DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2005/57

Seismic and petrophysical properties of Faroes basalt
SeiFaBa Workshop September 29 2005

Funded by the Sindri Group

Peter Japsen (ed.)

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MINISTRY OF THE ENVIRONMENT

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Earth Sciences

SIGILLUM UNIVERSITATIS HAFNIENSIS

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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G E U S

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Apparent burial functions of some physical properties in basaltic successions from the Faroe-Shetland region

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Early Cenozoic flood basalts are found throughout most of the Faroe-Shetland region. We have investigated burial related variation of logged properties using data from six exploration wells where the flood basalts apparently are at their maximum burial depth. The basalt successions represent basalts burried to depths varying from ca. 1100 to 3500 m. Overall neutron porosity decreases with depth while seismic velocity and density increase. Using all data from the six wells, crude trends are established representing porosity reduction and seismic velocity and density increase as functions of depth in flood basalts from the Faroe-Shetland region. Exponential decay functions may be used to obtain depth estimates from neutron porosity, sonic and density logs:

Due to large variation of all three properties within individual lava beds, there is considerably variation around the trends. However, the trends are still considered representative for flood basalts in the Faroe Shetland region, and may be used to estimate maximum burial depth of flood basalts from the region that have been denudated after maximum burial. Vestmanna-1 and Glyvursnes-1 wells are all drilled into denudated successions of flood basalt. Using the functions above we obtain the following thickness of the removed succession above the three wells: 2500 – 2700 m at Vestmanna and 1500 – 2300 m at Glyvursnes.

In the Faroe-Shetland region basalts at maximum burial depth shallower than 1000 m has not been drilled. However, on Iceland geothermal wells have been drilled into young (post-glacial) successions of basalts. Comparing data from three wells from Iceland with our data from the Faroe-Shetland region indicate that the apparent porosity trends observed in the Faroe-Shetland wells not is global. Even within the Faroe-Shetland region, burial estimates based on these trends should be treated very carefully, preferably in combination with other estimates.

It has been shown in previous studies that basaltic lavabeds are characterised by a high porosity lava-top of variable thickness and a low porosity lava-core. Within a single well minimum porosity, maximum density and velocity of all beds thicker than a threshold value (ca. 6 m) fall within a narrow range (e.g. Planke 1995). Detailed analysis of logged lavabeds in wells form the Faroe Shetland area indicate that although most lavabeds can be approximated by a simple two components system, alteration products complicates interpretation, as there influence varies among wells and even among beds in individual wells.

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Planke, S. 1994: Geophysical response of flood basalts from analysis of wireline logs: Ocean Drilling Program Site 642, Vøring volcanic margin. Journal of Geophysical Research, **99**(B5), 9279-9296.

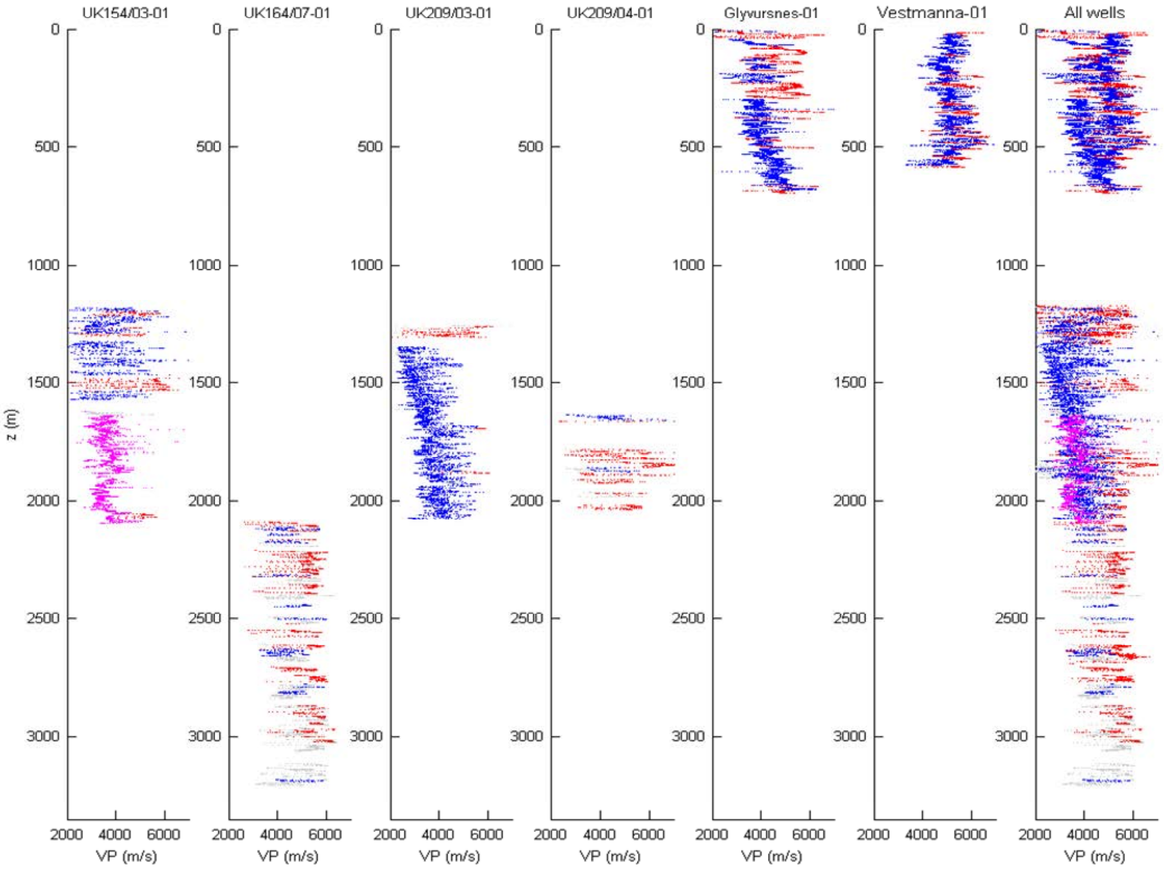

Figure 1. *Sonic velocity in basalt beds in well from the Faroe-Shetland area. Note overall velocity increase with depth. Blue: high-frequency lava beds, red: low-frequency lava beds, magenta: forset breccias (hyaloclastites).*

Velocity analysis from VSP and surface data at Vestmanna site

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Seismic VSP and surface data acquired at the Vestmanna site have been processed with the aim of evaluating the seismic velocity of the basalts. The seismic experiment around the Vestmanna borehole (which penetrates the Middle and Lower Series Basalts) comprises VSP, land and marine surface data. In total 8 Walk-Away profiles (200 to 1500 m offset), 2 fixed-offset VSPs (at 230 m and 610 m offset), one “zero offset” VSP, multichannel land records and a marine high resolution survey have been acquired.

The Offset-VSP data have been stacked to improve the signal/noise ratio while the Walk-Away data have been filtered by a combination of Butler & Russell (1993) and Butterworth bandpass filtering in order to eliminate severe 50 Hz electrical noise. The filtering considerably improves the data, enabling reliable first arrival picking and subsequent velocity analysis. Using first arrivals on the vertical component, the average horizontal velocity (4650-4950 km/s) is lower than the vertical velocity (5200 km/s) measured from the zero offset VSP data.

The direct arrival travel times picked on the WA and OVSP data have been used for anisotropy estimation using Gaiser’s method of the local phase slowness. For the data recorded in a single borehole, Gaiser (1990) proposed an approach which assumes lateral homogeneity of the overburden and VTI anisotropy for the target medium (here the basalt section). It is then possible to determine the vertical and horizontal components of the slowness vector from the Walk Away and OVSP data. The technique is based on fitting estimates of the horizontal and vertical slowness in the slowness domain. The slowness values related to the qP wave, calculated from the first arrivals on the vertical component, fit an ellipsoidal curve with a low degree of ellipticity that indicates at most only very weak anisotropic behaviour.

The high resolution seismic reflection survey of Vestmanna harbour, recorded with a sampling frequency of 22 kHz, allows us to investigate in detail the structure and thickness of sediments, which vary between 0-40 metres. Ray-trace modelling of the wide-angle data has been carried out using a model based on the bathymetry and sediment thickness variations and the borehole log data. A 400 m long (120-channel) land array with a combination of vertical and three-component geophones recorded all the shots fired for the walkway and the VSP data. These data have been binned in the offset domain to improve the S/N ratio. We are currently combining the arrivals recorded by the borehole and land array seismometers to construct an overall velocity model of the basalt section in the vicinity of the borehole.

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Butler, K.E. & Russell, R.D. 1993: Subtraction of powerline harmonics from geophysical records. *Geophysics* **58**, 898-903.

Gaiser, J.E. 1990: Transversely isotropic phase velocity analysis from slowness estimates, *J. Geophys. Res.* **95**, 11241-11254.

Petrophysical characterisation of basaltic rocks from nine wells from the Faroe-Shetland region

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Wireline logs through basaltic successions in seven exploration wells and two research wells from the Faroe Shetland area have been investigated. The basaltic successions can be divided into units of five different classes based on the overall response of mainly natural gamma radiation (GR), neutron porosity (NPHI), bulk density (RHOB), seismic velocity (VP) and resistivity (e.g. MSFL). These classes are:

1. *Low frequency lava beds*, which are characterised by high amplitude asymmetric log response with a period exceeding 5 meters on all porosity related logs (NPHI, RHOB, VP and resistivity logs). Typical velocity range is ca. 2000-6000 m/s at ca. 1500 m depth. Low frequency lava beds are frequently representing a single large lava flow of more than 5 meters thickness. The log responses are in these cases reflecting a vertical subdivision of the lava flow in an upper porous crust, a massive core and a thin lower porous crust.

2. *High frequency lava beds* are characterised by a erratic log response with a period which generally are less than 5 meters on all porosity related logs. Typical velocity range in a high frequency lava bed unit is ca. 2500-5500 m/s at ca. 1500 m depth. In the two cored wells it is seen that the low porosity intervals of high frequency lava bed units may correlate to individual thin flow units. The amplitude of deflections on log traces is generally less than in low frequency lava beds.

3. *Volcaniclastic sediments*, which are generally characterised by higher porosity than found in both classes of lava beds. In addition slightly higher natural gamma radiation is frequently observed in volcaniclastic sediment units. Typical velocity range in a low frequency lava bed unit is ca. 2000-3000 m/s at ca. 1500 m depth.

4. *Foreset breccias* (lava deltas) are characterised by porosities that generally are higher than in volcaniclastic sediments and amplitude of deflections that are less than in lava beds. Typical velocity range in a low frequency lava bed unit is ca. 3000-4500 m/s.

5. *Basaltic intrusives*, which are characterised by a symmetric high amplitude log response on the porosity related logs and low porosity. In shaley sediments the response of natural gamma radiation is also symmetric and the intrusives are characterised by low natural gamma radiation. Typical velocities of basaltic intrusives are ca. 6000 m/s at ca. 3000 m depth.

The NPHI log readings show the total amount of hydrogen which need not be the real porosity as hydrogen occur as secondary minerals in filled out vesicles in the basalt. It is frequently recommended to use the PEF and SP logs for problems involving secondary minerals. However, only limited success has actually been reported in literature, and hardly any related to basaltic successions. Therefore it is not certain how the preliminary results are to be interpreted. The PEF log is sensitive to minerals and rather insensitive to porosity. The Sp log (if useable) may indicate sections with movable fluids.

Examples of responses from 4 classes of volcanics are illustrated and the use of PEF and SP logs from one well is shown.

A comparison between log data from Faroes and Icelandic basalts

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An acoustic logging program was run in three wells in west Iceland in December 1998. The logging program and VSP surveys were a co-operation between Norsk Hydro, the Icelandic energy authorities (Orkustofnun) and Schlumberger. Orkustofnun selected three existing geothermal boreholes each c. 1 km deep that penetrated different geological sequences dominated by hyaloclastites (HH-1), flood basalts (LL-3) and a mixed environment (LA-10). A suite of logs were acquired in the three wells: dipole sonic imager (DSI), litho-density log (LDL), combined seismic imager (CSI), temperature (CPLT) and caliper (TCS).

The logs became available for the SeiFaBa project after Orkustofnun became part of the project in 2005. The geophysical logs (bulk density, compressional and shear slowness) have been quality controlled and Orkustofnun's lithological interpretation has been added to the log suite as a separate trace. The physical properties of the Icelandic basalts are very similar to those of the Faroes basalts with the main difference that the Icelandic basalt includes strata with higher porosity (lower density) than the Faroes basalts.

We observe a general overlap between data points for P-velocity versus density from basalts in three wells (Figure 1). Whereas the more deeply buried (and older) basalts from the Lopra-1 well include data of high density and velocity (range above c. 6.25 km/s), the shallow (and younger) basalts in the LL-3 well include data of low density and velocity (range below 3.5 km/s). However, the Glyvursnes-1 data deviate from the two other wells because bulk density data does not exceed c. 2.9 g/ccm (even though the corresponding velocity data are as high as those measured in the LL-3 well).

The deviation between the density log from Glyvursnes-1 and those from the two other wells corresponds to the discrepancy between core and log densities at high core densities (c. 3 g/ccm) observed in a comparison of data from the Glyvursnes-1 and Vestmanna-1 wells (Japsen & Waagstein 2005). The log measurements in the Glyvursnes-1 and the Vestmanna-1 wells were estimated at the same depths as where the core samples were taken and all core plugs were found to have higher densities than the log readings (Figure 2). Whereas density estimated from log and core data is similar below c. 2.8 g/ccm, log densities are progressively smaller than log densities for higher core densities. For the maximum core density of c. 3.1 g/ccm the corresponding log density is only c. 2.9 g/ccm. This deviation corresponds to the observed deviation between maximum densities in the Glyvursnes-1 well relative to the two other wells (Figure 1). The discrepancy may be due to a problematic calibration of the density tool used in the logging of the Glyvursnes-1 and Vestmanna-1 wells. This is now being investigated further.

We observe a good overlap between data points for P-velocity versus S-velocity from basalts in three wells (Figure 3). The overlap is especially clear between the data from the Lopra-1 and LL-3 wells where the Lopra-1 data represent the higher velocities and the LL-3 well the smaller velocities. This shift probably reflects the more shallow burial of the basalts in the LL-3 well compared to the Lopra-1 well (and an even greater burial of the basalts on the Faroes prior to their exhumation). The overlap of the two Vp-Vs trends probably corresponds to roughly similar mineralogical composition of the basalts on Iceland and the Faroes. The slightly lower Vp-Vs ratio observed for the Glyvursnes-1 well at high porosities may be due to difficulties in interpreting the full wave-form sonic data measured with a fairly simple instrument.

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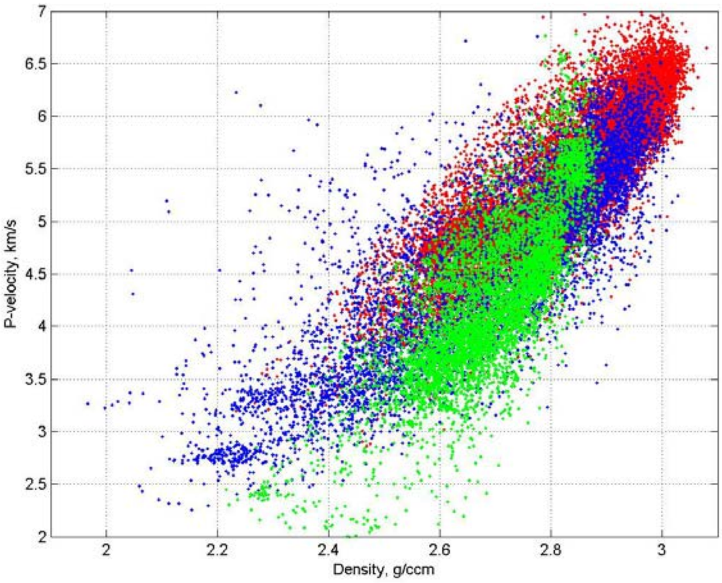

Figure 1. *Plot of Vp versus density from log data in three wells; Lopra-1 (red), LL-3 (blue) and Glyvursnes-1 (green). The plot reveals a general overlap between the three data sets, and that the Glyvursnes-1 well has no data points with densities above c. 2.9 g/ccm. The LL-3 well has data in the range between 2.2 and 2.5 g/ccm which is not well represented in the two other wells.*

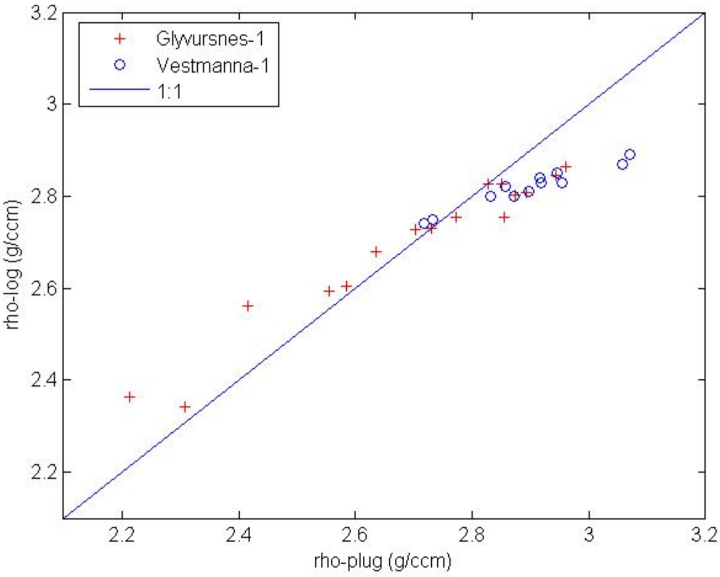

Figure 2. *Plot of density estimates (log versus water saturated core data at 300 bar). The plot shows density estimates based on log measurements in the Glyvursnes-1 and the Vestmanna-1 wells at the same depths as where the core samples were taken. Note that density estimated from log and core data is similar below c. 2.8 g/ccm, whereas log densities are progressively smaller than log densities for higher core densities. The discrepancy may be due to a problematic calibration of the density tool used in the logging of the two wells.*

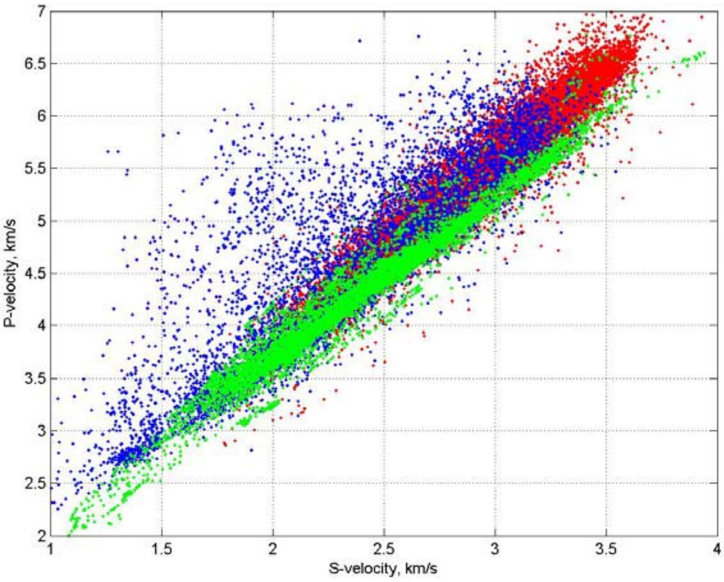

Figure 3. *Plot of Vp versus Vs from log data in three wells; Lopra-1 (red), LL-3 (blue) and Glyvursnes-1 (green). The plot reveals a general overlap between the datasets; especially between Lopra-1 and LL-3 whereas the data from Glyvursnes-1 is slightly shifted towards a low Vp-Vs ratio for high velocities.*

New field observations regarding the transitional zone between the middle and upper basalt series around the Faroe Islands

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The Faroe Islands are composed predominantly of a sequence of Palaeogene basalt lava flows, which have been subdivided into three basalt series: lower, middle and upper. According to Rasmussen & Noe-Nygaard (1969; 1970) the boundary between the Middle and Upper basalt series “corresponds to the lower surface of a series of two or three or even more flows (exceptionally only one flow) of compact, blue basalt, which are separated by zeolite-filled vesicular zones, or more rarely thin tuff beds” and this basal surface is referred to as the C-Horizon.

However, there is uncertainty concerning the position of the C-Horizon in the area to the south of Norðradalur on Streymoy due to the absence of the compact (low-Ti) aphyric to olivine microporphyritic basalts, commonly referred to as the C-horizon flows. However, logging and mapping across the middle and upper basalt series boundary on southern Streymoy, Hestur, Sandoy and Skúgvoy has led to the recognition of a number of key stratigraphic marker beds. These marker beds, or distinctive volcaniclastic sequences, has enabled a correlation across the central Faroe Islands, which has been tied into the known position of the C-horizon in the north of the Faroe Islands. One of these marker units is the Argir Beds, a 2.5-5.0 m thick sequence of bedded fine grained to granule-rich sandstones. Approximately 245 m below the base of the Argir Beds, is a 0.6-1.9 m thick green to red volcaniclastic sandstone. The base of this sandstone at Syðradalur, Streymoy has been correlated the C-horizon to the north.

To the north and northeast of Syðradalur, the boundary between the middle and upper basalt series is typically characterised by a marked, reddened, weathered flow top to plagioclase-phyric compound basalt lava flows. This weathered surface, or disconformity, is overlain by an omnipresent, reddened, medium grained volcaniclastic sandstone, containing abundant creamish woody plant fragments. This sandstone rarely exceeds 0.5 m in thickness and is commonly overlain by a maximum 25 m thick sequence of greyish volcaniclastic conglomerate beds, which in turn are sometimes overlain by medium grained to granule-rich sandstones. This northern volcaniclastic sequence is usually disrupted by one or sometimes more (low-Ti) aphyric to olivine microporphyritic basalts (C-Horizon flows) that display invasive features.

Consequently, the boundary between the middle and upper basalt series is represented by a regional disconformity and a volcaniclastic succession that is traceable across the Faroe Islands. Therefore, it is suggested that the base of the C-horizon should not correspond to the base of the C-Horizon flows but instead to the regional disconformity. The recognition of this regional disconformity and the overall updating of the geological map of the Faroe Islands is enabling a new lithostratigraphic nomenclature to be formalised following the guidelines of the *International Stratigraphic Commission* (Salvador 1994).

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Figure 1. *The* ca. *244 m high cliff face of Loftið, western Hestur. The C-horizon corresponds to the first obvious boundary between lava flows at the base of the cliff section. The cliff face is composed almost exclusively of compound-braided pahoehoe lava flows. From regional mapping of the central Faroe Islands it is suggested that this sequence may also occur in the Glyvursnes-1 borehole.*

Characterisation of basalt formation applying time variant frequency analysis

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[2]Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, DK-1350 Copenhagen K, Denmark
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In 2003 surface seismic data were acquired on Glyvursnes, Faroe Islands. Different source receiver combination (airgun-streamer, airgun-geophone, dynamite-geophone) were used to study the influence of different acquisition techniques. The Glyvursnes-1 borehole, located in the centre of the study area penetrates the boundary between the Upper and Middle basalt formation on Faroe Islands (C horizon) at 365 meters and TD at 700m. A seismic horizon (A') is identified Below TD of the borehole at ca. 0.6 s recording time (ca. 1390 m). We identify A' horizon as the boundary between the Middle and Upper basalt formation. This gives a total thickness of the Middle basalt formation of 1025 m significantly less than the 1400 m at Vestmanna (Waagstein, 1988).

Joint time frequency analysis was used to investigate the seismic data at various stages of processing and interpretation. Among different methods for joint time frequency analysis we selected the wavelet transform, as it is computational efficient and theoretically well found (Addison, 2002).

If properly scaled to account for signal decay, joint time frequency analysis of processed seismic data has potential as a tool for quantitative characterisation of seismic of the formations imaged by the data. This is illustrated by the time variant frequency plot of stacked traces of the seismic data from Glyvursnes (Figure 1). The "formation" between horizon C' and horizon A' is characterised by a narrower bandwidth and lower amplitudes than the "formations" above and below. Based on analysis of synthetic seismic data his is in support of our interpretation of horizon A' as the base of the Middle Basalt Formation on the Faroe Islands.

Application of joint time frequency analysis on raw data allows a rapid analysis of noise and signal. Frequency dependence of signature decay due to various attenuation mechanisms such as dissipation of energy and scattering can be observed directly (Figure 2 and 3) although the mechanism may not be identified for certain. The signature decay that is observed on the surface seismic data from

Glyvursnes is in accordance with attenuation studies based on zero-offset VSP data from the Glyvursnes 1 well showing that the basalts below Glyvursnes are characterised by low Q-factors (Shaw et al. 2004).

As joint time frequency analysis provide an estimate of the waveform at any sample, we may also parameterise the decay of the waveform on along any seismic trace, if the seismic signal is successfully isolated. This has possibly potential for routine evaluation of spatial and offset dependent changes of the “decay function”.

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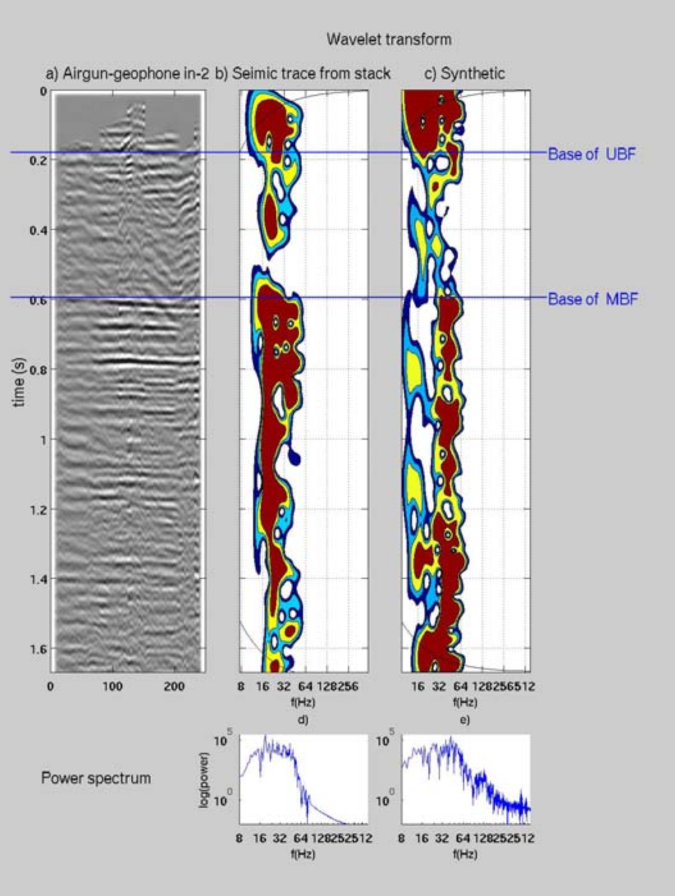

Figure 1. a) *Inline-2 from airgun-geophone stacked data;* **b)** *wavelet transform of trace from the stack;* **c)** *wavelet transform of the synthetic seismogram generated from the adjusted model;* **d)** *and* **e)** *power spectra of seismic trace and synthetic seismogram.*

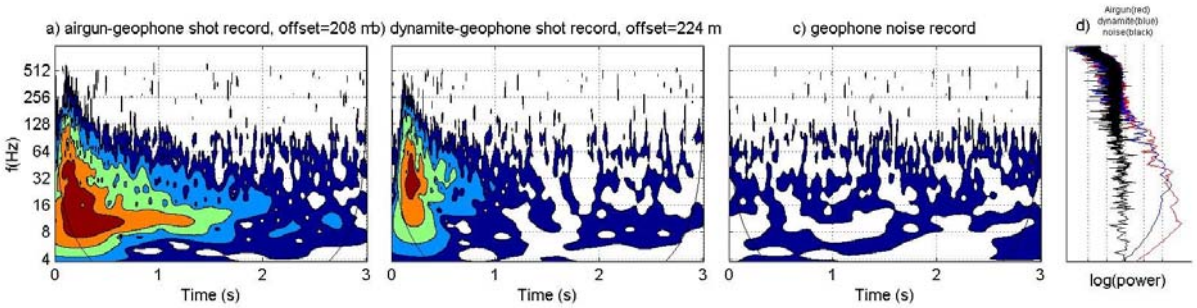

Figure 2. *Plot of the continuous wavelet transforms of geophone recording on channel 110 (station 74). Contour levels are adjusted to background noise level increasing exponentially to maximum value of airgun-geophone wavelet spectrum.* **a)** *Airgun-geophone, offset 208 m;* **b)** *dynamite-geophone, offset 224 m;* **c)** *geophone noise record;* **d)** *frequency spectra of all three records.*

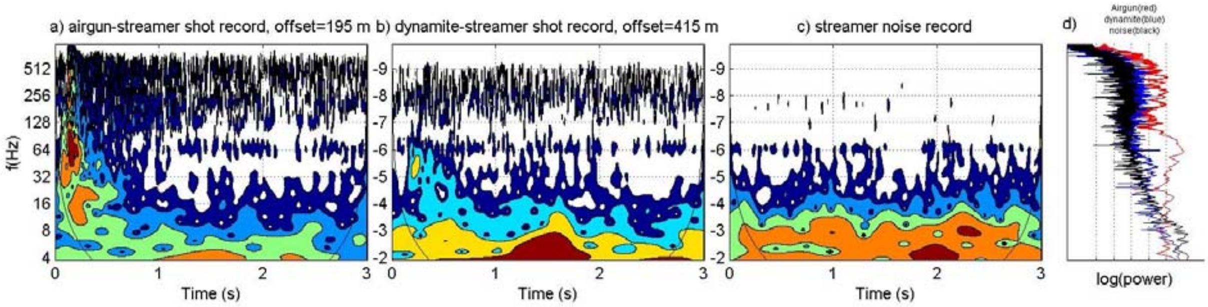

Figure 3. *Plot of the continuous wavelet transforms of streamer channel 130 (station 90). Contour levels are adjusted to background noise level increasing exponentially to maximum value of airgun-streamer wavelet spectrum.* **a)** *Airgun-streamer, offset 195 m;* **b)** *dynamite-streamer, offset 415 m;* **c)** *streamer noise record;* **d)** *is the frequency spectra of all three records.*

Heterogeneity and Seismic Properties of Faroe Islands Basalts

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Possible mechanisms for apparent or actual energy loss in basalt have been investigated.

A simple 1-D plane-layered model was generated using log data from the Vestmanna and Glyvursnes wells. Apparent attenuation caused by the resulting inter-bed multiples was not sufficient to account for observed values from the real VSP data. This differs from basalts in other areas of the North Atlantic, where studies have concluded that 1-D scattering is the dominant attenuation mechanism.

A 2-D model was then generated by qualitatively perturbing the 1D-model, to simulate basalt outcrops observed on the Faroes (Figure 1). This produced significantly greater scattering attenuation (Figure 2). 3-D heterogeneity increases the level of scattering further and may therefore be responsible for significant energy loss in basalts.

Statistical studies of the borehole logs from Vestmanna, Glyvursnes and Lopra were carried out to determine the dominant spatial frequency of basalt structures. Power spectral analyses (Dolan et al, 1998) reveal that rather than a few dominant length-scales, basalts show self-similarity and scale-invariance. This is characterized by the Hurst exponent H, which is calculated from the slope of the power spectrum. H values below 0.5 indicate self-similarity with greater fluctuation, whereas H values above 0.5 indicate self-similarity with less fluctuation. The Hurst exponents, and the scales at which they apply, vary between localities (Figure 3).

Power spectral analyses provide only second-order statistics, which are insufficient for model construction. To extract more structure from the data, multi-fractal analyses can be carried out using the wavelet transform modulus maxima method (Bacry et al, 1993). The intensity and the intermittency of the fluctuating signals is now quantified (Figure 4). Multi-fractal analysis allows more accurate rescaling of a 2-D or 3-D model based on real data.

The pattern of lobes and undulations at various scales, unique to each locality, will be crucial in investigating interface and volume scattering. Ongoing work will include the construction of a rigorously constructed model using multiplicative cascades.

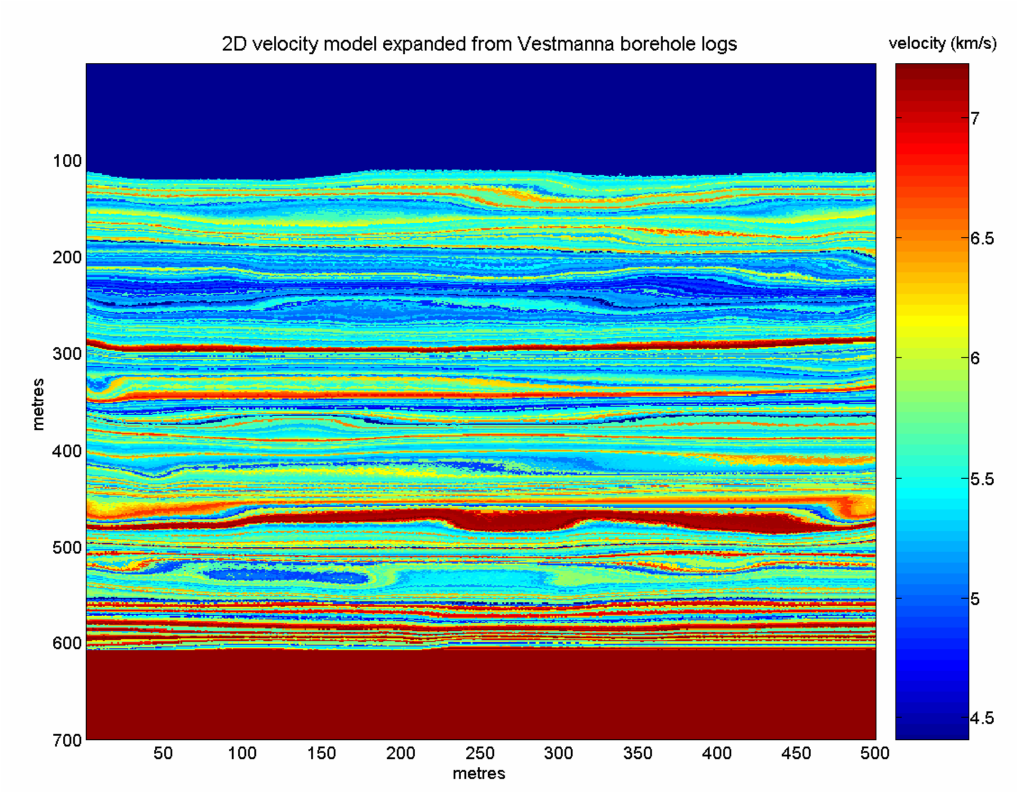

Figure 1. *A 2-D model generated by perturbing the 1D-model. Lobes and undulations simulate basalt outcrops observed on the Faroes.*

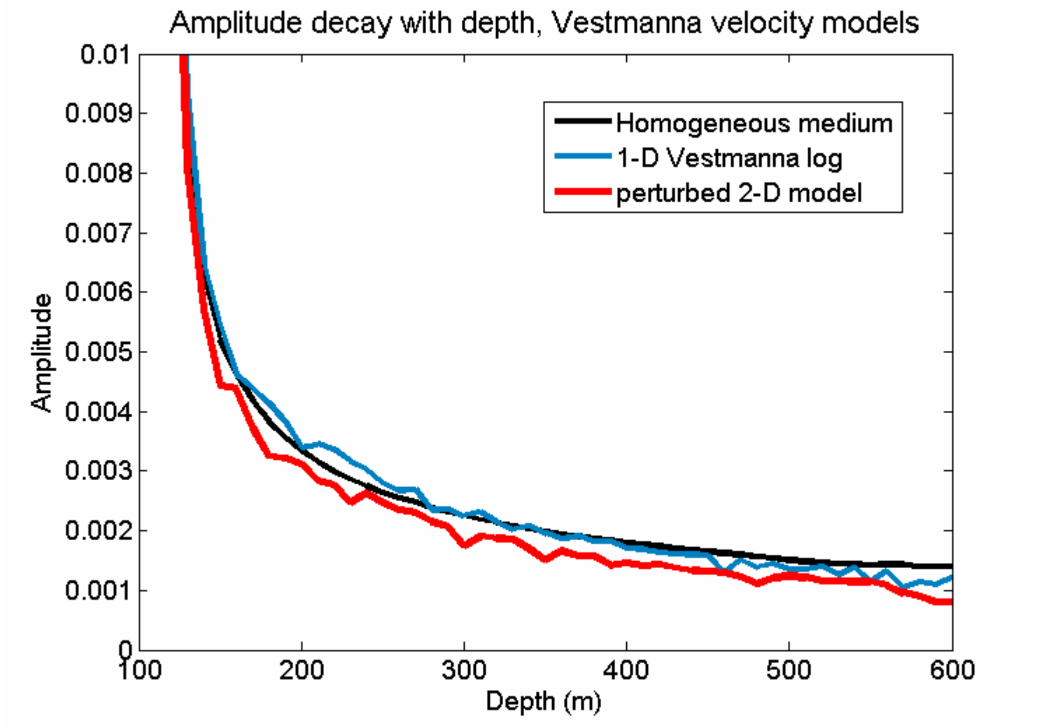

Figure 2. *Comparison between the first arrival amplitudes of three velocity models based on Vestmanna data.*

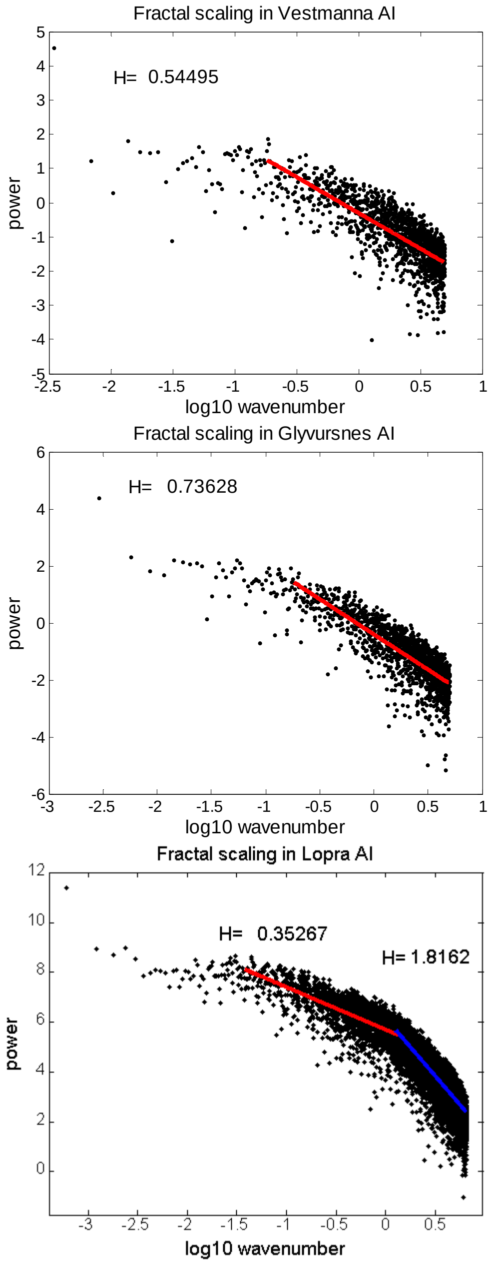

Figure 3. *Power spectra of acoustic impedance from Vestmanna, Glyvursnes and Lopra. The degree of scale-invariance, characterised by the Hurst exponent, H, differs between localities.*

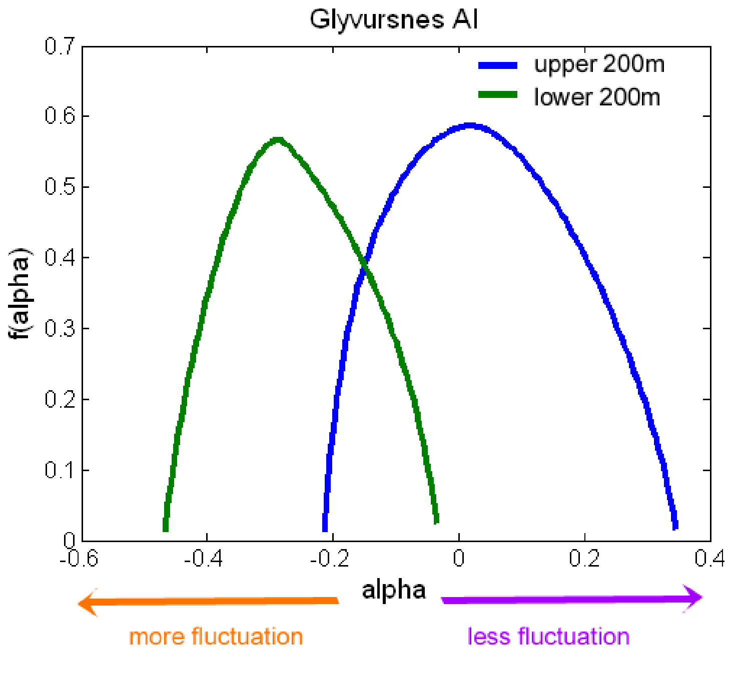

Figure 4. *Multi-fractal spectra of acoustic impedances for Glyvursnes.*

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Comparison of wire-line log and core data from the flood basalt succession of the Faroe Islands

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The first half of the presentation deals with the issue of log quality. The formation-density logs run by Robertson Geologging (RG) in the Glyvursnes and Vestmanna-1 wells give up to 0.2 g/cm^3 lower densities for massive basalt than bulk density measurements of water-saturated core samples (at 100 bar). Porous basalts and volcaniclastic rocks, on the other hand, tend to give too low densities as compared with the measurements on cores. Robertson Geologging has been unwilling to supply calibration data for any of their tools. However, from log header and ‘user function’ data provided by RG together with the logs, we have been able to reconstruct the overwritten raw data of the long-spacing data channel of the density tool. We have then devised a new set of calibration coefficients ‘0’ and ‘1’, which, with the same RG ‘user function’, gives a linear 1:1 correlation of log and core data within the presumed limits of statistical uncertainty. The correction procedure will be explained in detail and revised density logs made available for download.

The second half of the presentation deals with correlations between some rock physical and geochemical data on drill samples and wireline log data from the existing three deep (>600 m) wells into the Faroes basalt succession.

Presently, core data are available mainly from the two fully-cored wells at Glyvursnes and Vestmanna. A comparison between the porosity measured with the neutron porosity sonde and the core porosity shows that neutron porosity is on average 5% higher than core porosity. This is typical for basalts because the logging tool measures the hydrogen content of the formation, which is recalculated to pore water to give a porosity estimate. In altered basalts, hydrogen occurs partly in hydrous minerals of the matrix, especially in clay minerals and zeolites. The content of crystal-bound water in 60 basalts and volcaniclastic sediments from the Glyvursnes core has been analysed and compared with the total content of volatiles released by ignition of the dry rock powder. The water content varies from about 0.2 to 6.9 wt% and accounts for almost all of the weight loss on ignition. No data on crystal water is available for the Vestmanna-1 well. Using total volatiles as a proxy for matrix water and subtracting this water from the neutron porosity response, an almost 1:1 correlation with the core porosity is obtained for both wells. This procedure thus allows a correction of neutron porosity data of any well at depths where standard major element rock chemistry data are available provided that the volatile component is dominantly water, not carbonates or sulphides.

When the neutron porosity is corrected for volatiles, a strong correlation is obtained with the sonic properties of the core. A substantial improvement in the correlation with sonic log data is also obtained, especially for the Glyvursnes well (Fig. 1a and b). It shows that if core data are available for control, sonic logs can be used for a rough estimate of porosity.

Bulk density is a function of both pore fluid and rock matrix. In most rocks, porosity is far more important than the matrix or grain density. However, grain density of fresh basalts varies slightly with mineralogy. The density of fresh, crystalline, massive basalt may be estimated from the chemical composition of the rock by assuming that the mineral composition can be approximated by a set of standard minerals computed from a major element analysis, the so-called CIPW mineral norm. The upper 2.5 km of the 3.65-km deep Lopra-1/1A well on Suðuroy consists of on average 20 m thick basalt flows with massive centres. Chemical data on cuttings or cores have been published for most of the flows, while a bulk density log exists from about 180 m to T.D. The grain density computed from the chemical analyses of lavas between 180 and 2500 m shows a modest large-scale variation between 3.07 and 3.13 g/cm^3 (omitting altered basalts with >2% volatiles). The samples are typically from the massive central part of the flows. A close estimate of the maximum bulk density of individual flows may therefore be obtained in most cases from the density log by simply using a depth window of 20 m around each sample. This maximum bulk density is generally lower than the grain density, varying from 2.89 to 3.10 g/cm^3, and shows no clear correlation with grain density. The difference between the two density estimates indicates that even the most massive parts of the thick flows are somewhat altered. The main hydrous mineral in the massive basalt is clay replacing former glass or olivine or filling tiny interstitial pores.

The natural gamma log, which is run routinely during most standard log runs, measures the gamma-ray intensity of radioactive isotopes in the formation. The gamma rays are almost exclusively produced by isotopes of potassium, thorium and uranium. The concentration of K, Th and U has been analysed in 60 samples from the Gluvursnes well in order to evaluate the relative contribution of the different rock types to the gamma log response. The analysis shows that gamma-ray peaks are due mainly to mobilisation of potassium and uranium during alteration processes, while thorium is almost immobile.

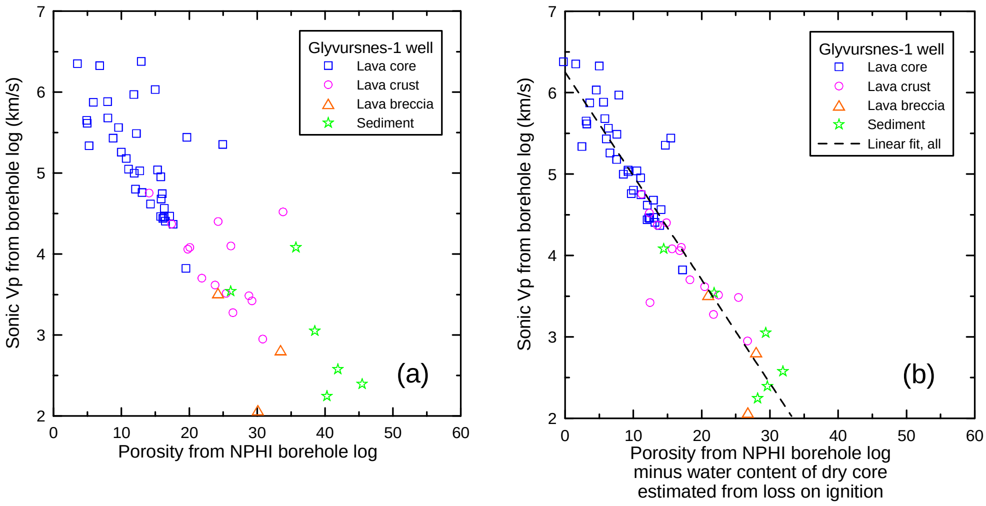

Figure 1. *Sonic* Vp *versus (a) original neutron porosity and (b) neutron porosity corrected from matrix water in core, Glyvursnes-1 well, southern Streymoy, Faroe Islands. The content of matrix water is estimated from the loss on ignition.*