Seismic imaging of basalts at Glyvursnes, Faroe Islands: hunting for future exploration methods in basalt covered areas

U.K Petersen,[1*] M.S. Andersen,[1,2] R.S. White,[3] and SeiFaBa Group

Introduction

Obtaining good sub-basalt seismic images is known to be problematic (Ziolkowski et al., 2003; White et al., 2003). Although the properties of basalts are quite different from those of most sediments Planke (1999) suggested that seismic energy is transmitted through basalt in much the same way as through sediments so the problem of seismic imaging through basalts amounts to the conventional task of separating primary energy from noise, even though the noise including multiples may be considerable. The physical properties of basalt are markedly different from those of the overlying and underlying sediments. Strong reflections due to high impedance contrasts at the top (and bottom) of the basalts leads to significant loss of transmitted seismic energy (Fruehn et al., 2001). Large variations of intrinsic properties along vertical cross-sections of basalt flows have been demonstrated and quantified by analyses of well-logs from wells penetrating successions of flood basalts (Planke, 1994) and from surface mapping (e.g., Self et al., 1998; Thordarson and Self, 1998). This causes the stratigraphic filtering effects of basalt successions to be more severe than that of sediments (Maresh and White, 2005; Shaw et al., 2004). Lateral variations in the thicknesses of sediments interbedded between basalt flows and in the thickness of the upper porous part of basalt flows have been demonstrated by detailed investigations in exposed flood basalts (Self et al., 1998; Thordarson and Self, 1998). The roughness of inter-beds causes 3D scattering of seismic energy, as demonstrated in studies comparing stratigraphic filtering and the effective quality factor, Q, of basalt successions (e.g., White et al., 2005; Shaw et al., 2005; Shaw et al., 2004).

Taking these problems into consideration, experiments have been performed in the last decade using: longer offsets (both synthetic aperture, and longer streamers) to improve the signal-to-noise ratio and NMO resolution and to allow processing of post-critical reflections; larger energy sources to increase the general energy level; low-frequency tuning to allow for better penetration through basalts (characterised by low Q values); and shot-by-shot recording of the source signature and combination of OBS and seismic reflection data to improve velocity estimates. In one experiment all of the above-mentioned techniques were applied, providing considerable improvements in sub-basalt imaging relative to previous work (Spitzer and White, 2005; White et al., 2005). An other parameter for seismic acquisition is the orientation of the seismic line relative to the flow direction of the basalt flows (Reshef et al., 2003). However, poor effective transmission of seismic energy, scattering, strong multiple reflections, multiple mode conversions, and low-pass filtering of the energy that propagates through a layer of stacked basalt flows are still hampering routine imaging for petroleum exploration in sediment basins covered by basalts (Maresh and White, 2005). This was demonstrated by the UK164/07-01 well where the base of a basaltic succession was found 700 m deeper than anticipated from interpretation of seismic reflection data (Archer et al., 2005). In order to obtain imaging quality and detail comparable to those obtained in other sedimentary basins, further improvements are necessary.

The SeiFaBa Project (Seismic and petrophysical properties of Faroes Basalts), sponsored by the Sindri group, aims to create data-derived models for the propagation of seismic energy in basalt to provide a basis for better sub-basalt imaging. The project comprises drilling of the Glyvursnes-1 wells near Tórshavn on the Faroe Islands (Figure 1), core analysis for intrinsic physical parameters, recording of VSP and offset-VSP data in the Glyvursnes-1 and Vestmanna-1 wells, and surface seismic wide-angle and reflection data around the Glyvursnes-1 and Vestmanna-1 wells (Japsen et al., 2005). At both sites these investigations of the elastic properties of basalts are made at a number of different scales. In this paper we present surface seismic reflection data from SeiFaBa experiment at Glyvursnes in the summer of 2003 illustrating that basalts can be imaged effectively using relatively small energy sources (250 g dynamite; 2.6-litre airgun cluster) and that stratigraphic details of flood-basalt constructions can be identified and characterized based on analysis of seismic data and then correlated to well data. We also demonstrate how different acquisition and processing techniques influence the effective frequency content of seismic reflection data and thus the effective propagation through and imaging of the basalts.

[1] *University of the Faroe Islands, Noatún 3, FO-100 Tórshavn, Faroe Islands.*
[2] *Geological Survey of Denmark and Greenland, Østervold Gade 10, Copenhagen C, DK-1350, Denmark.*
[3] *University of Cambridge, Bullard Laboratories, Madingley Road, Cambridge CB30EZ, UK.*
[*] *uni@setur.fo.*

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Geological setting

A lava pile about 3 km thick with minor intercalations of volcaniclastic sediments is exposed on the Faroe Islands (Rasmussen and Noe-Nyggard, 1970). Below the exposed section a further 3 km or so of basalt was penetrated in the Lopra-1/1A well without reaching the base of the volcanic succession (Hald and Waagstein, 1984). Andersen (2002) suggested that about 1 km of basalt could have been present above the section exposed on the Faroes. The total stratigraphic thickness of basalt on the Faroe Block would thus be about 7 km, possibly more. Deep seismic results from wide angle experiments confirm this estimate (e.g., Richardson et al., 1999).

Rasmussen and Noe-Nygaard (1970) divide the exposed basalt into three series (Figure 1) representing different stages and ages of volcanism. Although Rasmussen and Noe-Nygaard's stratigraphy has been retained, their three series have informally been treated as formations in recent literature (e.g., Waagstein, 1988). In this paper we follow this tradition: the lower basalt formation (LBF), the middle basalt formation (MBF), and the upper basalt formation (UBF). The LBF (stratigraphic thickness about 900 m, (3000 m when including the lower part found in the Lopra-1A well) and the UBF (stratigraphic thickness about 675 m) consist of thick basaltic lava beds. The lava flows are typically 10-30 m thick in the LBF and 5-10 m thick in the UBF with thin beds of interbasaltic tuff-clay sediments. The MBF (stratigraphic thickness about 1350 m) consists of thin (about 1-2 m) pahoehoe flow units, often forming flowfields up to about 20 m thick. Sediment/tuff beds are of minor importance in the MBF. The base of the LBF sub-aerial basalts is found at about 2450 m in Lopra-1A (Boldreel, in press) and the lowermost 1000 m of the drilled basalt succession on the Faroes comprises mostly hyaloclastic basaltic rocks commonly with massive basalt toward the bottom of the Lopra-1A (Waagstein personal communication, September 2005).

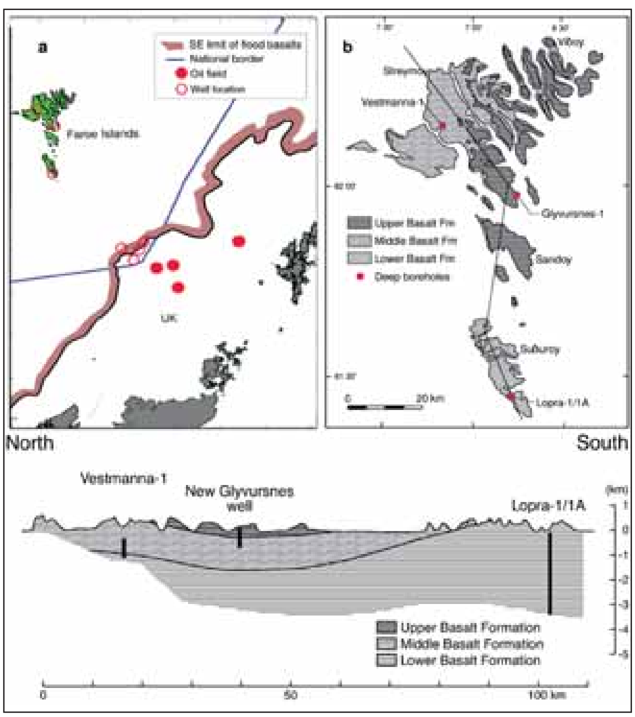

Figure 1 *Upper* **a**, *Location of the Faroe Islands relative to the extent of flood basalts. Drilled wells in the Faroes are shown as red open circles, producing oil wells are shown as red filled circles and the international border of the Faroes territory is shown as a blue line (modified from Sørensen, 2003). Upper* **b**: *Geological map of the Faroe Islands showing the locations of deep boreholes (Vestmanna-1, Glyvursnes-1 and Lopra-1/1A) and the distribution of the three Palaeogene basalt formations (modified from Waagstein, 1988). Lower: Geological section through the Faroe Islands and the three wells shown (modified from Waagstein, 1988). Location of profile is shown on upper figure* **b**.

Well logs

Full-waveform sonic and bulk-density logs in Vestmanna-1 and Glyvursnes-1 boreholes were acquired as part of the SeiFaBa project (Japsen et al., 2005). Details of the physical properties of the Vestmanna-1 and Glyvursnes-1 will be published elsewhere. The Lopra-1/1A well was logged in 1996 and P-wave sonic and bulk-density logs are available from the depth interval 200-3100 m in this well. The Vestmanna-1 and Lopra-1 well are displaced about 28 and 55 km, respectively, from Glyvursnes. However, lateral continuity of all three lava formations on the Faroe Islands is well documented (e.g., Rasmussen and Noe-Nyggard, 1970; Waagstein, 1988). It is thus likely that Vestmanna-1 and Lopra-1/1A represent the general character of the MBF and LBF below Glyvursnes.

Composite velocity and density logs corresponding to the ideal stratigraphic profile (Rasmussen and Noe-Nyggard, 1970) were constructed for the sequence below Glyvursnes using logs from Glyvursnes-1, Vestmanna-1, and Lopra-1 (Figure 2). Velocities and densities in intervals of the MBF and LBF that have not been logged are represented by logged intervals in the Vestmanna-1 and Lopra-1 that are similar based on the description of the wells (Hald and Waagstein, 1984) and on the regional mapping of the Faroes (Rasmussen and Noe-Nyggard, 1970).

Synthetic seismic data

A synthetic seismogram (without correction for geometrical spreading and other attenuation) was generated from the composite logs corresponding to the ideal stratigraphic profile using a source signature extracted from stacked airgun-geophone data (Figure 3b). Note the distinct changes in character at the UBF-MBF and MBF-LBF boundaries. The synthetic seismogram shows that the signals returning from the UBF and LBF are characterized by higher amplitude and more internal character than the signal from the MBF.

Joint time-frequency analysis carried out by means of wavelet transforms (Torrence and Compo, 1998), both of the

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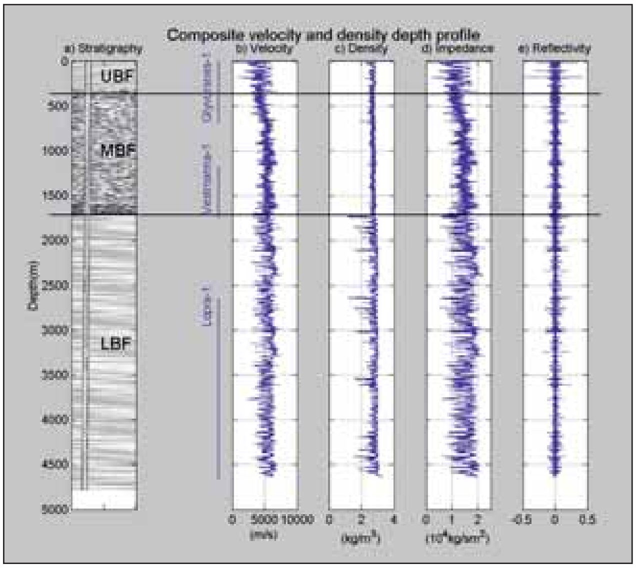

Figure 2 *Composite velocity and density logs for the total stratigraphic sequence below Glyvursnes, constructed using the logs from Glyvursnes-1, Vestmanna-1 and Lopra-1 (the actual well segments are labelled between a) and b), see also Figure 1).* **a**) *The stratigraphic division mapping the boundaries of various stages of volcanism (modified from Rasmussen and Noe-Nygaard, 1970). The base of the UBF and the base of the MBF are drawn as black horizontal lines across the figure;* **b**) *composite velocity log. The uppermost part of Vestmanna-1 log is used to represent the missing interval in the MBF and the uppermost part of the Lopra-1 log is used to represent the missing interval in the LBF;* **c**) *composite density log;* **d**) *and* **e**) *show the calculated acoustic-impedance and the reflection coefficient series. The repeated log sequences can be identified on the composite logs.*

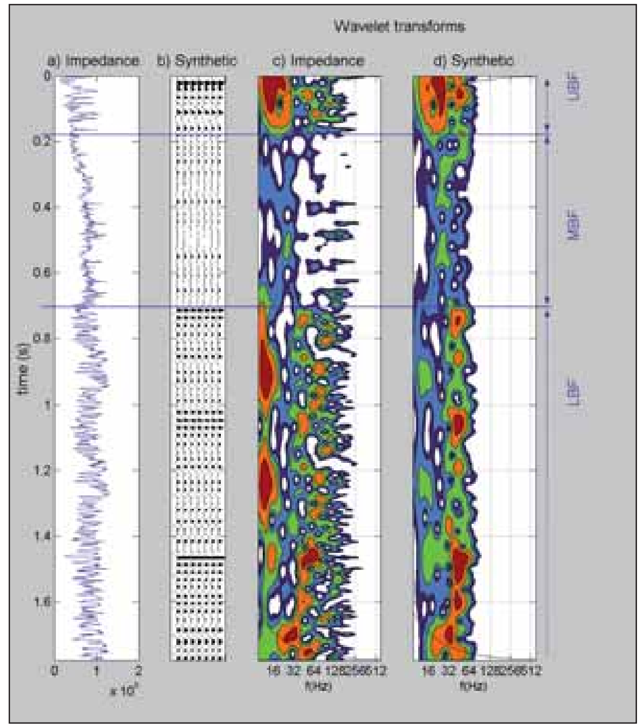

Figure 3 **a**) *Acoustic impedance from composite logs in time domain;* **b**) *Synthetic seismogram generated by means of the acoustic impedance and a source signature extracted from stacked airgun-geophone data (bandwidth 12-60 Hz) without correction for geometrical spreading or other attenuation;* **c**) *Wavelet transform of acoustic impedance. The acoustic impedance and synthetic seismogram traces are normalized by standard deviation (Torrence and Compo, 1998). Contour levels in c) and d). Contour levels are increasing exponentially.*

acoustic impedance series and synthetic seismogram, show that the MBF is characterised by generally lower amplitudes and a different frequency distribution than that of the UBF or LBF (Figure 3c and d).

Seismic data

In the summer of 2003 we acquired a composite seismic data set at Glyvursnes, on the Faroe Islands, including near-vertical-incidence seismic data using six different combinations of energy source and receiver: airgun-geophone and airgun-streamer, each with two different airgun sources; dynamite-geophone and dynamite-streamer. The layout for a selected part of the survey used for the data presented in this paper is shown in Figure 4.

Acquisition

The airgun-geophone/streamer data were acquired on a 96-channel streamer moored between a small jack-up rig near the shoreline and a tugboat at the other end (group interval 6.25 m, depth 3 m) and a line of 80 geophone stations (station interval 5 m, every fourth station had 3-component geophones, the remainder had only vertical geophones). The deployment of the streamer was very sensitive to weather conditions and tidal current and parts of the acquisition were done only with airgun-geophone recordings. The seismic sources used were a 4x40 in^3 (2.6-litre) sleeve-gun cluster and a 560 in^3 (9.2-litre) Solera-Ggun

The dynamite-geophone/streamer data comprised only a few shot-points. The seismic source was 250 g of standard dynamite (burning velocity 3000 m/s) placed in 3 m deep holes, cemented and packed. The dynamite-geophone data were acquired with a line of 120 stations (station interval 5 m) and shot-points at 10 m intervals along the line with the same source parameters as above. In the following discussion we will refer only to data acquired with the 4x40 in^3 sleeve-gun cluster and with dynamite.

Pre-stack noise analysis

Initial comparisons of shot gathers indicate that the streamer data are characterized by considerable noise deriving from a number of different sources while geophone gathers recorded with the same source are characterized by significantly less

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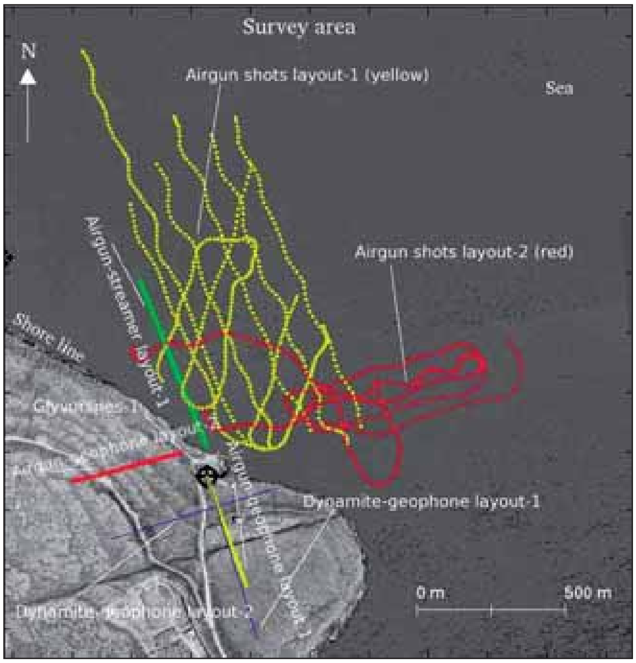

Figure 4 *Air photo of the Glyvursnes survey area showing the layout of a selected part of the survey to be presented in this paper. The airgun-geophone/streamer data were acquired with a 96-channel moored streamer (green line offshore; group interval 6.25 m, depth 3 m) and a line of 80 geophone stations (yellow and red line onshore; station interval 5 m). Layout-1 recorded at the same time on streamer and geophones (yellow geophone line and green streamer line) while during layout-2 recorded only on geophones (red geophone line). Shot-points are plotted with colours respective to the recording geophone layout. The dynamite-geophone/streamer data were recorded on layout-1 (green and yellow line). For the dynamite-*geophone *data there were two layouts (blue lines). Position of Glyvursnes-1 well is shown (black circle with plus sign).*

noise. Time-variant frequency analysis of single raw unprocessed traces based on a continuous wavelet transformation [using a Morlet wavelet with centre frequency 0.995 Hz (Addison 2002)] provides additional information about the composition of the signal and noise (Figures 5 and 6). For short recording times, and at frequencies below 256 Hz, the ambient noise on the geophones is small compared to the seismic signal (Figure 5). The bandwidth of the seismic signal from both sources decays with time reflecting the relatively low effective Q value in the basalts below Glyvursnes (Shaw et al. 2004; Shaw et al. 2005).

Although the dynamite charge used has much higher (5 times) initial chemical energy than the potential energy in the airgun, the airgun produces a better and stronger seismic signal. Most of the energy in the dynamite shot is presumably lost due to non-elastic deformation at the shot site. The centre frequency of the dynamite shots is slightly higher than that of the airgun shots (Figure 5 and Figure 6).

For logistic reasons the streamer was moored at a shallow depth (3 m). Thus the surface ghost gives rise to strong attenuation of the seismic signal at frequencies below about 60 Hz. At the same time the background noise is very strong at frequencies below about 30 Hz (Figure 6c). In addition to ambient noise, the streamer data are characterized by high-frequency noise (~128-512 Hz) caused by reverberations of the seismic signal in the water column. The combined effect of ambient noise, the ghost and reverberations in the water column is to reduce the effective bandwidth, and thus the penetration of the seismic signal recorded on the streamer relative to the signal recorded on the geophones (cf. Figure 5a and Figure 6a). However, the streamer still records a useful seismic signal for recording times up to around 1 s.

The low-frequency background noise on the streamer that we experienced during the data acquisition at Glyvursnes was to a large extent related to the special deployment of the moored streamer during this experiment. In more standard marine operations, the background noise is generally lower. Furthermore, in deep water the source and streamer depths may be adjusted to create the optimum bandwidth at the target depth using signal analysis such as that embodied in Figure 5 and Figure 6 and knowledge of the source signature and the frequency decay in the formation to be penetrated by the seismic signal. However, in the streamer data from the Glyvursnes 2003 experiment, our data has a relatively low effective bandwidth.

Preliminary processing

Generally all the recorded geophone data are dominated by refractions from shallow depths. Refractions in the dynamite-geophone data were removed by top mutes while *f-k* filtering was used for the airgun-geophone data. On the streamer data, refractions and low-frequency coherent noise from an unknown source were removed with surgical mutes.

Although the noise analysis indicates that time-variant filtering before stack is a relevant process, time-invariant filtering was preferred for the preliminary processing presented here. The airgun data were bandpass filtered at 12-14-50-60 Hz (Ormsby) while the dynamite data were filtered at 12-14-100-120 Hz (Ormsby). The dynamite-geophone data and airgun-streamer data were processed assuming a 2D geometry. A 2D filter was applied to the stacked airgun-streamer data (mixing three samples and 11 traces). Airgun-geophone data were processed with 3D geometry. Velocity analysis was performed on selected supergathers. Picked stacking velocities compare well with RMS velocities calculated from the composite velocity log of the ideal stratigraphic profile of the Faroes. Before display, automatic gain control (AGC) was applied with two different windows at 100 ms and 500 ms; traces were blended at a ratio of 1:1. A composite profile along the transect (Figure 7) illustrates the quality of the processed data obtained with the combinations dynamite-geophone, airgun-geophone and airgun-streamer (Figure 8). Although stacking improves the coherency of

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primary reflections, the frequency content of the signal and the signal-to-noise ratio seen on the pre-stack data (Figure 5 and Figure 6) are clearly reflected in the quality of the final stack (Figure 8). The UBF-MBF boundary, which was penetrated in Glyvursnes-1, is not clear in any of the three data sets. However, horizon C' located at about 0.2 s in the dynamite-geophone and dynamite-airgun data ties well to the UBF-MBF boundary in the well. A prominent reflection at about 0.6 s, horizon A', is interpreted as the MBF-LBF boundary. The general character of the successions above and below horizon A' compares well with the character of the UBF and MBF respectively in the synthetic seismogram of the ideal profile (Figure 3b). Although the earth filter and stacking modify the frequency content of the reflected signal, the narrower frequency range of the MBF compared to the UBF and LBF observed on synthetic data is replicated in the stacked and scaled data from Glyvursnes (Figure 9). We consider this further support that horizon-A' represents the MBF-LBF boundary.

Results and discussion

Joint time-frequency analysis in the form of continuous wavelet transformation on unprocessed pre-stack data shows that the higher frequencies of the seismic data trace are reduced drastically with depth below the surface (Figure 5 and Figure 6). The overall best signal-to-noise ratio is obtained with the airgun-geophone combination.

A zero-offset VSP survey recorded in the Glyvursnes-1 borehole by Shaw (2004) demonstrated strong attenuation of the higher frequencies of the seismic signal (low Q value) below Glyvursnes. In accordance with these observations, we see that the effective bandwidth of the surface seismic data is reduced dramatically with time (Figure 5b). From an original bandwidth of about 4-128 Hz, the bandwidth is reduced to 5-20 Hz at a depth of 1.6 s (about 5300 m). This explains the supremacy of the airgun to the dynamite as a seismic source. The airgun generates a lower-frequency signal (centred at approximately 16 Hz; Figure 5a), than the dynamite (centred at approximately 32 Hz; Figure 5b) and is thus better suited for transmitting seismic signals through the basalt.

A composite profile consisting of data acquired with three different acquisition methods (Figure 8) shows that the frequency content of the signal and the signal-to-noise ratio seen in the unprocessed pre-stack data (Figure 5 and Figure 6) are reflected in the quality of the final stack. Simple stacking improves the imaging of the primary reflections.

A threefold subdivision of the seismic profile is distinct in the airgun-streamer, airgun-geophone and dynamite-geophone data. Two high-amplitude successions, one above horizon C' (0-0.16 s) and one below horizon A' (0.59 s) and

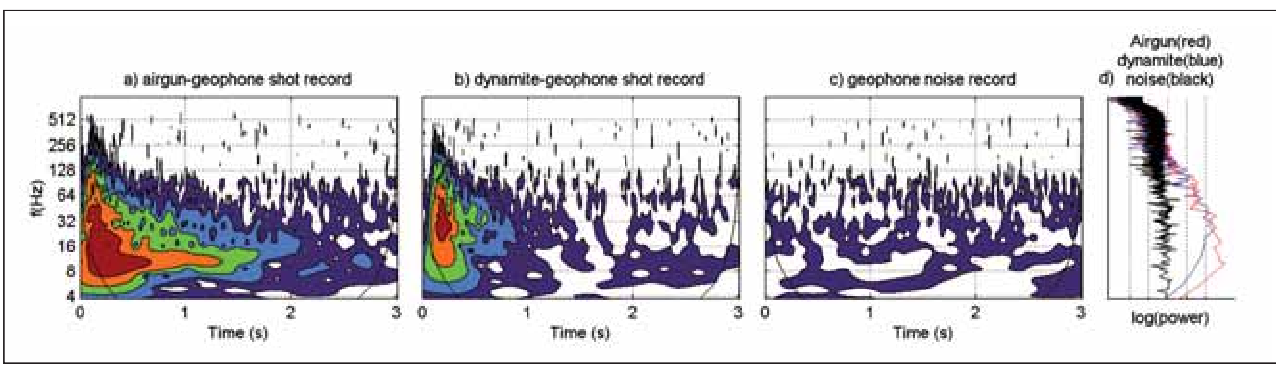

Figure 5 *Shows the continuous wavelet transforms of geophone channel 110 (station 74). a) Airgun-geophone, offset 208 m; b) Dynamite-geophone, offset 224 m; c) Geophone noise record; d) Frequency spectra of all three records. Values are not scaled. Contour levels are increasing exponentially and are the same for a), b) and c).*

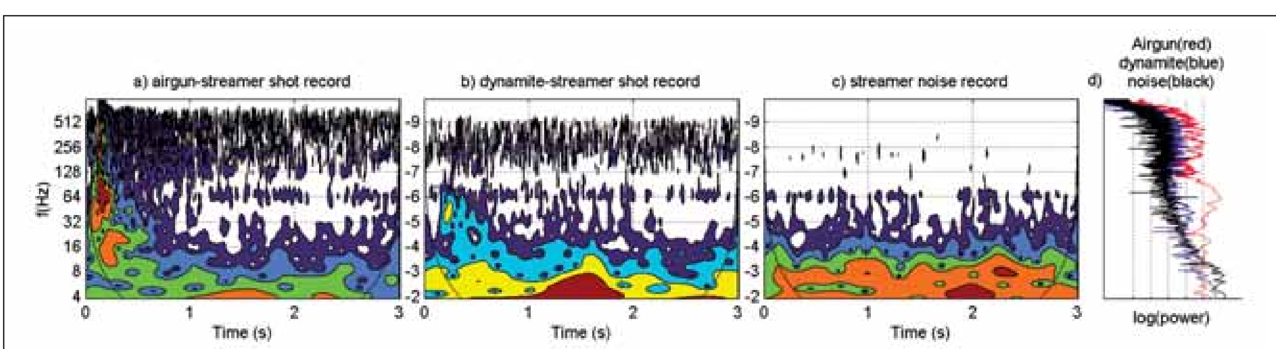

Figure 6 *Shows the continuous wavelet transforms of streamer channel 130 (station 90). a) Airgun-streamer, offset 195 m; b) Dynamite-streamer, offset 415 m; c) Streamer noise record; d) Is the frequency spectra of all three records. Values are not scaled. Contour levels are increasing exponentially and are the same for a), b), and c).*

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a low amplitude succession (between 0.16 and 0.59 s) are clearly identified. By comparing synthetic data of the ideal profile (Figure 3b) with stacked data (Figure 8), it appears plausible that horizon A' is a reflection from (or close to) the boundary between the MBF and LBF. Furthermore, with data comparable to those acquired at Glyvursnes it might be realistic to identify the MBF by its reflection character. Multiples appear to be of minor importance above horizon A'. Although we expect multiples might be important below horizon A', we have not addressed this topic during the preliminary processing, which was aimed at understanding the nature of horizon A' below Glyvursnes.

The UBF-MBF boundary was found at about 340 m (from mean sea level) in the Glyvursnes-1 borehole (Waagstein, personal communication). Depth conversion of the seismic reflection data places the MBF-LBF boundary at a depth of 1390 m, and we thus estimate the total thickness of the MBF to be about 1050 m below Glyvursnes.

This is less than the 1350 m for the total thickness of the MBF found by Rasmussen and Noe-Nygaard (1970) in the northern part of the Faroes and the 1400 m reported from around Vestmanna (Waagstein 1988). It thus appears that the MBF thins towards the south and east. This is in general accordance with Waagstein (1988), who found that the thickness of the MBF is less between Sandoy and Suðuroy than at Vestmanna. The reason for the apparent south- and eastward thinning of the MBF could be that the amount of lava available during emplacement of the MBF was not sufficient to allow all the flows to reach Glyvursnes if their source was to the northwest. However, gradual eastward thinning of the MBF was not observed during mapping of the Faroe Islands (Rasmussen and Noe-Nyggard, 1970). Alternatively the Glyvursnes area may have been uplifted relative to the Vestmanna area after emplacement of the LBF possibly giving rise to faulting. Unfortunately, the present data do not allow us to choose among the two above-mentioned or other feasible hypotheses for the thinning of the MBF.

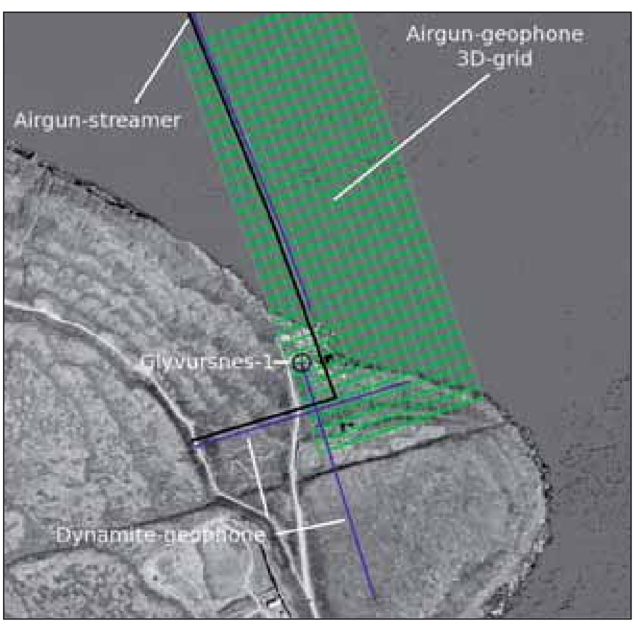

Figure 7 *Air photo of Glyvursnes survey area showing CDP positions of the 2D-processed airgun-streamer and dynamite-geophone data (blue lines), and grid for the 3D processed airgun-geophone data (green lines). The grid shows every inline and every 5th crossline. The black line shows the approximate position of combined dynamite-geophone, airgun-geophone and airgun-streamer profile in Figure 8. Position of Glyvursnes-1 borehole is also shown.*

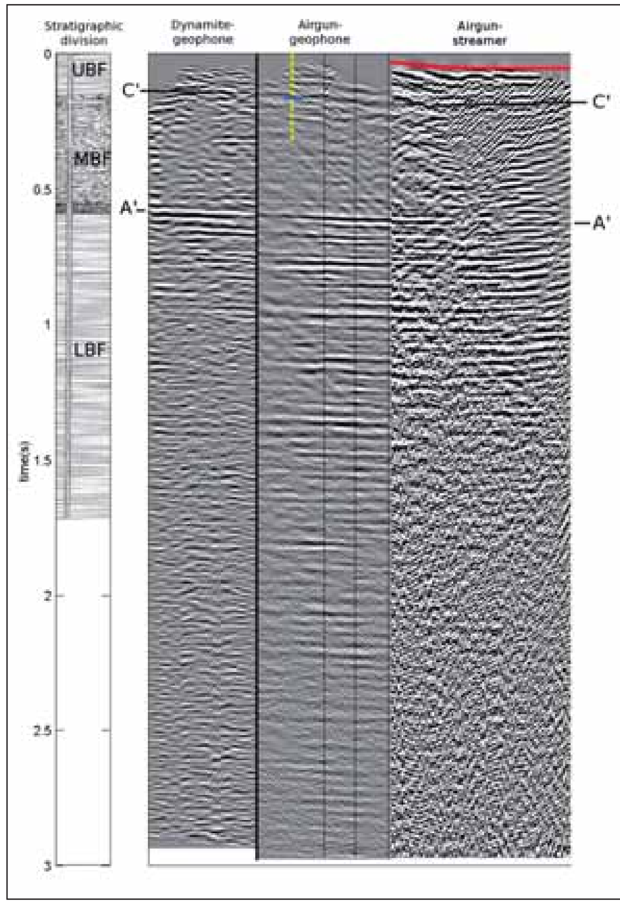

Figure 8 *shows the combined profile. See Figure 7 for location. An adjusted stratigraphic model is plotted to the left. A threefold subdivision of the seismic profile is distinct both in the airgun-geophone/streamer and dynamite-streamer data. Two high-amplitude successions (0-0.16 s and 0.59 s to end of record) and a low-amplitude succession (0.16-0.59 s) are clearly identified. By comparing this figure to Figure 3b (synthetic from composite logs), we see that the low-amplitude succession is characterised by a frequency content that is comparable to that of the synthetic seismogram through the MBF, while the frequency content of the lower high-amplitude succession is comparable to that of the LBF. Horizon C' ties well to the UBF-MBF boundary in the well (blue marker on yellow line). A' is interpreted to be the MBF-LBF boundary. The red line is the seabed derived from bathymetric information.*

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When considering possible errors in the estimate of the thickness of the MBF below Glyvursnes, one has to bear in mind that the Glyvursnes-1 well had a check-shot at 600 m depth, which constrains the time-depth relation down to this depth. Any significant error in the estimated thickness is thus due to erroneous velocities below 600 m. From 600 m to horizon A', a variation of the interval velocities of ± 10% affects the depth of horizon A' by ± 80 m. It is thus unlikely that the thickness of the MBF at Glyvursnes is comparable to the thickness at Vestmanna, unless an unrealistic average velocity around 7000 m/s is considered likely, or the interpretation of horizon A' as the MBF-UBF boundary is rejected.

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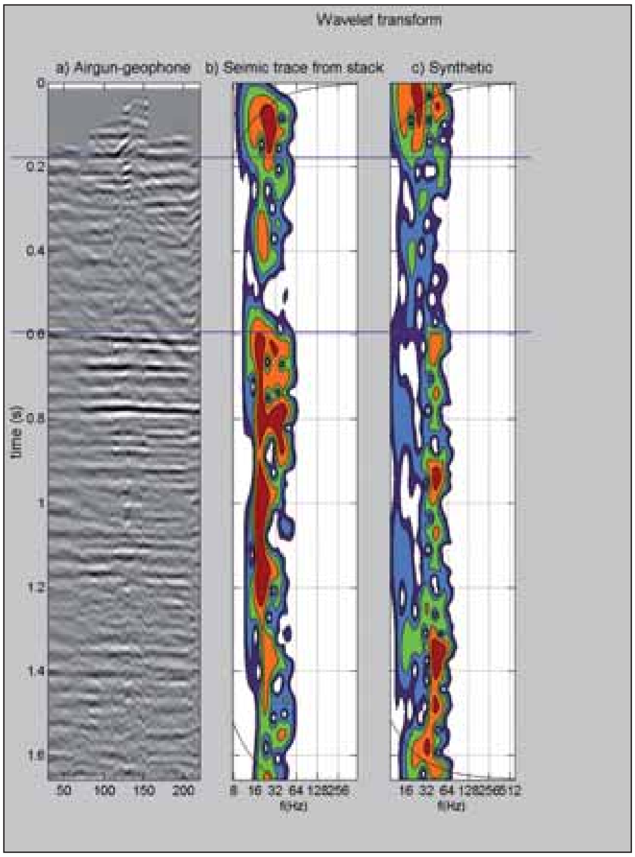

Figure 9 a) *Inline-2 from airgun-geophone stacked data;* **b)** *Wavelet transform of trace from the stack; c) Wavelet transform of the synthetic seismogram generated from the adjusted model. The seismic trace and the synthetic seismogram are normalized by standard deviation (Torrence and Compo, 1998). Contour levels are increasing exponentially. By comparing with Figure 3, we see the same generally lower amplitude and different frequency content for the signal arriving from the MBF than for the signal arriving from the UBF or LBF. This is thus a further verification of the interpretation of the base of MBF (horizon A') and adjustment of the thickness of the MBF. AGC has been applied to the seismic data, resulting in a higher amplitude level for the MBF.*

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