from a reprocessed FSB 1999 line transecting the Corona Ridge. Highlighted are examples of events which give a preferred image, corresponding to the analysis picks made. The left side of the image (northwest) demonstrates thickening of the Palaeogene flood basalts compared to the right side (southeast) showing extensive piles of sills intruded into the Flett sub-basin (Figure 2). Figure 6 shows the composite image obtained from the update after re-migration and stacking over the initial (100%) reference velocity function. The final reprocessed time image (Figure 7b) transecting many of the major intra-basinal highs and sub-basins in the Faroe-Shetland Basin shows a dramatic improvement over the original version (Figure 7a), particularly with respect to previously poorly imaged Mesozoic and Palaeozoic structure, but without compromising the frequency content of the post-basalt Tertiary section.

Reference models for pre-stack depth migration and implications

The final stacking velocities from time reprocessing were used for an initial (iteration 0) run of 2D Kirchhoff pre-stack depth migration with a comparison made to previous picks that omitted full sequence migration multi-velocity analysis in the derivation of the initial velocity model. Figure 8 shows the equivalent reference models in time converted to interval velocity and smoothed appropriately. The resultant depth migration comparison is shown in Figure 9. The CMP gathers input to the migration are identical but the version incorporating full sequence migration multi-velocity analysis is clearly superior with much better focusing of sub-basalt events. This version is taken through a number of iterations of hybrid gridded tomography.

The hybrid gridded approach is essential to prevent 'leakage' of tomographic updates across sharp velocity contrasts, typically but not exclusively, at the top and base basalt level. Starting from the initial reference model (iteration 0) the

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tomographic updates are conducted in geologically constrained layers from the water bottom downwards. A mask is applied to deeper layers with significant velocity contrast across major boundaries and shallower updates locked once residual curvature on the image gathers becomes negligible. Each iteration is described in Figure 10 with reference to the stratigraphic column for the Faroe-Shetland Basin petroleum system shown in Figure 11.

In the initial reference model and after tomographic updates, a remarkable low velocity zone is observed within the northern Corona Ridge which is anomalous in relation to other intra-basinal highs in the Faroe-Shetland Basin. Filtered gravity data acquired alongside the FSB surveys show a Bougeur gravity low in the same area, unaffected by rift oblique faulting (Figure 12). Given the improved seismic image from reprocessing, it is conceivable that this portion of the northern Corona Ridge could be a locally inverted basin, comprised of a set of sub-vertical fault blocks.

Conclusions

We demonstrate a significant improvement in image quality through the reprocessing of our FSB surveys using the three processing approaches outlined. Careful attention to the preservation and enhancement of low frequency signal and the attenuation of noise in multiple domains is seen to be crucial to improving signal-to-noise beneath the basalt. We show there is no need to compromise the frequency content of the overlying Tertiary section when reprocessing shallow towed datasets for sub-basalt targets. The third approach, interpretation-led full sequence migration multi-velocity analysis, is seen to be the key to improving the structural interpretability of concealed Mesozoic and Palaeozoic structures. The migration velocity field derived from stacking velocities provides a superior starting model for initial passes of gridded hybrid tomography. On the basis of this model and correlation with gravity data we diagnose a significant anomaly over the Corona Ridge implying a locally inverted basin distinct from neighbouring intra-basinal highs in the Faroe-Shetland Basin, requiring further investigation.

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