DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2006/29

Seismic and petrophysical properties of Faroes basalts (the SeiFaBa project) Final Report

Funded by the Sindri group

Peter Japsen, Morten Sparre Andersen, Lars Ole Boldreel,
Regin Waagstein, Robert S. White, Michael Worthington
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To be released 01.01.2008

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Introduction

The SeiFaBa project ('Seismic and petrophysical properties of Faroes Basalt', 2002–2006) was funded by the Sindri Group as part of the programmes for licensees within the Faroese offshore area. The aim of the project was to provide a unique dataset and new understanding of the seismic and petrophysical properties of the Faroes basalts with special focus on the subaerially extruded flood basalts. Drilling of a new well at Glyvursnes and relogging of the Vestmanna-1 well in combination with the extensive dataset for the Lopra-1 borehole would provide valuable new stratigraphic control of the Upper, Lower and Middle Basalt Formations as well as understanding of the physical differences between these formations. The proposed well site at Glyvursnes gave optimal conditions for combining VSP offset with onshore and offshore surface seismic experiments. The relations of sonic velocities of basalt to porosity, composition, stress and fluid content could be studied through detailed analysis of well logs and core material. Such studies would aim at achieving explanations for the sonic response of basalt in terms of physical and compositional properties, bridging the gap between the different scales of data acquired from outcrops, cores, well logs and surface seismic as well as a better understanding of the seismic signatures of flood basalt successions.

The SeiFaBa project is based on a Research Agreement between Atlanticon on behalf of the Sindri Committee and the Geological Survey of Denmark and Greenland (GEUS) on behalf on the scientific partners in the project (the universities of Cambridge, Copenhagen, Oxford and the Faroe Islands). The purpose of the Research Agreement was to specify the conditions governing the payments to be made in respect to the project by Atlanticon and to set out the rights and obligations of the parties; e.g. scope of the work, project period, work plans as well as progress and milestone reports. GEUS and the scientific partners signed a Collaboration Agreement to specify the organization of the work of the project and to set out the rights and obligations of the parties; e.g. semi-annual meetings in the Project Coordinating Committee.

Milestone reports as outlined in the Research Agreement including this Final report have been submitted to the Sindri group as well as eight SeiFaBa progress reports. Additional work will be carried out after the submission of the Final report: The research of Dr Giovanni Bais at the University of Cambridge will last as planned until October 1 2006 (under the direction of Prof Robert White). The PhD thesis of Felicia Shaw at the University of Oxford will be completed in the summer 2006 (under the direction of Prof Michael Worthington). The PhD thesis of Uni K. Petersen at the University of the Faroe Islands is also to be

completed in the summer 2006 (under the direction of Dr Morten S. Andersen). Publication of a number of scientific papers documenting the results of the SeiFaBa project are thus to be expected over the coming years.

The present report contains a Summary of activities and results that highlights several aspects of the outcome of the project related to the investigations ranging from studies of core samples to surface seismic investigations with a focus on Faroes basalt, but including parallels to the properties of the Palaeogene basalts in the waters east of the Faroes and of Plio-Pleistocene basalts on Iceland. Moreover, the report contains a chapter with summaries of the project reports, a chapter with papers published during the project or in press and papers from the PhD thesis under preparation and finally a chapter with extended abstracts and abstracts to be presented at the Sindri Conference in Tórshavn, September 2006. The final report is accompanied with a cd containing pdf files with all items in the List of reports and publications.

Summary of activities and results

Drilling and logging at Glyvursnes and Vestmanna

A new 700 m deep scientific well (Glyvursnes-1*)* with continuous coring was successfully drilled autumn 2002 near Tórshavn through the boundary between the Upper Basalt Formation (UBF) and the Middle Basalt Formation (MBF) and the existing Vestmanna-1 well was reamed prior to running an extensive logging programme (Waagstein & Andersen 2004).

The Glyvursnes-1 well, located on the headland 2 km southeast of Tórshavn with the top of the surface casing at 16.6 m above sea level was drilled by the Finnish drilling contractor SMOY. The drilling method was diamond core drilling with fresh water flushing. The core was partly described visually on-site and later fully using a set of high quality digital core photos. The observed structural and petrographic features allowed the drilled succession to be subdivided into flow-units based on abundance and size of vesicles and presence of chilled surfaces and sediments.

The existing 660 m deep Vestmanna-1 borehole penetrating the lower part of the MBF with TD 100 m into the Lower Basalt Formation (LBF) was originally drilled in 1980. It had to be reamed prior to logging due to partly blocking by precipitation of white tufa along the wellbore. The reaming operation was terminated at 615 m due to stuck pipe.

An extensive suite of slim hole wire-line logs was run in both wells by Robertson Geologging. The logging programme comprised acquisition of the following logs: optical televiewer, three arm caliper, formation density, focussed electric, full waveform/compensated sonic, natural gamma spectroscopy and temperature/conductivity. The log quality is generally acceptable except for the spectral gamma logs due to lack of proper calibration. The full waveform sonic logs recorded with a tool with only two receivers are affected by high frequency noise causing difficulties to pick the shear waves. As the processing results from RG of the full waveform sonic logs were considered unsatisfactory time-consuming additional processing passes to enhance results were undertaken both by the Norwegian company Logtek and by GEUS.

The logging runs were made with only one tool at a time. As a good integration of wire-line log and core data is paramount to the project a tedious task of depth matching was carried out. It was carried out in two steps. First the formation density runs were chosen as the master run to which the depths of all other runs were compared. Afterwards the wire-line log runs were compared and adjusted with the drill cores. The depth shifts have been applied to the composite logs and composite LAS-files.

The well results are highlighted in the composite logs in the scale 1:500 showing all log runs together with general lithology and petrography of the cores. For simplicity only a dis-

tinction between sediments, brecciated lava crust, vesicular lava crust and massive lava core is made in the lithology column. The wire-line logs reflect clearly the bedding and other features seen in the core. For example the massive core of thicker flow-units comes out clearly with high bulk density, high sonic velocities, high resistivity and low neutron porosity.

The boundary between the Upper (UBF) and Middle Basalt formations (MBF) in the new Glyvursnes-1 well was picked at a depth of 355 m. It is picked at the base of 9 m simple flow of aphyric basalt with a very low gamma ray response morphologically and lithological similar to the so-called C-horizon exposed some 6 km west of the well-site. It overlies a 0.8 m thick very fine-grained reddish sediment. The drilled succession consists dominantly of compound lava flows of thin flow-units of plagioclase-phyric basalts with vesicular crusts characteristic to pahoehoe lava. 150 complete flow-units have been identified in MBF and 99 in UBF. The mean thickness of the flow-unit is 2.2 m in MBF increasing to a mean thickness of 3.4 m in UBF. Thick flow-units above 10 m are only present in the upper 300 m of the well section. Sediments make up 1.3 % of the drilled succession. Most sediment layers are thin and increase in abundance and thickness upwards. Details on the lava succession in Vestmanna-1 is given in Waagstein and Hald (1984).

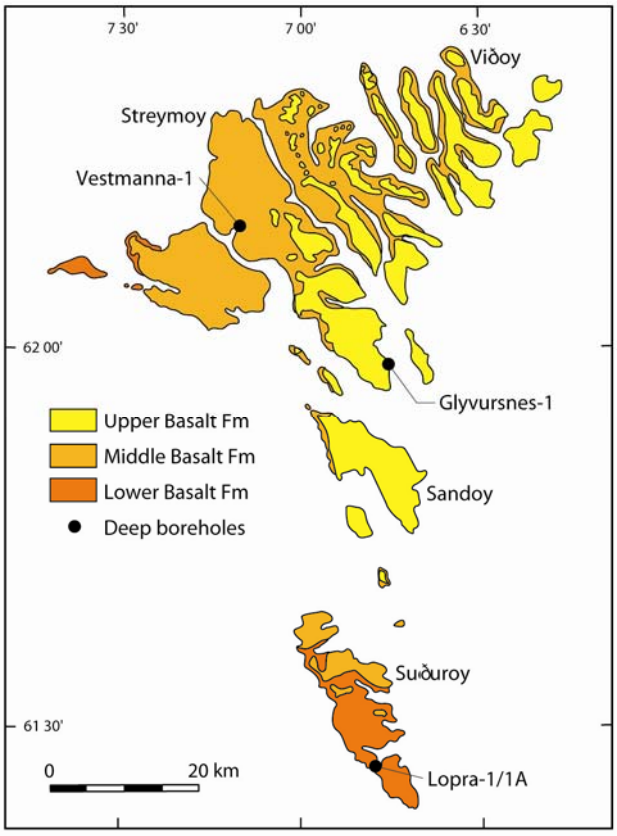

Figure 1. *Geological map of the Faroe Islands showing the location of deep boreholes and the distribution of the three Palaeogene basalt formations (modified from Waagstein 1998; Japsen 2005).*

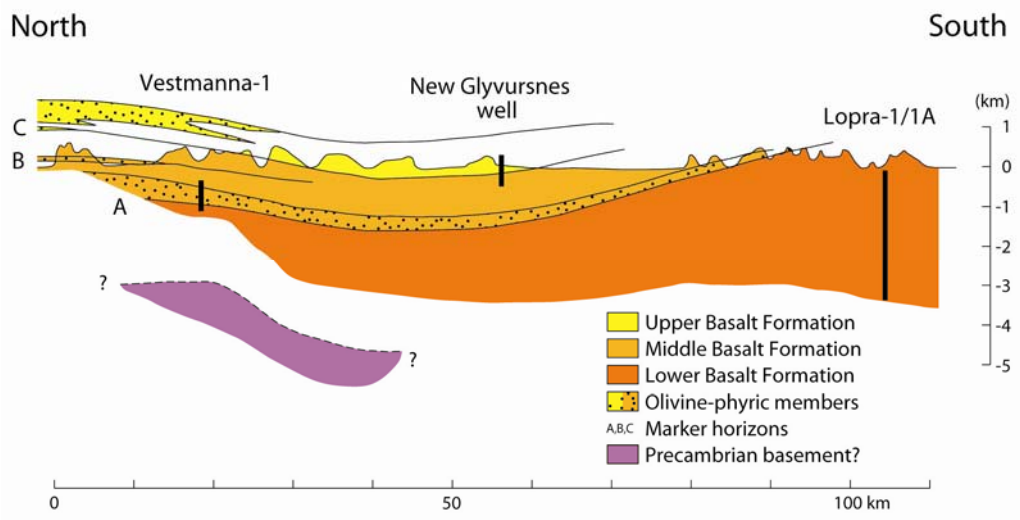

Figure 2. *Stratigraphical position of deep boreholes in the Faroe Islands (modified from Waagstein 1988; Japsen 2005).*

Classification scheme of basaltic rocks

A simple classification scheme of basaltic rocks has been developed to distinguish such rocks from silisiclastic sediments or hard rocks such as rhyolites penetrated by drill holes (Andersen et al. 2005; Andersen & Boldreel 2006). The classification is based on log data supplemented by descriptions of cuttings and sidewall cores. The study is based on wireline logs from 7 UK offshore exploration wells (UK154/03-01; UK164/07-01; UK164/25-01; UK164/25-01Z; UK205/09-01; UK209/03-01; UK209/04-01; UK209/09-01) and from two research wells on the Faroes Islands (Glyvursnes-1; Vestmanna-1). Completion reports and description of sidewall cores were available for most of the wells (Andersen et al. 2005). Full cores were available from the two research wells (Vestmanna-1 and Glyvursnes-1) and the wireline logs in these wells were correlated to core descriptions (Waagstein & Andersen 2003). Wireline log-based stratigraphy of flood basalts has also been established from the Lopra-1/1A (Boldreel 2006).

A method has been developed for subdivision of basaltic successions into five different classes (Fig. 3). The classification is based on the overall response of natural gamma radiation (GR), neutron porosity (NPHI), bulk density (RHOB), seismic velocity (VP) and resistivity (e.g. MSFL). The five classes are:

1. Simple lavaflows (referred to as low-frequency lava beds in Andersen et al. 2005) are characterised by high-amplitude asymmetric log response on all porosity related logs (NPHI, RHOB, VP and resistivity logs). The typical velocity range is very wide 2–6 km/s at c. 1.5 km depth. Low-frequency lava beds often represent a single, large lava flow, more than 5 m thick. The log response reflects a vertical subdivision of the lava flow in an upper porous crust, a massive core and a thin lower porous crust. In the two cored wells a similar subdivision can be defined by visual inspections. However, significant discrepancies may occur between the subdivision based on wireline logs and the subdivision based on visual core inspection; e.g. where a visually defined compound lavaflow (see below) has a log response similar to a low-frequency lava bed.

2. Compound lavaflows (referred to as high-frequency lava beds in Andersen et al. 2005) are characterised by a log response with a period which generally is less than 5 m on all porosity-related logs. The typical velocity range is 2.5—5.5 km/s at c. 1. 5 km depth. The amplitude of deflections on log traces is generally less than in low-frequency lava beds. In the two cored wells it is seen that the low-porosity intervals of high-frequency lava bed may correlate with individual thin flow units.

3. Volcaniclastic sedimentary units are generally characterised by higher porosity (NPHI) than found in both classes of lava flows. The typical velocity range in a volcaniclastic unit is c. 2–3 km/s at c. 1.5 km depth. Slightly elevated natural gamma radiation is frequently observed in volcaniclastic sedimentary units.

4. Foreset breccias units which may be ascribed as lava deltas (not shown in the figure) are characterised by porosities (NPHI) that generally are higher than in volcaniclastic sediments and amplitude of deflections that are less than in lava beds. Typical velocity range in foreset breccias units is 3—4.5 km/s.

5. Basaltic intrusives (hypabysal) are characterised low porosity (NPHI) and by a symmetric high amplitude log response on the porosity-related logs. Typical velocities are c. 6 km/s at c. 3 km depth. In shaley sediments the response of natural gamma radiation is also symmetric and the intrusives are characterised by low natural gamma radiation.

Furthermore, a detailed characterisation of individual units consisting of basaltic material may be established using log response components (characteristic patterns of one or more log trace within a part of the unit).

A database of physical properties for basaltic rocks estimated from wireline logs has been established and statistical values have been calculated that support the 5 classes mentioned above (Andersen et al. 2005). The range of the porosity-related parameters appear mainly to reflects burial depth and a preliminary linear relation between seismic velocity and depth for basaltic successions has been established using data from the seven UK exploration wells (Andersen & Boldreel 2006). The velocity-depth trend for the UK wells is different from a trend based on data from the Faroese wells.

Seismic attenuation of seismic signals due to stratigraphic filtering in basaltic successions has been modelled in several wells. The results indicate that attenuation due to stratigraphic filtering may reduce the seismic signal considerably at all frequencies. The Q-factor is generally estimated to be above 40 indicating that frequency-dependent attenuation observed in some seismic experiments (Q<40) is caused by other sources than stratigraphic filtering (cf. Shaw et al. 2006). Results of the detailed analysis of seismic attenuation at Glyvursnes and Vestmanna are presented in the section Seismic attenuation.

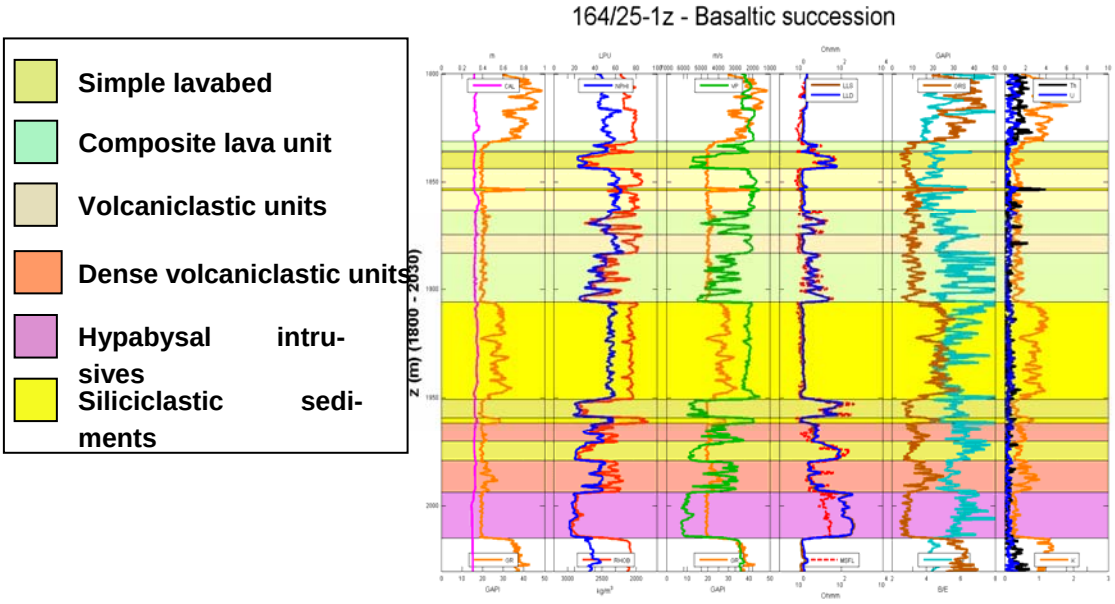

Figure 3. *Classification of volcanic units in 164/25-1z.*

Rock physics analysis of Faroese and Icelandic basalts

The acoustic properties of basalts have been analyzed based on sonic log data from three Faroese and three Icelandic boreholes and ultrasonic laboratory measurements on 43 1.5" core plugs from the three Faroese boreholes (Japsen & Mavko 2006; see Olsen 2005, Olsen et al. 2005). The Faroese boreholes are Lopra-1/1A, Vestmanna-1 and Glyvursnes-1 that penetrate the Palaeogene basalts of the Lower, Middle and Upper Basalt Formations (UBF, MBF and LBF) and these rocks are mainly subaerial flood basalts apart from hyaloclastites below c. 2.5 km depth in Lopra-1. The Icelandic wells penetrate volcanic rocks of Plio-Pleistocene age and cover a mixed environment: HH-1 (95% hyaloclastites), LA-10 (45% submarine and 45% subaerial basalts) and LL-3 (95% subaerial basalts).

We find a tight correlation between sonic Vp and He-porosity based on core data irrespective of basalt facies and well (only data for sediment samples deviate). The core data also reveal a well-defined relation between Vp and Vs, which is to be expected from rocks of broadly similar composition. However, there is a significant scatter in plots of Vp versus density and this scatter is related to the range of grain (matrix) densities from 2.7 to 3.1 g/ccm (Fig. 4). Low grain densities represent altered samples with high content of light minerals such as zeolite and clay.

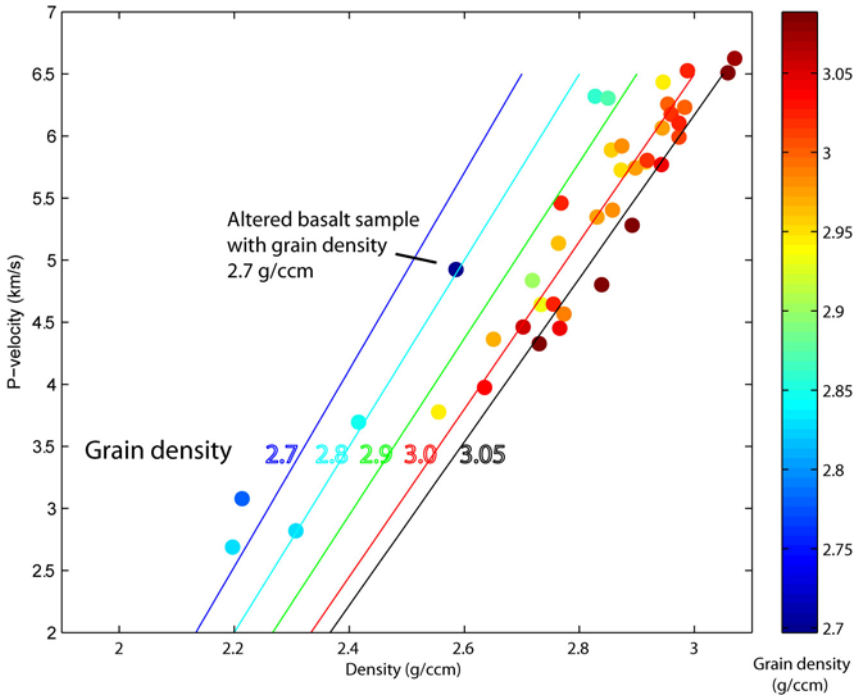

Figure 4. *Plot of ultrasonic data for water saturated core samples from Glyvursnes-1, Lopra-1 and Vestmanna-1 measured at 300 bar: Vp versus density colorcoded by grain density. Straight lines represent different grain densities for a linear velocity-porosity trend given by equation (6) in Japsen & Mavko (2006). Note the general good fit between the datapoints and the model that predict rocks with smaller grain densities to plot to the left in the diagram. Data points for sediments (Vp < 3.5 km/s) do not necessarily have to fit the model.*

Two main Vp-density trends can be distinguished for flood basalts based on the log data (Fig. 5): (1) a trend of relatively low Vp compared to density (the UBF in Glyvursnes-1; the flood basalts in LL-3), and (2) a trend of relatively high Vp compared to density (the LBF in Lopra-1). The properties of the MBF are transitional between the two trends. The Glyvursnes-1 data from this interval represents both the high and the low trend, whereas the Vestmanna-1 data represent a very high trend. The analysis of the Vp-density relation for the core data shows that the outlying samples towards low densities are characterized by low grain density. Hence the relatively high Vp-density trend defined for the log data in these wells for the MBF also must be characterized by low grain densities. This means that the low Vp-density trend represents basalt with unaltered matrix with high grain density and the high trend represents altered basalt with a low grain density.

The transition from the low Vp-density trend of fresh basalts to the high trend of altered basalts within the MBF occurs concurrently with an increase of the sonic velocity and density with depth even though there is no increase in the flow thickness. This indicates that that there probably is a net influx of mass into the altered basalt leading to higher densities (growth of zeolites).

Grain density of the core samples is found to be inversely correlated with Loss on Ignition (LoI) for all rock types and approaches a minimum density of 2.7 g/cm^3 at a maximum Loss

on Ignition of 8 Wt.%. (Japsen & Waagstein 2005). LoI is primarily a measure of the water released when the sample is heated to about 1000ºC. The rocks with the highest loss are the most altered ones and consist dominantly of water-bearing secondary minerals as smectite clay and various zeolites. There is a high correlation between neutron porosity (log-value estimated at the depth of the core) minus He-porosity (core) and the volume of water bound in secondary minerals. Neutron porosity measures the amount of hydrogen whether present in pore water or bounded in crystals and it is on average about 8 % too high as compared to gas porosities. The difference between neutron and He-porosity is thus a measure of mineral bound water.

Matrix (or grain) density for the core samples varies systematically with bulk density and alteration of the rocks. A grain density of 3.05 g/ccm is taken as an approximation for unaltered basalt (Japsen & Mavko 2006). For sediments in Faroese wells we assign the mean sample value of 2.8 g/ccm. Measurements on fresh Icelandic basalt lava indicate that 3.05 g/ccm is a reasonable pick (Omar Sigurdsson pers. comm.), and we also apply that value for volcanic sediments in Icelandic wells. Dolerites in Lopra-1 have smaller densities than for the surrounding basalt and we assign a matrix density of 3.02 g/ccm for these rocks. We convert log density to porosity based on these values for the matrix density for different lithologies and a pore water density of 1 g/ccm (and thus overestimate porosity of altered basalts).

The matrix properties of unaltered flood basalts were estimated by comparing acoustic log data from Lopra-1 with the self-consistent formulation of Berryman (1995): bulk modulus, K = 83.4 GPa; shear modulus, G = 40.1 GPa and grain density, ρ = 3.05 g/ccm. Comparison of the model with the log data for Faroese and Icelandic wells reveals a good agreement, but the Glyvursnes-1 data appear to be biased towards relatively high values of Vs.

A modified upper and lower Hashin-Shtrikman model has been estimated to model the velocity-porosity relation for basalt. We have tested a model with the following properties at a maximum porosity of 45%: K = 5.55 GPa, G = 3.2 GPa and the above properties at zero porosity. We find that most data points for all wells fall within the upper and lower bounds defined by this model. There is however, a considerable ambiguity in the relation between velocity and porosity as estimated from bulk density due to the wide range of grain densities. Sonic velocity is thus a proxy for the porosity of basalt and a median model defined by the mean of the upper and lower bounds may thus provide reasonable estimates of basalt porosity from sonic data.

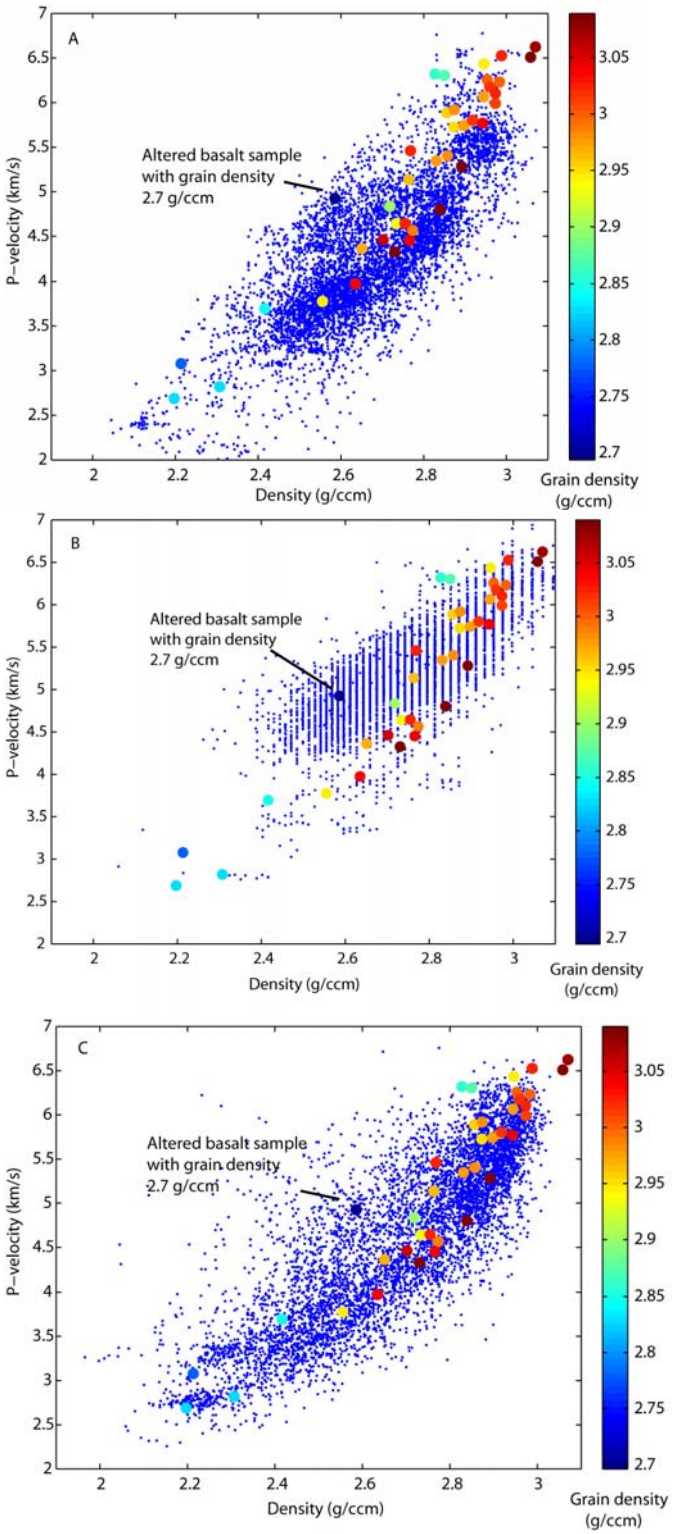

Figure 5. *Plot of Vp versus density for water saturated core data at 300 bar (all samples) and log data for (A) Glyvursnes-1, (B) Vestmanna-1 and (C) LL-3. The low-density part of the relatively high Vp-density trend for the altered MBF in the two Faroese wells is only represented by one sample. The low Vp-density trend represents basalt with unaltered matrix with high grain density (most of the Glyvursnes log data and the LL-3 log data) and the high trend represents altered basalt with a low grain density (the Vestmanna log data). The core data are shifted slightly towards higher Vp values compared to the log data.*

Seismic data acquisition at Glyvursnes and Vestmanna

Four seismic field experiments were carried out as part of the SeiFaBa Project: Two at Glyvursnes (2002, 2003) and two at Vestmanna (2004).

Glyvursnes seismic experiment, 2002

In June 2002, a small experiment was carried out by University of Faeroe Islands and Aarhus University (Petersen et al. 2003). This experiment was mainly aimed at obtaining sufficient data to investigate problems related to acquisition of near-vertical incidence and wide-angle seismic data in the Glyvursnes area. During this survey an external radio source, which induced a high frequency signal of unacceptable amplitude were identified, 500 MHz ground waves originating from the Loran-C transmitter at Eide. New antialias filters were designed in consultation with Geometrix and tested in the field during the winter 2002-2003. The new filters performed as expected and removed the Loran-C noise to a level below detection.

Otherwise the Glyvursnes seismic experiments 2002 showed that data suitable to investigate propagation of seismic waves in the basalts a Glyvursnes could be acquired using near-vertical incidence and wide-angle seismic methods.

Glyvursnes seismic experiments, 2003

In 2003 a two seismic experiments were carried out (Fig. 6a; Andersen et al. 2004). Vertical seismic profiles in Glyvursnes-1 were acquired in June-July and surface seismic data were acquired in September.

Prior to and during the first experiment, a dense array of 45 Guralp (6TD) three component seismometers were deployed. During periods of controlled source seismic shooting all sites maintained a sampling rate of 200 samples/second. For intervening periods when recording earthquakes a sampling rate of 100 samples/second was used. A three component tool was build for the VSP experiment. Three SM-7M 10 Hz geophones were arranged orthogonally and attached to a custom made hydraulic clamping system. The source was a 150 cu. inches Sodera G-gun fired in specially constructed ponds. The data was recorded on CD in SEG-Y format with a Geometrics Geode seismic recording system. Sample interval 0.125 ms. A Vertical VSP, a 242 m offset VSP and a 415 m offset VSP were acquired.

In September 2003 surface seismic data was acquired using three different energy sources 250 g dynamite in 3 m deep holes, 2 x 380 cu. inches Sodera G-gun cluster and a 4 x 40 cu. inches Haliburton slevegun cluster. Data were recorded on a marine streamer, vertical and 3-component geophones. Two vertical component near-vertical seismic incidence profiles at right angles to each other and a grid with pseudo-3D coverage were all acquired with 5 m receiver interval and 10 m shot interval using the dynamite source. Three 400 m profiles at 45° to each other were acquired using both airgun sources and a geophone string with vertical geophones every 5 m and 3-component geophones every 25 m. Two marine near-vertical seismic incidence pseudo-3D grid using the 4 x 40 slevegun clusters recorded on a streamer with 6.5 m group interval and the above mentioned geophone receiver arangement. The three component downhole receiver were clamped permanently at 400 m recording three component data during acquisition of most of the marine shoots.

Figure 6. *Left (A): Overview of part of the survey area. giving an idea of data coverage during Glyvursnes 2003 surface seismic experiment. Key to symbols: Red cross: autonomous seismometers; blue lines (onshore): geophone strings for vertical component reflection seismic profiles; red lines geophone strings for mixed 1C and 3C onshore-offshore seismic profiles; red lines offshore: approximate streamer positions during onshore-off seismic experiments; yellow and green crosses shot positions for two suites of marine reflection profiles with lateral offsets*
Right (B): Multiple shot locations for walk-away and azimuthal profiles at Vestmanna – at 400-, 600- and 800-m-offsets: shot over 26th-29th June 2004. 3 x 40 cu. in. (120 cu. in.) sleeve-guns were used throughout this acquisition.

Vestmanna seismic experiment, 2003

During June and July 2004 various VSP and offset VSP surveys were carried out at the Vestmanna-1 well (Fig. 6b; Petersen et al. 2005).

A 400 metre geophone line was deployed in an easterly direction from the borehole. This consisted of 120 vertical geophones cemented to outcrop at 5 metre intervals and a three component geophone every 4th location. 9 6TD Guralp seismometers were deployed west of the borehole to a maximum offset of 1200 metres. Airgun shots were fired in a natural pond 18 m from the well using a 2 x 40 cu. inches Haliburton slevegun cluster and in the Vestmanna fjord using a 3 x 40 cu. inches Haliburton slevegun cluster. A vertical offset VSP, two offset VSP were acquired with offsets of 230 and 610 m and walkaway azimuthal

surveys were acquired. A boomer survey of Vestmanna Fjorð was conducted in order to obtain accurate information on the nature and thickness of sediments in the fjord.

Seismic processing

Processing of the seismic data and further analysis were carried out as ph.d./post.doc. projects at the universities of Cambridge, Faeroe Islands and Oxford. Surface seismic reflections from Glyvursnes were processed in the Faeroe Islands, VSP and offset VSP data in Oxford and azimuthal data from Vestmanna and Glyvursnes in Cambridge (Petersen et al. 2003, 2005). See the following sections.

Seismic attenuation estimated from VSP data acquired at Glyvursnes and Vestmanna

The poor quality of most seismic reflection images within and beneath basalts is likely to be due to a combination of factors whose relative importance varies for different survey locations. The three boreholes at Glyvursnes, Vestmanna and Lopra provide an outstanding source of data for the determination of both the petrophysical and seismic properties of basalts in the Faroe Islands region and how these properties might vary laterally. In addition to estimating the values of seismic attenuation (Q) of the rocks at Glyvursnes and Vestmanna, we have also attempted to deduce the attenuation mechanisms, since this knowledge is required when assessing how the effective Q might vary laterally throughout a survey region (cf. Shaw et al. 2006).

Values of seismic Q determined from VSP data acquired at wells at Lopra, Glyvursnes and Vestmanna in the Faroe Islands are all sufficiently low to be a dominant cause of the poor quality of seismic reflection images. Figure 7 shows histograms of the range of values of effective Q determined at Vestmanna and Glyvursnes.

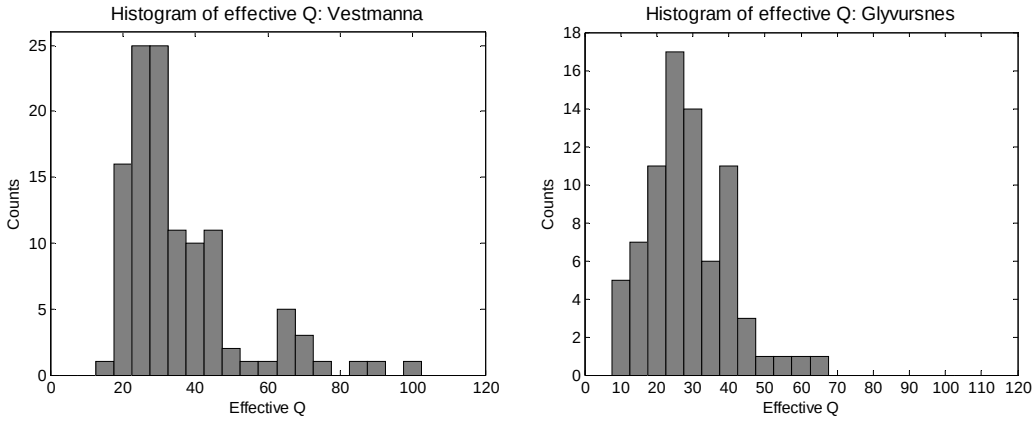

Figure 7. *Histogram of effective Q values determined from VSP data in (a) the Vestmanna borehole and (b) the Glyvursnes borehole.*

However, the possible causes of the low Q have been found to vary between the three borehole localities. Christie *et al*. (2006) concluded that 1-D scattering is the dominant at-

tenuation mechanism at Lopra. It is possible, based on our modelling studies, to come to the same conclusion for the UBF in the top half of the Glyvursnes hole. However, within the MBF in the bottom half of the Glyvursnes hole (360-700 m) and at Vestmanna, very little attenuation can be attributed to 1-D scattering. In Figure 8 it can be seen that the character of the acoustic impedance in the top half of the Glyvursnes hole is markedly different from the remainder of the logs displayed.

Results from 3-D elastic wave numerical modelling with a hypothetical basalt model constructed on the basis of field observations indicate that very little scattering attenuation is caused by lateral variations in basalt structure. However, the low values of effective Q observed at Glyvursnes and Vestmanna can be explained as resulting from a combination of 1-D scattering and intrinsic attenuation due to seismic wave induced fluid flow within pores and micro-cracks.

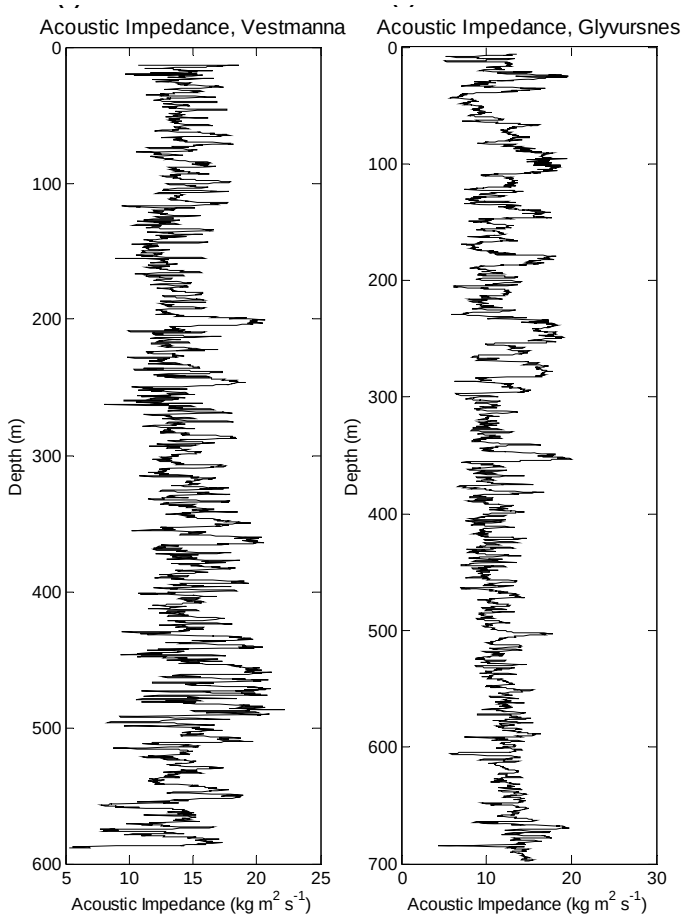

Figure 8. *Acoustic impedance logs from the Glyvursnes and Vestmanna boreholes.*

This study adds to the now substantial number of observations of seismic attenuation within basalt sequences in the North Atlantic region and reinforces the general conclusion that low values of effective Q are to be expected. However, the causes of the high attenuation may vary greatly from one locality to another.

Processing and interpretation of surface seismic data acquired at Glyvursnes

The seismic data acquired around the Glyvursnes-1 borehole makes it possible to compare borehole data (wireline logs) with surface seismic data acquired using different acquisition techniques (Fig. 9). Data were acquired on vertical geophones, 3-component geophones and a marine streamer using two different marine sources and dynamite shots in 3 m deep boreholes (Andersen et al 2004).

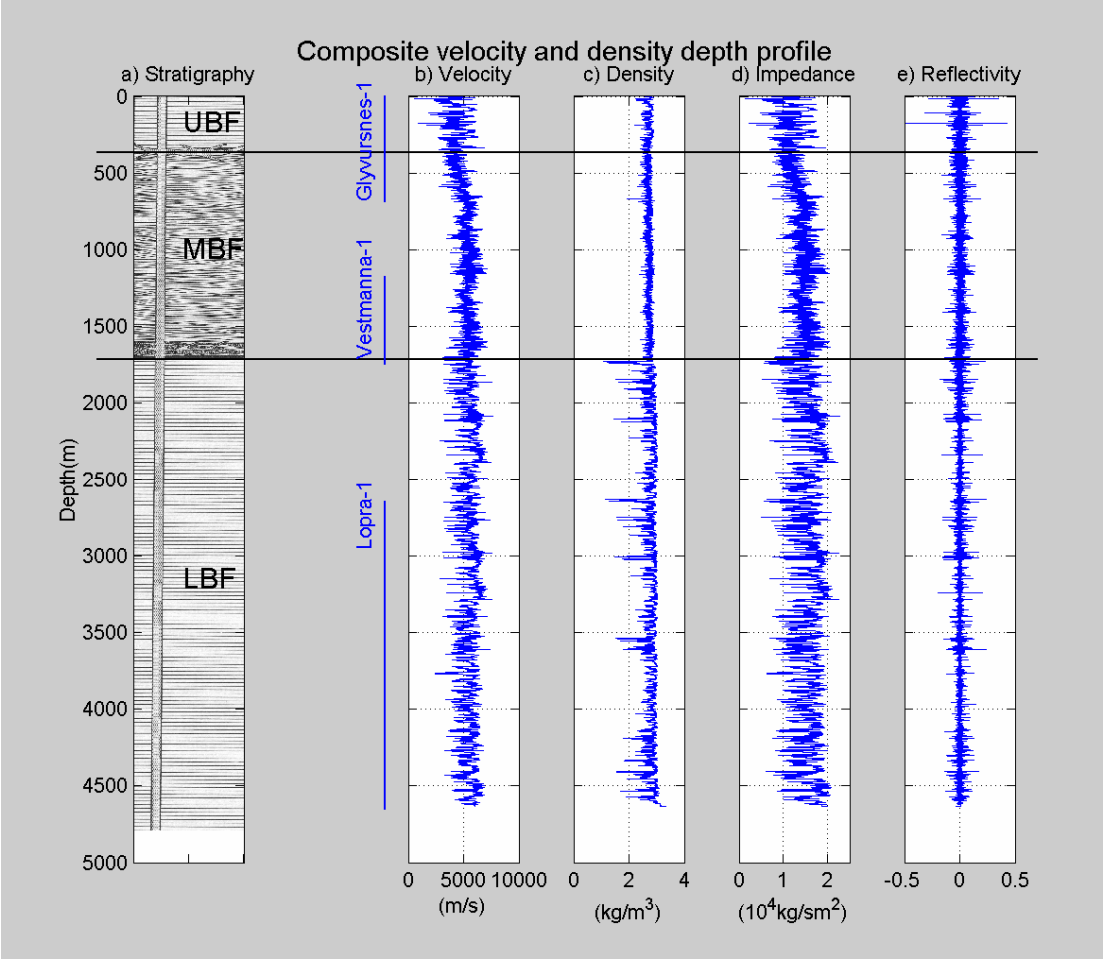

Figure 9. *Composite velocity and density logs for the total stratigraphic sequence below Glyvursnes, constructed using the logs from Glyvursnes-1, Vestmanna-1 and Lopra-1. a) Stratigraphic subdivision (modified from Rasmussen & Noe-Nygaard 1970). The base of the UBF and the base of the MBF are drawn as black horizontal lines across the figure; b) composite velocity log. The uppermost 485 m of Vestmanna-1 are used to represent the missing interval in the MBF and the uppermost 720 m of Lopra-1 are used to represent the missing interval in the LBF; c) composite density log; d) and e) calculated acoustic-impedance and the reflection coefficient series. From Petersen et al. 2006.*

The signal quality of the data recorded by the different combination of source and receivers were compared using time variant frequency analysis of individual traces using a wavelet transform (Figs 10, 11; Petersen *et al.* 2006). This analysis demonstrates a strong time

dependent decay for all source-receiver combinations, especially of high frequency seismic data. Qualitatively this is in good agreement with attenuation estimates obtained from analysis of the down-going waves in the zero offset VSP from Glyvursnes-1 (Shaw *et al.* 2004, 2006).

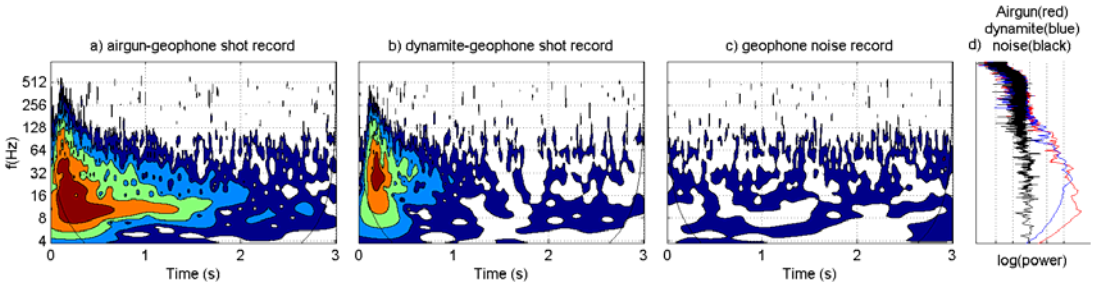

Figure 10. *Plot of the continuous wavelet transforms of geophone channel 110. a) Airgun-geophone, offset 208 m; b) dynamite-geophone, offset 224 m; c) geophone noise record; d) frequency spectra of all three records. Contour levels are increasing exponentially.*

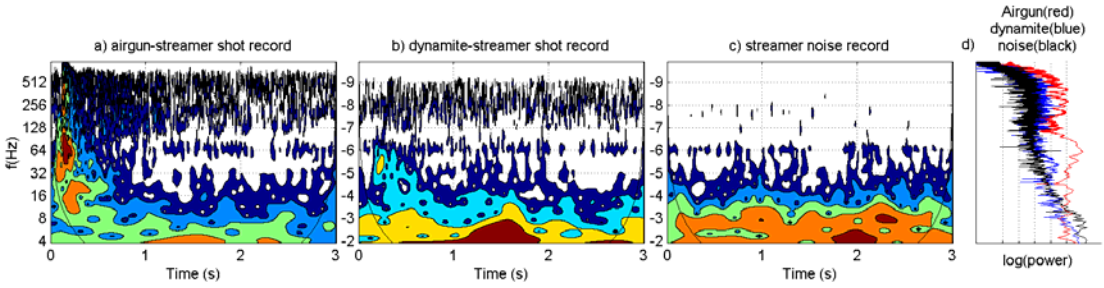

Figure 11. *Plot of the continuous wavelet transforms of streamer channel 130. a) Airgun-streamer, offset 195 m; b) dynamite-streamer, offset 415 m; c) streamer noise record; d) the frequency spectra of all three records. Contour levels are increasing exponentially.*

The time variant frequency analysis indicates that a seismic signal, not necessary primary reflections, should be expected to a recording time of 3 s when 160 cu. inches airgun shots are recorded on geophones (Fig. 10a), but only to about 1 s recording time when recorded on the streamer (Fig. 10b). When dynamite shots are recorded on geophones a seismic signal is expected to ca. 1-1.5 s recording time (Fig. 11a). Due to the higher frequencies in dynamite shots, better resolutions may be achieved at shallow depth. Due to the weak signal (Fig. 11b), dynamite shots were not recorded systematically on the streamer.

Processing and further analysis is focused at highlighting and identifying phases within the time-windows of seismic data for the different source-receiver combinations. Coherent events are seen to a recording time of at least 3 s in the airgun-geophone data, ca. 2 s in the dynamite-geophone data and to ca 1.5 s in the airgun streamer data, highlighting the ability of stacking to enhance weak coherent signal (not obvious in individual traces). Recording time should thus be constrained by stacking tests rather than signal analysis on individual traces.

The stacked sections are characterised by sub-horizontal, almost planar reflections (Fig. 12). Dip is therefore of little help constraining multiple events or other arrivals not being primary P-wave reflections. Two fairly distinct and coherent reflections are picked on the stacked sections from all three acquisition combinations (horizons A' and C'). The succes-

sion below horizon A' is characterised by strong continuous internal reflectors and the strength of internal reflectors decreases gradually with depth (recording time). The succession A'-C' is characterised by weak reflectors, which mostly are non-continuous. This is best seen in the dynamite-geophone and airgun-geophone data. The succession above horizon C' is incompletely imaged due to the shallow depth. However, internal reflections are strong and fairly continuous. It is suggested that the contrasting character of the three successions defined by horizon A' and C' replicate the contrasting character of the three exposed basalt formations on the Faeroe Islands. Therefore Horizon A' is interpreted to be approximately equivalent to the LBF-MBF boundary while horizon C' corresponds to the MBF-UBF boundary.

Shaw et al. (2006, in press/this volume) suggest that 1D scattering is one of the main reasons for the low Q-values obtained from the zero offset VSP in Glyvursnes-1 (see the Section Seismic attenuation). We should thus expect short period interbed reverberations to be a significant constituent of the reflected seismic energy. Planke (1994) pointed out that the bed thickness in basalt successions generally is small compared to the wavelength of the seismic signal and concluded that reflections in the seaward dipping reflector sequence around ODP well 642E mostly represented tuning of reflections from individual bed boundaries. Bed thickness in the LBF on the Faroe Islands is on average around 20 m, well below the dominant wavelength in the seismic signal. Coherent events below horizon A' on the stacked sections is thus likely not to represent reflections from individual beds, but at best complex interferences of tuned primaries and short period reverberations. However, even a coherent event constituted by interferences of tuned primaries and short period reverberations carry information about geology corresponding approximately to the TWT time of the event. Coherent events below horizon A' in stacked sections of the dynamite-geophone and airgun-geophone (Fig. 12) is thus likely to contain relevant geophysical information, as we believe long period interbed multiples is scarce.

The processing and interpretation of the surface seismic data acquired at Glyvursnes in 2003 indicate that imaging of the basalt succession encountered at Glyvursnes is possible. Decay of the source signature with depth into the formation and correct stacking velocities are key factors controlling the quality of the final stack of the basalt succession. As proposed by Planke et al. (1999) seismic imaging of basalt thus amounts to the conventional task of separating primary energy from noise.

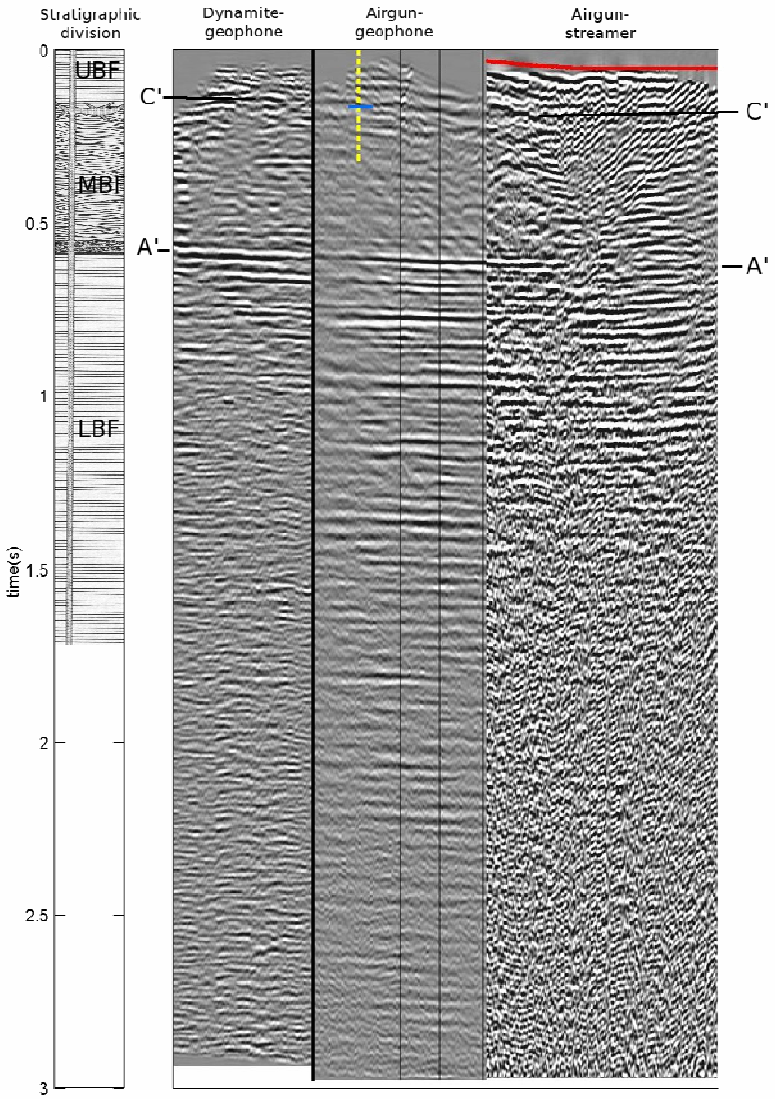

Figure 12. *Combined profile of the total stratigraphic sequence below Glyvursnes (Fig. 1) and the seismic data. A threefold subdivision of the seismic profile is distinct both in the airgun-geophone-streamer and dynamite-streamer data. Two high-amplitude successions (above C' and below A') and a low-amplitude succession (between A' and C') are clearly identified. The red line is the seabed derived from bathymetric information. The blue marker on the yellow line is the UBF-MBF boundary in the well.*

Seismic velocities, anisotropy and seismic imaging of Vestmanna basalts from integrated borehole and wide-angle data

Borehole data, vertical seismic profiles, near-offset and wide-angle seismic reflection data have been used to investigate the velocities, anisotropic properties and internal imaging of layered basalts at Vestmanna harbour (Fig. 13) (Bais et al. 2006). Here the 660 m Vestmanna-1 borehole penetrates the lower 550 m of homogeneous “pahoheoe” lavas of the Middle Basalt Formation (MBF) and into the 10–30 m thick, “aa” lava type flows of the Lower Basalt Formation (LBF). We have correlated the ultrasonic-scale velocity measurements from the borehole with the seismic-scale velocities and reflection images derived from VSP and surface data.

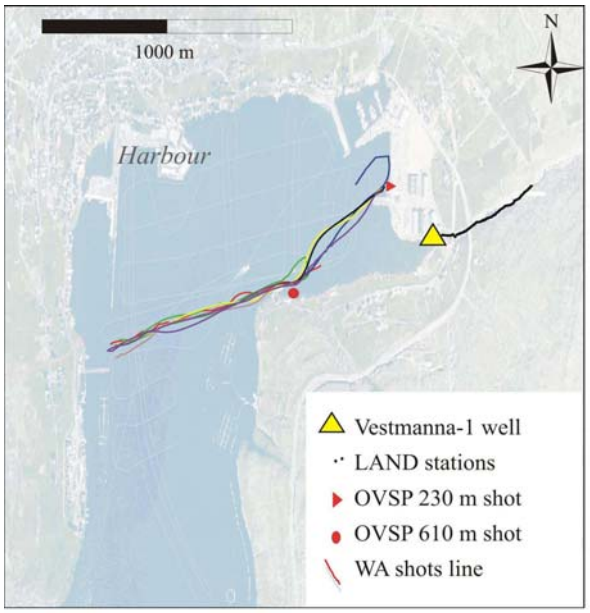

Figure 13. *Location map of the Vestmanna survey. Seismic data were acquired from a 3component sensor in the borehole and from a 120-channel 3-component Geometrics geophone array extending away from the borehole on basalt outcrops. We recorded a vertical seismic profile (VSP), six offset VSPs (OVSP) with borehole sensors at 50 m depth intervals, and six wide-angle (WA) profiles into the borehole receivers and the land array (LAND).*

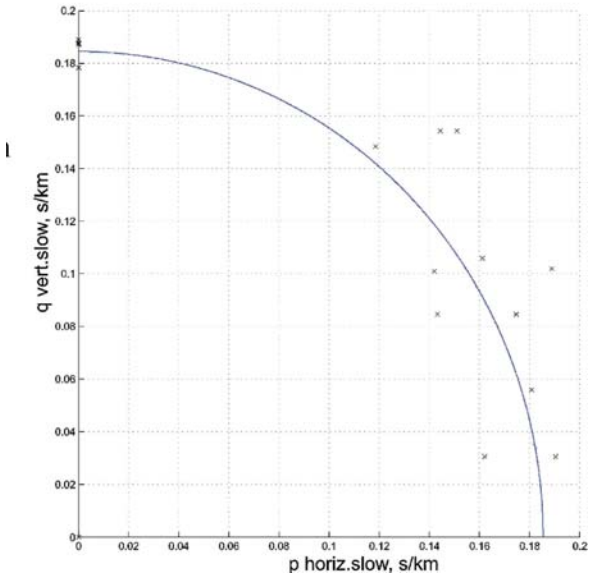

Figure 14. *Plot of vertical versus horizontal slowness. Phase slowness analysis shows a horizontal to vertical slowness ratio of 1.005. This indicates that anisotropy from the layered basalts is less than 0.5%, even smaller than the value of 1% derived by theoretical calculation from the layered structure.*

Using the phase-slowness method of Gaiser (1990) on the first arrivals on OVSP and WA data we find that the observed anisotropy from the layered basalts is less than 0.5%, even smaller than the value of 1% derived by theoretical calculation from the layered structure (Fig. 14).

The geometry of the borehole (WA, VSP, OVSP) plus land acquisition allows rays to be recorded over a wide range of illumination angles: the P wave velocity model calculated from the first arrivals by an isotropic ray tracing code shows average velocities of 5200–5800 m/s with an overall increase with depth. The observed travel-times from borehole and wide-angle P-wave data match well with those predicted from the borehole logging measurements.

Reflection profiles from our data show a strong and continuous intra-basalt reflector at 600 m depth (Fig. 15): This does not correlate exactly with the MBF-LBF boundary but is produced by a 30 m thick basalt flow ~40 m deeper. Synthetic seismogram modelling confirms that 10–30 m thick basalt layers of the LBF are capable of producing strong reflections from individual layers, whereas the thin (average < 2 m) layers of the MBF produce reflectivity from the interference effect of multiple thin layers, as reported by Smallwood *et al.* (1998) from the basalt sequence in eastern Iceland. This highlights the important result that strong and readily identified intra-basalt reflectors may not necessarily be caused by the main stratigraphic horizons or discontinuities, but rather are a seismic response to the particular sequence of layered basalts resulting from an interference pattern.

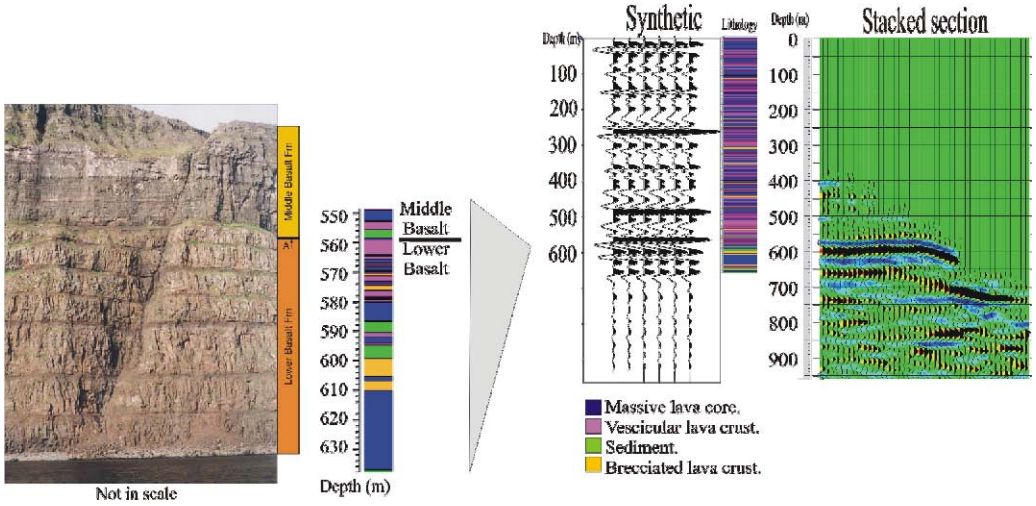

Figure 15. *Correlation between log and seismic stacked data: the strong reflection is immediately below the MBF-LBF boundary.*

References

Andersen, M.S., Worthington, M., Mohammed, N.G., White, R.S., Shaw F. & Petersen, U.K. 2004: Seismic experiments at Glyvursnes June-December 2003, Acquisition report, Contribution to the SeiFaBa project. Funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2004/37**, 34 pp.

Andersen, M.S., Boldreel, L.O. & Hansen, H.K. 2005: Analysis of wireline logs through basaltic successions in nine wells from the Faroe-Shetland area. Danmarks og Grønlands Geologiske Undersøgelse Rapport Rapport **2005/3**, 170 pp.

Bais G., White R. S., Worthington M. H., Andersen M. S. & SeiFaBa Group 2006: The seismic response of Faroe basalts from integrated borehole and wide-angle seismic data, 68th Meeting European Association of Geoscientists and Engineers, Vienna, 5pp., expanded abstract A033, 4 pp.

Berryman, J.G., 1995: Mixture theories for rock properties, in: A Handbook of Physical Constants, Ahrens, T.J., ed., American Geophysical Union, Washington, 236 pp.

Boldreel, L.O. 2006. Wire-line log-based stratigraphy of flood basalts from the Lopra-1/1A. Geological Survey of Denmark and Greenland Bulletin **9**, 39–53.

Boldreel, L.O. & Andersen, M.S. & the SeiFaBa group 2006: Efffect of burial on in situ properties of flood basalt successions in the Faroe-Shetland Region. The Sindri Conference, Tórshavn, September 2006.

Christie, P., Gollifer, I. & Cowper, D. 2006: Borehole seismic studies of a volcanic succession from the Lopra-1/1A borehole in the Faroe Islands, N.E. Atlantic, Geological Survey of Denmark and Greenland Bulletin **9**, in press.

Gaiser, J.E. 1990: Transversely isotropic phase velocity analysis from slowness estimates, Journal of Geophysical Research **95**, 11241–11254.

Japsen, P. & Mavko, G. 2006: Rock physics analysis of sonic velocities in basalts from Faroes and Icelandic wells. Contribution to the SeiFaBa Project. Funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2006/28**, 91 pp.

Japsen, P. & Waagstein, R. 2005: Preliminary analysis of ultrasonic and geochemical properties of core samples from Glyvursnes-1 and Vestmanna-1, Faroe Islands. Contribution to the SeiFaBa project. Funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/19**, 39 pp.

Japsen, P., Andersen, C., Andersen, H.L., Andersen, M.S., Boldreel, L.O., Mavko, G., Mohammed, N.G., Pedersen, J.M., Petersen, U.K., Rasmussen, R., Shaw, F., Springer, N., Waagstein, R., White, R.S. & Worthington M. 2005: Preliminary results from investigations of seismic and petrophysical properties of Faroes basalts in the SeiFaBa project. In*:* Doré, A.G. & Vining, B.A. (eds): Petroleum Geology: North-West Europe and Global Perspectives: Proceedings of the 6th Petroleum Geology Conference. Geological Society, London, 1461-1470.

Olsen, D. 2005: Special Core Analysis for the SeiFaBa Project. Ultrasonic velocity measurements on plug samples from the Vestmanna-1 and Glyvursnes-1 wells, Faroe Islands. Danmarks og Grønlands Geologiske Undersøgelse Rapport Rapport **2005/10,** 65 pp (1 cd).

Olsen, D., Jørgensen, M. & Guvad, C. 2005: Special Core Analysis for the SeiFaBa Project. Ultrasonic velocity measurements on 12 plug samples from the Lopra-1, Vestmanna-1 and Glyvursnes-1 wells, Faroe Islands. Danmarks og Grønlands Geologiske Rapport **2005/76**, 32 pp, Appendix (1 cd).

Petersen, U.K., Andersen, M.S. & Andersen, H.L. 2003: Glyvursnes seismic experiment, summer 2002. Field report and preliminary data analysis. A Sindri progress report. University of the Faroe Islands, 24 pp, Appendix.

Petersen, U.K., Andersen, M.S., White, R.S., Worthington, M.H., Mohammed, N.G., Shaw, F., Normark, E. & Trinhammer, P. 2005: Preliminary processing of the seismic data acquired in the vicinity of wells Glyvursnes-1 and Vestmanna-1. Contribution to the SeiFaBa project. Funded by the SINDRI Group. University of the Faroe Islands, 36 pp (1 cd).

Petersen, U.K., Andersen, M.S., & White, R.S., 2006: Seismic imaging of basalts at Glyvursnes, Faroe-Islands – Hunting for future exploration methods in basalt covered areas. First Break **24**, 45–52.

Planke, S. 1994. Geophysical Response of Flood Basalts from Analysis of Wire Line Logs - Ocean Drilling Program Site-642, Voring Volcanic Margin. Journal of Geophysical Research-Solid Earth **99(B5)**, 9279–9296.

Planke, S., Alvestad, E., Eldholm, O. 1999. Seismic characteristics of basaltic extrusive and intrusive rocks. The Leading Edge **March**, 342–348.

Rasmussen, J., Noe-Nyggard, A. 1970. Geology of the Faeroe Islands. C. A. Reitzels Forlag, København.

Shaw, F., Worthington, M.H., White, R.S., Andersen, M.S. & Petersen, U.K. 2005: Seismic attenuation in Faroe Island basalts. EAGE 67th Conference & Exhibition — Madrid, Spain, 13–17 June 2004. 4 pp.

Shaw, F., Worthington, M.H., White, R.S., Andersen, M.S., Petersen, U.K. & the SeiFaBa Group 2006: Seismic attenuation in Faroe Islands basalts. Accepted for Geophysical Prospecting (pending minor revisions).

Smallwood, J.R., White, R.S. and Staples, R.K. 1998. Deep crustal reflectors under Reydarfjördur, eastern Iceland: Crustal accretion above the Iceland mantle plume. *Geo*physical J. Int. **134**, 277–290.

Waagstein, R. 1998: A geological field guide to the Palaeogene flood basalts of Suðeroy, Faroe Islands. Danmarks og Grønlands Geologiske Undersøgelse Rapport **1998/30**, 46 pp.

Waagstein, R. & Andersen, C. 2004: Well completion report: Glyvursnes-1 and Vestmanna-1, Faroe Islands. Contribution to the SeiFaBa project funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/99**, 67 pp (1cd).

Waagstein, R. & Hald, N. 1984: Structure and petrography of a 660m lava sequence from the Vestmanna-1 drill hole, lower and middle basalt series, Faeroe Islands. In: Berthelsen, O., Noe-Nygaard, A. & Rasmussen, J. (eds) The Deep Drilling Project 1980–81 in the Faeroe Islands. Føroya Frodskaparfelag, Torshavn, 39–70.

List of publications

Papers

Japsen, P., Andersen, C., Andersen, H.L., Andersen, M.S., Boldreel, L.O., Mavko, G., Mohammed, N.G., Pedersen, J.M., Petersen, U.K., Rasmussen, R., Shaw, F., Springer, N., Waagstein, R., White, R.S. & Worthington M. 2005: Preliminary results from investigations of seismic and petrophysical properties of Faroes basalts in the SeiFaBa project. In*:* Doré, A.G. & Vining, B.A. (eds): Petroleum Geology: North-West Europe and Global Perspectives: Proceedings of the 6th Petroleum Geology Conference. Geological Society, London, 1461 - 1470.
File name: 2005_Japsen_etal_PGC_Seifaba.pdf

Japsen, P., Andersen, M.S., Boldreel, L.O., Waagstein, R., White, R.S. & Worthington, M. 2004: Seismic and petrophysical properties of Faroes basalts (SeiFaBa project). Geological Survey of Denmark and Greenland Bulletin **4**, 53-65.
File name: 2004_Japsen_etal_ROSA.pdf

Petersen, U.K. 2006: Propagation, decay, phase conversion and recording of seismic waves in the basalt succession at Glyvursnes, the Faroe Islands - Summary of thesis in preparation. In: Japsen, P. , Andersen, M.S., Boldreel, L.O., White, R.S., Waagstein, R., Worthington, M. & the SeiFaBa group. Seismic and petrophysical properties of Faroes basalts (the SeiFaBa project) Final Report. Funded by the Sindri group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2006/29**.
File name: 2006_Petersen_propagation.pdf

Petersen, U.K., Andersen, M.S., White, R.S. & the SeiFaBa Group 2006: Seismic imaging of basalts at Glyvursnes, Faroe Islands: hunting for future exploration methods in basalt covered areas. First Break **24**, March 2006. In: Japsen, P. , Andersen, M.S., Boldreel, L.O., White, R.S., Waagstein, R., Worthington, M. & the SeiFaBa group. Seismic and petrophysical properties of Faroes basalts (the SeiFaBa project) Final Report. Funded by the Sindri group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2006/29**.
File name: 2006_Petersen_First_Break24.pdf

Shaw, F. 2006: 1-D heterogeneity and statistical studies of the Faroes wireline logs. 10 pp, 5 tables, 13 figures. In: Japsen, P. , Andersen, M.S., Boldreel, L.O., White, R.S., Waagstein, R., Worthington, M. & the SeiFaBa group. Seismic and petrophysical properties of Faroes basalts (the SeiFaBa project) Final Report. Funded by the Sindri group.
File name: 2006:_Shaw_1D_heterogeneity.pdf

Shaw, F., Worthington, M.H., White, R.S., Andersen, M.S., Petersen, U.K. & the SeiFaBa Group 2006: Seismic attenuation in Faroe Islands basalts. Accepted for Geophysical Prospecting (pending minor revisions).
File name: 2006_Shaw_etal_Geoph_Prosp.pdf

Reports

Andersen, M.S., Boldreel, L.O. & Hansen, H.K. 2005: Analysis of wireline logs through basaltic successions in nine wells from the Faroe-Shetland area. Danmarks og Grønlands Geologiske Undersøgelse Rapport Rapport **2005/3**, 170 pp.
File name: 2005_03_Andersen_etal.pdf

Andersen, M.S., Worthington, M., Mohammed, N.G., White, R.S., Shaw F. & Petersen, U.K. 2004: Seismic experiments at Glyvursnes June-December 2003, Acquisition report, Contribution to the SeiFaBa project. Funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2004/37**, 34 pp.
File name: 2004_37_Andersen_etal.pdf

Gommesen, L. 2005: SeiFaBa well log analysis, lithology and rock physics. Ødegaard A/S Report 04.26074.01, 23 pp.
File name: 2005_Gommesen_Ødegaard.pdf

Gommesen, L. & Ahmed M. 2005: SeiFaBa log analysis of Icelandic wells, Lithology and Rock Physics. Ødegaard A/S Report 03.24036.02, 29 pp.
File name: 2005_Gommesen_Ahmed_Ødegaard.pdf

Japsen, P. (ed.) 2005: Seismic and petrophysical properties of Faroes basalt. SeiFaBa Workshop September 29 2005. Contribution to the SeiFaBa project. Funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/57**, 24 pp.
File name: 2005_57_Japsen_ed_Workshop.pdf

Japsen, P., Andersen, M.S., Boldreel, L.O., White, R.S., Waagstein, R., Worthington, M. & the SeiFaBa group 2006: Seismic and petrophysical properties of Faroes basalts (the SeiFaBa project) Final Report. Funded by the Sindri group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2006/29**.
File name: 2006_29_Japsen_etal.pdf

Japsen, P. & Mavko, G. 2006: Rock physics analysis of sonic velocities in basalts from Faroes and Icelandic wells. Contribution to the SeiFaBa Project. Funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2006/28**, 91 pp.
File name: 2006_28_Japsen_Mavko.pdf

Japsen, P. & Waagstein, R. 2005: Preliminary analysis of ultrasonic and geochemical properties of core samples from Glyvursnes-1 and Vestmanna-1, Faroe Islands. Contribution to the SeiFaBa project. Funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/19**. 39 pp.
File name: 2005_19_Japsen_Waagstein.pdf

Jørgensen, O. 2005: Zeolites and other secondary minerals in the drill core Glyvursnes-1, Faroe Islands. Contribution to the SeiFaBa project. Funded by the Sindri Group. 18 pp, 11 figs.
File name: 2005_Jørgensen_SAMA.pdf

Madsen, T. 2006. The Vágar Tunnel, Faroe Islands. Geological Profile. Result of field work 2002. Jardfeingi. 18 pp, 2 tables, 12 figures, 1 enclosure.
File name: 2006_Madsen_Jardfeingi_Vagar_Tunnel.pdf

Mavko, G. & Japsen, P. 2005: Rock physics analysis of sonic velocities in wells Lopra-1, Glyvursnes-1 and Vestmanna-1. Danmarks og Grønlands Geologiske Undersøgelse Rapport Rapport **2005/17**. 29 pp.
File name: 2005_17_Mavko_Japsen.pdf

Mavko, G., Japsen, P. & Boldreel, L.O. 2004: Preliminary rock physics analysis of basalts in the Lopra-1 well. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2004/96**, 11 pp.
File name: 2004_96_Mavko_etal.pdf

Olsen, D. 2005: Special Core Analysis for the SeiFaBa Project. Ultrasonic velocity measurements on plug samples from the Vestmanna-1 and Glyvursnes-1 wells, Faroe Islands. Danmarks og Grønlands Geologiske Undersøgelse Rapport Rapport **2005/10,** 65 pp (1 cd).
File name: 2005_10_Olsen.pdf

Olsen, D., Jørgensen, M. & Guvad, C. 2005: Special Core Analysis for the SeiFaBa Project. Ultrasonic velocity measurements on 12 plug samples from the Lopra-1, Vestmanna-1 and Glyvursnes-1 wells, Faroe Islands. Danmarks og Grønlands Geologiske Rapport **2005/76**, 32 pp, Appendix A (1 cd).
File name: 2005_76_Olsen_etal.pdf

Passey, S.R. 2005: Geology of Glyvursnes, Streymoy, Faroe Islands. A Contribution to the SeiFaBa project. Funded by the Sindri Group. Jardfrødisavnid, 24 pp, 1 map.
File name: 2005_Passey_Jardfrødisavnid_report.pdf
File name: 2005_Passey_Jardfrødisavnid_map.pdf

Petersen, U.K., Andersen, M.S. & Andersen, H.L. 2003: Glyvursnes seismic experiment, summer 2002. Field report and preliminary data analysis. A Sindri progress report. University of the Faroe Islands, 24 pp, Appendix.
File name: 2003_Petersen_etal_2002_Field_Rep.pdf

Petersen, U.K., Andersen, M.S., White, R.S., Worthington, M.H., Mohammed, N.G., Shaw, F., Normark, E. & Trinhammer, P. 2005: Preliminary processing of the seismic data acquired in the vicinity of wells Glyvursnes-1 and Vestmanna-1. Contribution to the SeiFaBa project. Funded by the SINDRI Group. University of the Faroe Islands, 36 pp (1 cd).
File name: 2005_Petersen_etal_G1_V1.pdf

Waagstein, R. & Andersen, C. 2004: Well completion report: Glyvursnes-1 and Vestmanna-1, Faroe Islands. Contribution to the SeiFaBa project funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/99**, 67 pp (1cd).
File name: 2003_99_Waagstein_Andersen.pdf

Abstracts

Andersen, M.S., Boldreel, L.O. & the SeiFaBa group 2006: Lithological analysis of wireline logs through flood basalts in 8 exploration wells in the Faroe-Shetland Region. The Sindri Conference, Tórshavn, September 2006.
File name: 2006_Andersen_Boldreel_Sindri_Torshavn_Log.pdf

Andersen, M.S., Boldreel, L.O. & the SeiFaBa group 2006: In situ properties to flood basalt successions in 8 exploration wells in the Faroe-Shetland Region. The Sindri Conference, Tórshavn, September 2006.
File name: 2006_Andersen_Boldreel_Sindri_Torshavn_InSitu.pdf

Bais, G., White, R.S., Worthington, M.H. & Andersen, M.S. Submitted to EAGE 2006: The seismic response of Faroe basalts from integrated borehole and wide-angle seismic data. EAGE 68th Conference & Exhibition – Vienna, Austria, 12-15 June 2006.
File name: 2006_Bais_etal_EAGE_Vienna.pdf

Bais, G., White, R.S., Worthington, M.H., Shaw, F., Andersen, M.S. & the SeiFaBa group 2006: Seismic velocities, anisotropy and attenuation of Faroe Islands basalts. The Sindri Conference, Tórshavn, September 2006.
File name: 2006_Bais_etal_Sindri_Torshavn.pdf

Boldreel, L.O. & Andersen, M.S. & the SeiFaBa group 2006: Efffect of burial on in situ properties of flood basalt successions in the Faroe-Shetland Region. The Sindri Conference, Tórshavn, September 2006.
File name: 2006_Boldreel_Andersen_Sindri_Torshavn.pdf

Japsen, P., Waagstein, R., Andersen, C., Andersen, M.S., Djurhuus, J., Mavko, G., Boldreel, L.O., Pedersen, J.M., Petersen, U.K., Rasmussen, R., Springer, N., White, R.S., Worthington, M. & Shaw, F. 2003: Sub-basalt imaging – new insight from investigations of petrophysical and seismic properties of Faroes basalts (SeiFaBa project). Petroleum Geology Conference, London, 1 p.
File name: 2003_Japsen_etal_Petr_Geol_Conf_London.pdf

Japsen, P., Waagstein, R., Andersen, C., Andersen, M.S., Djurhuus, J., Mavko, G., Boldreel, L.O., Pedersen, J.M., Petersen, U.K., Rasmussen, R., Springer, N., White, R.S., Worthington, M. & Shaw, F. 2004: Sub-basalt imaging – new insight from investigations of petrophysical and seismic properties of Faroes basalts (SeiFaBa project). Faroe Islands Exploration Conference, 1 p.
File name: 2004_Japsen_etal_FO_Expl_Conf.pdf

Japsen, P., Mavko, G., Waagstein, R., Olsen, D. & the SeiFaBa group 2006: Rock physics analysis of sonic velocities in basalts from Faroese and Icelandic wells. The Sindri Conference, Tórshavn, September 2006.
File name: 2006_Japsen_etal_Sindri_Torshavn.pdf

Mohammed, N.G., White, R.S., Worthington, M., Andersen, M.S., Shaw, F., Petersen, U.K. & SeiFaBa Group 2004: Seismic properties of Faroese basalts. Faroe Islands Exploration Conference, 1 p.
File name: 2004_Mohammed_etal_FO_Expl_Conf.pdf

Mohammed, N.G., White, R.S., Worthington, M., Andersen, M.S., Shaw, F. & Petersen, U.K. 2004: Seismic properties of Faroese basalts. Geophysical Research Abstracts **6**, 1p.
File name: 2004_Mohammed_etal_Geoph_Res_Abs_6.pdf

Petersen, U.K., Andersen, M.S., Worthington, M., White, R.S., Mohammed, N.G. & Shaw, F. 2004: A small reflection seismic experiment on Faroe Island during summer 2003, preliminary results. Faroe Islands Exploration Conference, 1p.
File name: 2004_Petersen_etal_FO_Expl_Conf.pdf

Petersen, U.K., Andersen, M.S., Worthington, M., White, R.S., Mohammed, N.G. & Shaw, F. 2005: A small reflection seismic experiment on Faroe Islands during summer 2003. EGU General Assembly, Vienna, April 2005, 1 p.
File name: 2005_Petersen_etal_EGU_Vienna.pdf

Shaw, F., Worthington, M., Andersen, M.S. & Petersen, U.K. 2004: A study of seismic attenuation in basalt using VSP data from a Faroe Islands borehole. EAGE Paris 2004, 4 pp.
File name: 2004_Shaw_etal_EAGE_Paris.pdf

Shaw, F., Worthington, M.H., White, R.S., Andersen, M.S. & Petersen, U.K. 2005: Seismic attenuation in Faroe Island basalts. EAGE 67th Conference & Exhibition — Madrid, Spain, 13 - 17 June 2004. 4 pp.
File name: 2005_Shaw_etal_EAGE_Madrid.pdf

Waagstein, R., Boldreel, L.O. & Andersen C. 2003: An integrated petrophysical approach to the sub-basalt imaging problem using well logging data to link measurements from cores and seismic surface experiments. Geophysical Research Abstracts **5**(09388), 2 pp.
File name: 2003_Waggstein_etal_Geoph_Res_Abs_5.pdf

Waagstein, R. & the SeiFaBa group 2006: Integration of wire-line log and core data from Glyvursnes-1 and Vestmanna-1, Faroe Islands. The Sindri Conference, Tórshavn, September 2006.
File name: 2006_Waagstein_etal_Sindri_Torshavn.pdf

Summaries of reports

Andersen, M.S., Boldreel, L.O. & Hansen, H.K. 2005: Analysis of wireline logs through basaltic successions in nine wells from the Faroe-Shetland area. Danmarks og Grønlands Geologiske Undersøgelse Rapport Rapport **2005/3**, 170 pp.

Andersen, M.S., Worthington, M., Mohammed, N.G., White, R.S., Shaw F. & Petersen, U.K. 2004: Seismic experiments at Glyvursnes June-December 2003, Acquisition report, Contribution to the SeiFaBa project. Funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2004/37**, 34 pp.

Gommesen, L. 2005: SeiFaBa well log analysis, lithology and rock physics. Ødegaard A/S Report 04.26074.01, 23 pp.

Gommesen, L. & Ahmed M. 2005: SeiFaBa log analysis of Icelandic wells, Lithology and Rock Physics. Ødegaard A/S Report 03.24036.02, 29 pp.

Japsen, P. (ed.) 2005: Seismic and petrophysical properties of Faroes basalt. SeiFaBa Workshop September 29 2005. Contribution to the SeiFaBa project. Funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/57**, 24 pp.

Japsen, P., Andersen, M.S., Boldreel, L.O., White, R.S., Waagstein, R., Worthington, M. & the SeiFaBa group 2006: Seismic and petrophysical properties of Faroes basalts (the SeiFaBa project) Final Report. Funded by the Sindri group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2006/29**.

Japsen, P. & Mavko, G. 2006: Rock physics analysis of sonic velocities in basalts from Faroes and Icelandic wells. Contribution to the SeiFaBa Project. Funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2006/28**, 91 pp.

Japsen, P. & Waagstein, R. 2005: Preliminary analysis of ultrasonic and geochemical properties of core samples from Glyvursnes-1 and Vestmanna-1, Faroe Islands. Contribution to the SeiFaBa project. Funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/19**. 39 pp.

Jørgensen, O. 2005: Zeolites and other secondary minerals in the drill core Glyvursnes-1, Faroe Islands. Contribution to the SeiFaBa project. Funded by the Sindri Group. 18 pp, 11 figs.

Madsen, T. 2006. The Vágar Tunnel, Faroe Islands. Geological Profile. Result of field work 2002. Jardfeingi. 18 pp, 2 tables, 12 figures, 1 enclosure.

Mavko, G. & Japsen, P. 2005: Rock physics analysis of sonic velocities in wells Lopra-1, Glyvursnes-1 and Vestmanna-1. Danmarks og Grønlands Geologiske Undersøgelse Rapport Rapport **2005/17**. 29 pp.

Mavko, G., Japsen, P. & Boldreel, L.O. 2004: Preliminary rock physics analysis of basalts in the Lopra-1 well. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2004/96**, 11 pp.

Olsen, D. 2005: Special Core Analysis for the SeiFaBa Project. Ultrasonic velocity measurements on plug samples from the Vestmanna-1 and Glyvursnes-1 wells, Faroe Islands. Danmarks og Grønlands Geologiske Undersøgelse Rapport Rapport **2005/10,** 65 pp (1 cd).

Olsen, D., Jørgensen, M. & Guvad, C. 2005: Special Core Analysis for the SeiFaBa Project. Ultrasonic velocity measurements on 12 plug samples from the Lopra-1, Vestmanna-1 and Glyvursnes-1 wells, Faroe Islands. Danmarks og Grønlands Geologiske Rapport **2005/76**, 32 pp, Appendix A (1 cd).

Passey, S.R. 2005: Geology of Glyvursnes, Streymoy, Faroe Islands. A Contribution to the SeiFaBa project. Funded by the Sindri Group. Jardfrødisavnid, 24 pp, 1 map.

Petersen, U.K., Andersen, M.S. & Andersen, H.L. 2003: Glyvursnes seismic experiment, summer 2002. Field report and preliminary data analysis. A Sindri progress report. University of the Faroe Islands, 24 pp, Appendix.

Petersen, U.K., Andersen, M.S., White, R.S., Worthington, M.H., Mohammed, N.G., Shaw, F., Normark, E. & Trinhammer, P. 2005: Preliminary processing of the seismic data acquired in the vicinity of wells Glyvursnes-1 and Vestmanna-1. Contribution to the SeiFaBa project. Funded by the SINDRI Group. University of the Faroe Islands, 36 pp (1 cd).

Waagstein, R. & Andersen, C. 2004: Well completion report: Glyvursnes-1 and Vestmanna-1, Faroe Islands. Contribution to the SeiFaBa project funded by the Sindri Group. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/99**, 67 pp (1cd).

Analysis of wireline logs through basaltic successions in nine wells from the Faroe-Shetland area

Andersen, M.S., Boldreel, L.O. & Hansen, H.K.
GEUS Rapport 2005/3

Summary. Wireline logs through basaltic successions in seven exploration wells and two research wells from the Faroe Shetland area have been investigated. The two research wells, the Vestmanna-01 and Glyvursnes-01, were fully cored and the wireline logs are in these wells correlated to core descriptions. Basaltic rocks are characterised by low concentrations of the most common radioactive isotopes, and basaltic successions are thus characterised by low natural gamma radiation compared to most other rock types. In the Faroe Shetland area natural gamma radiation may generally be used to distinguish between siliciclastic sediments and basaltic rock types. The basaltic successions can be divided into units of five different classes based on the overall response of 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. 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. In the two cored wells a similar subdivision can be defined by visual inspections. However, significant discrepancies are seen between the subdivisions based on wireline logs and the subdivisions based on visual core inspection. Examples where a fairly complex succession defined by visual core inspection has a log response of a low frequency lava bed are present in Vestmanna-01 and Glyvursnes-01.
2. *High frequency lava beds* are characterised by log response with a period which generally are less than 5 meters on all porosity related logs. The amplitude of deflections on log traces are generally less than in low frequency lava beds. 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. However, the correlation is not perfect. Typical velocity range in a low frequency lava bed unit is ca. 2500-5500 m/s at ca. 1500 m depth.
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 an 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 re-

sponse 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 ranges of intrinsic values of parameters measured by the logging tools vary from well to well. This may to some extent reflect imperfect calibration of the logging tools as indicated by the large variation of the level of natural gamma radiation measured in the basaltic succession in the different wells (e.g. 3-10 GAPI in UK 154/03-01 and 22-56 GAPI in UK 205/09-01). However, the different ranges of intrinsic values of porosity related parameters measured in the different wells appear mainly to be related to burial/depth. Preliminary linear relation between seismic velocity and burial depth and between bulk density and burial depth for basaltic successions has been estimated using data from the seven exploration wells:

$$z = (VP\text{-}2499\ m/s) \cdot 1.06\ s \quad \text{and}$$

$$z = (RHOB\text{-}2159\ kg/m^3) \cdot 5.23\ m^4/kg.$$

Fractionation in shallow magma chambers may also produce depth related variation of seismic velocity and density, which may be approximated by linear relations. This should be taken into consideration when it is planned to use one of the two burial functions above or similar functions.

Seismic attenuation of seismic signals due to stratigraphic filtering in basaltic successions is modelled. The model responses indicate that attenuation due to stratigraphic filtering may reduce the seismic signal considerably at all frequencies. The Q-factor is generally above 40 indicating that frequency dependent attenuation observed in some seismic experiments (Q<40) is caused by other sources than stratigraphic filtering. In the deviated well (UK164/25-01 and 01z) subtle differences was found in the basalt succession over a short distance (30 m) indicating that continuity in basalt successions may play a role in this context. Statistical values for the properties of basaltic units and a data base containing a synopsis of data related to all picked units are compiled.

Seismic experiments at Glyvursnes June-December 2003. Acquisition report

Andersen, M.S., Worthington, M., Mohammed, N.G., White, R.S., Shaw F. & Petersen, U.K.
GEUS Rapport 2004/37

Summary. In 2003 Cambridge University, Oxford University and the University of the Faroe Islands acquired seismic data on and around Glyvursnes, the Faroe Islands. The data were acquired as part of a larger project addressing the petrophysic and seismic properties of Faroes basalts. The SeiFaBa Project, sponsered by the Sindri Group.
Data were acquired for four different experiments, which in combination with analysis of the logs from the and petrophysical analyses of plugs from the core from the Glyvursnes-1

borehole provide a unique dataset for detailed analysis of seismic wave propagation through the Faroese basalts at different scales. The data acquired are:

- VSP, offset VSP's and multilevel offset VSP's (June-July 2003)
- Surface seismic reflection data (September 2003)
- Wide-angle multi-channel seismic data for investigation of lateral anisotropy using both high resolution geophones and autonomous seismometers for the recording (September 2003)
- Broadband data for seismic tomography (June-December 2003)

This report covers the acquisition of seismic data at Glyvursnes in June-July and September 2003. The main report provides the crucial facts about the VSP experiments carried out in June-July 2003 and the high resolution surface seismic experiments carried out in September 2003. Details concerning recording with the autonomous seimometers (Guralp 6TD's) are provided in a separate report "Sindri: Petrophysical and seismic properties of Faroese basalts, 6TD Technical Field Report" included as an appendix to the main report. Detailed information needed for further work with the data are included in the digital appendixes to this report.

SeiFaBa well log analysis, lithology and rock physics

Gommesen, L.
Ødegaard A/S Report 04.26074.01, 2005

Summary. The objective of the study was to quality-control and analyse the well log suites from three Faroe Islands wells with focus on the elastic properties of the sub-surface basalt formations. This was done in order to obtain knowledge about the rock physics behaviour of the Faroe basalts. The study is based on the recalibrated density log for the Glyvursnes-1 and a Vestmanna-1 well, provided by GEUS in November 2005, and is thus an updated version of a previous Ødegaard report (04.26074.01). The three wells are Lopra-1, Glyvursnes-1, and Vestmanna-1. The study included several phases: 1) loading of data, 2) well log quality control of log data, 3) rock physics analysis, where the elastic properties, petrophysical properties and different lithological and geological units are studied through cross plots analysis. The Lopra-1 only represent Lower Basalt Fm, Glyvursnes-1 represents Middle and Upper Basalt Fms whereas Vestmanna-1 represents Lower and Middle Basalt Fms.

The well log analysis showed that: (1) The quality of the well log data is generally good: However, data that deviates from the general trends observed in Lopra-1 generally correlate to intervals of high rugosity (caliper minus bitsize). Noteworthy is also the strong VP-VS relationship of Glyvursnes-1 which may suggest that the shear velocity log have undergone too intense processing. (2) Flag curves, which flag out different lithologies, were established to ease lithology dependent cross plot analysis. The lithology interpretation was supplied by GEUS for all three wells and were grouped as: "Undefined", "Transition", "Sediments", "Top flows/Crust", "Top Breccia", "Massives/Core", "Dolorites", "Hyaloclastites".

The cross plot analysis showed that: (1) For each well we observe a relatively wide bulk density range (all formations). The compressional velocity is observed to increase with increasing bulk density. (2) Based all three wells and independent of geological formation the Dolorites and Massives/Core are observed to be elastically stiffer than Top Breccia, Top flows/Crust and Sediments and define the upper end member for both acoustic impedance and bulk density. The lower end member is not well defined and Top Breccia, Top flows/Crust and Sediments all show a variation in bulk density acoustic impedance. (3) For a study of both Massives/Core and Top flows/Crust data we observe that the Upper Basalt Fm. for a given bulk density has a significantly lower acoustic impedance relative to the Lower Basalt Fm. The Middle Basalt Fm. separates into two distinct data clouds, where one is following the Upper Basalt Fm. trend and the other follows the Lower Basalt trend. (4). Based all three wells and independent of geological formation the compressional velocity - shear velocity relationship is observed to be robust and independent of basalt class. (5). The Hyaloclastites (Lopra-1 only) follow the overall trends of the three wells. Here bulk density indicates a higher minimum porosity compared to Massives/Cores.

SeiFaBa log analysis of Icelandic wells, Lithology and Rock Physics

Gommesen, L. & Ahmed M.
Ødegaard A/S Report 03.24036.02, 2005.

Summary. The objective of the study was to quality-control and analyse the well log suites from three Icelandic wells with focus on the elastic properties of the sub-surface basalt formations. This was done in order to obtain knowledge about the rock physics behaviour of the Icelandic region and then compare it with the Faroe Islands Wells. The three Icelandic wells are HH-01, LA-10, and LL-03. Log data for these wells were acquired from Orkustofnun and Norsk Hydro and provided by GEUS as part of the SeiFaBa Project. The study included several phases: 1) loading of data, 2) well log quality control of log data, 3) rock physics analysis, where the elastic properties, petrophysical properties and different lithological and geological units are studied through cross plots analysis.

The well log analysis showed that the quality of the well log data is generally good: However, the data that deviates from the general trends is observed in HH-01 and LL-03. Noteworthy is also that there is no resistivity and neutron porosity data available for the three wells. Calliper log is also missing for LA-10. Flag curves, which flag out different lithologies, were established to ease lithology dependent cross plot analysis. The lithology interpretation was supplied by GEUS for all three wells and were grouped as: classes of “Basalts”, classes of “Sediments”, “Tuff”, and “Dolerites”.

The cross plot analysis showed that: 1. For each well we observe a relatively wide bulk density range (all formations). The compressional velocity is observed to increase with increasing bulk density. 2. Based on the three wells and independent of geological formation the dolorites are observed to be elastically stiffer than basalts and Sediments and define the upper end member for both acoustic impedance and bulk density. The lower end member is not well defined as the basalts and sediments all show a variation in bulk density acoustic impedance. 3. Based on the three wells and independent of geological formation

the compressional velocity - shear velocity relationship is observed to be robust and independent of basalt class.

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

Japsen, P. (ed.)
GEUS Rapport 2005/57

List of abstracts included:

Apparent burial functions of some physical properties in basaltic successions from the Faroe-Shetland region (Morten S. Andersen and Lars Ole Boldreel)

Velocity analysis from VSP and surface data at Vestmanna site (Giovanni Bais, Robert S. White, Michael H. Worthington, Morten Sparre Andersen and Felicia Shaw)

Petrophysical characterisation of basaltic rocks from nine wells from the Faroe-Shetland region (Lars Ole Boldreel and Morten Sparre Andersen)

A comparison between log data from Faroes and Icelandic basalts (Peter Japsen and Lars Gommesen)

New field observations regarding the transitional zone between the middle and upper basalt series around the Faroe Islands (Simon R. Passey)

Characterisation of basalt formation applying time variant frequency analysis (Uni P. Petersen, Morten Sparre Andersen, Robert S. White, Michael H. Worthington and Felicia Shaw)

Heterogeneity and Seismic Properties of Faroe Islands Basalts (Felicia M. J. Shaw)

Comparison of wire-line log and core data from the flood basalt succession of the Faroe Islands (Regin Waagstein and Peter Japsen)

Rock physics analysis of sonic velocities in basalts from Faroes and Icelandic wells

Japsen, P. & Mavko, G.
GEUS Rapport 2006/28

Summary. We have analysed the acoustic properties of basalts based on sonic log data from three Faroese and three Icelandic boreholes and ultrasonic laboratory measurements on 43 1.5” core samples from the three Faroese boreholes. The Faroese boreholes are Lopra-1/1A (LP-1), Vestmanna-1 (VM-1) and Glyvursnes-1 (GL-1) that penetrate the Palaeogene basalts of the Lower, Middle and Upper Basalt Formations (UBF, MBF and LBF) and these rocks are mainly subaerial flood basalts apart from hyaloclastites below c.

2.5 km depth in the LP-1 well. The Icelandic wells penetrate volcanic rocks of Plio-Pleistocene age and cover a mixed environment: HH-1 (95% hyaloclastites), LA-10 (45% submarine and 45% subaerial basalts) and LL-3 (95% subaerial basalts).

We find a tight correlation between sonic Vp and He-porosity based on core data irrespective of basalt facies and well (only data for sediment samples deviate). The core data also reveal a well-defined relation between Vp and Vs, which is to be expected from rocks of broadly similar composition. However, there is a significant scatter in plots of Vp versus density and this scatter is related to the range of grain (matrix) densities from 2.7 to 3.1 g/ccm. Low grain densities represent altered samples with high content of light minerals such as zeolite and clay.

Two main Vp-density trends can be distinguished for flood basalts based on the log data: (1) a trend of relatively low Vp compared to density (the UBF in the GL-1 well; the flood basalts in the LL-3 well), and (2) a trend of relatively high Vp compared to density (the LBF in the LP-1 well). The properties of the MBF are transitional between the two trends. The GL-1 data from this interval represents both the high and the low trend, whereas the VM-1 data represent a very high trend. However, towards the base of VM-1, we observe a 'reversal' of the Vp-density trend within the thin sequence of the LBF penetrated by the well. The analysis of the Vp-density relation for the core data shows that the outlying samples towards low densities are characterized by low grain density. Hence the relatively high Vp-density trend defined for the log data in these wells for the MBF also must be characterized by low grain densities. This means that the low Vp-density trend represents basalt with unaltered matrix with high grain density and the high trend represents altered basalt with a low grain density.

The transition from the low Vp-density trend of fresh basalts to the high trend of altered basalts within the MBF occurs concurrently with an increase of the sonic velocity and density with depth even though there is no increase in the flow thickness. This shows that the transition from fresh to altered basalt is accompanied by an increase in velocity and density and thus probably also by net influx of mass leading to higher densities (growth of zeolites). This means that data points along a high Vp-density trend represents samples with relatively high velocity compared to density, because filling of the pore space with zeolites and clay increases velocity and only changes density of low-porosity basalts slightly.

Maximum values of velocity and density of Icelandic flood basalts are generally higher than for the unaltered Faroese basalts of the UBF, but the two data sets follow the same velocity-density trend. These observations suggest that the smallest porosities are reached in the Icelandic basalts where the flow units are the thicker and that elastic moduli and density of the basalt matrix must be almost identical for these basalts of very different age.

Matrix (or grain) density for the core samples varies systematically with bulk density and alteration of the rocks. A grain density of 3.05 g/ccm is taken as a fair approximation for unaltered basalt with the higher values (almost 3.1 g/ccm) interpreted as outliers related to anomalous content of heavy minerals and lower values (minimum 2.7 g/ccm) corresponding to more altered rock. For sediments in Faroese wells we assign the mean sample value of 2.8 g/ccm. Measurements on fresh Icelandic basalt lava indicate that 3.05 g/ccm is a

reasonable pick (Omar Sigurdsson pers. comm.), and we also apply that value for volcanic sediments in Icelandic wells. Dolerites in Lopra-1 have smaller densities than for the surrounding basalt and we assign a matrix density of 3.02 g/ccm for these rocks. We convert log density to porosity based on these values for the matrix density for different lithologies and a pore water density of 1 g/ccm.

We estimate the mineral end-point properties of flood basalt with zero porosity by comparing log data from the Lopra-1 well with the self-consistent formulation of Berryman (1995) where the models represents the pore space as a collection of ellipsoidal inclusions. We find that the following matrix properties yield consistent values of aspect ratios based on both Vp and Vs data: bulk modulus, K = 83.4 GPa; shear modulus, G = 40.1 GPa and grain density, ρ = 3.05 g/ccm. Comparison of the inclusion model with the log data for Faroese and Icelandic wells reveals good agreement between the mineral end-point and the data points with porosities close to zero and that the predicted aspect ratios are similar for both Vp and Vs. However, the Glyvursnes-1 data appear to be biased towards relatively high values of Vs.

A modified upper and lower Hashin-Shtrikman model has been estimated to model the velocity-porosity relation for basalt. The model describes how the dry bulk and shear moduli, K and G increase as porosity is reduced along either a lower or an upper bound from a maximum value, ϕmax, to mineral end-point properties at zero porosity. We have tested a model with the following properties at the maximum porosity of 45%: K = 5.55 GPa, G = 3.2 GPa and the above properties at zero porosity. We find that most data points for all wells fall within the upper and lower bounds defined by this model. There is however, a considerable ambiguity in the relation between velocity and porosity as estimated from bulk density due to the wide range of grain densities. Sonic velocity is thus a proxy for the porosity of basalt and a median model defined by the mean of the upper and lower bounds may thus provide reasonable estimates of basalt porosity from sonic data.

Preliminary analysis of ultrasonic and geochemical properties of core samples from Glyvursnes-1 and Vestmanna-1, Faroe Islands

Japsen, P. & Waagstein, R.
Rapport 2005/19

Summary. The relations between physical properties, petrography and chemical composition of core samples from the Glyvursnes and Vestmanna wells have been studied. The acoustic properties of the 28 water saturated core samples were analysed at the highest confining pressure available for all samples, 300 bar. The data reveal a general trend of increasing velocity, both P and S, as porosity is reduced and only one data point deviate from the trend. Porosity ranges from almost 0% to c. 33%, Vp range from 2.8 to 6.6 km/s and Vs from 1.4 to 3.7 km/s. Vp-Vs ratios are typical around 1.8 to 1.85, but two sediment samples have Vp/Vs around 2 and one core sample has a very deviating value, also at 2. The data for samples of lava core, crust and breccia and sediment follow the same velocity-porosity trend, but two high-porosity sediment samples have significantly higher Vp-Vs ratio

than the lava samples. There is no systematic difference between the velocity-porosity and Vp-Vs relations Glyvursnes and Vestmanna samples.

We compare the core data with a modified upper Hashin-Shtrikman bound (MUHS) that describes the properties of the water-saturated rock as porosity varies between 0% and the critical porosity (the total porosity at the point when the rock would fall apart). We obtain a first-order fit with the core data and the MUHS bound by assuming a critical porosity of 30% and the following mineral properties: bulk modulus, K = 85 GPa; shear modulus, G = 42 GPa and matrix density, ρ = 3.07 g/ccm.

The log measurements in the Glyvursnes-1 and the Vestmanna-1 wells have been estimated at the same depths as where the core samples were taken: density, neutron porosity, Vp and Vs. The comparison of core and log density shows a good correlation, but for high core densities all core plugs have significantly higher densities than the log readings. The comparison of core porosity and the neutron porosity log shows that the neutron porosity overestimates porosity significantly (mean difference -8%). The comparison of Vp and Vs for core and log data shows a very good correlation. There is no difference in the correlation between the core and log data between Glyvursnes and Vestmanna.

Sixty core samples from the Glyvursnes-1 well have been chemically analysed and examined in thin section. The sediments are all tuffs, that is altered volcanic ash. Most basalts are glomerophyric. The glomerocrystic aggregates consist mainly of phenocrysts of plagioclase. However, they are often intergrown with phenocrysts of olivine and sometimes also with small phenocrysts of pyroxene.

The fine groundmass of the basalts consists mainly of plagioclase and pyroxene, but contains small amounts of Fe-Ti-oxides and usually also some olivine. The groundmass contains variable amounts of mesostasis, which consists of clay, zeolites or other secondary minerals replacing interstitial glass or filling interstitial voids. The olivine in the basalts is completely replaced by clay or other secondary minerals in all but two samples. The plagioclase is generally fresh although often showing incipient alteration. The pyroxene is almost always completely unaltered. The basalts contain variable amounts of gas vesicles or tiny pores. The vesicles or pores are usually partly or completely filled with secondary minerals, mostly clay or zeolites. The gas porosity measurements are generally considerably higher than those estimated from thin sections. This suggests that many pores are thinner than the thickness of the thin section (c. 0.03 mm). The basalts are quartz tholeiites and olivine tholeiites.

Grain density is positively correlated with the content of total iron, which is residing mainly in Fe-Ti-oxides, pyroxene and olivine in fresh basalts. The grain density is systematically lower in lava crust than in lava core for the same iron content and this suggests that a larger part of the iron is residing in clay in the lava crust than in lava core and is in keeping with the higher degree of alteration of lava crusts.

Grain density is inversely correlated with Loss on Ignition (LoI) for all rock types and approaches a minimum density of 2.7 g/cm^3 at a maximum Loss on Ignition of 8 Wt.%. LoI is primarily a measure of the water released when the sample is heated to about 1000ºC. The

rocks with the highest loss are the most altered ones and consist dominantly of water-bearing secondary minerals as smectite clay and various zeolites.

There is a high correlation between neutron porosity (log-value estimated at the depth of the core) minus He-porosity (core) and the volume of water bound in secondary minerals. Neutron porosity measures the amount of hydrogen whether present in pore water or bounded in crystals and it is on average about 8 % too high as compared to gas porosities. The difference between neutron and He-porosity is thus a measure of mineral bound water. When neutron porosity is corrected for fixed water the correlation between Vp and porosity measured by wire-line logging is very similar to that measured on plugs in the laboratory.

There is a good correlation between K_2O content and natural gamma-ray response (log), and the potassium content increases more rapidly than the gamma-ray intensity. This shows that the relative contribution from Th and U is lower in the high-K than in the low-K rocks and suggests that the potassium in the former rocks has been increased by secondary alteration processes. Potassium is known to be highly mobile during such processes, while Th is considered relatively immobile.

Zeolites and other secondary minerals in the drill core Glyvursnes-1, Faroe Islands

Jørgensen, O.
Scandinavian Asbetos & Mineral Analysis (SAMA) Report 2005

Summary. The report describes the zeolites and other secondary minerals deposited in veins and vesicles of the core from the borehole Glyvursnes-1, Faroe Islands. The zeolite assemblages have been used to estimate that the mineralization of the basalt took place at temperatures between 50 and 100° C, corresponding to temperatures of the mesolite zone. The palaeothermal gradient is estimated to have been 46 ± 16°C/km and a linear extrapolation of the gradient places the palaeosurface of the Upper Basalt Formation at an altitude of 1430 ± 767 m above present-day sea level. The degree of mineralization of the vesicles in the basalt varies from nearly empty to completely mineralized and a continuous transition has been found between these two end points. All types of mineralized vesicles (amygdales) exist side by side within the basalt. The degree of mineralization has been classified into the three classes of empty, partially- and completely-filled vesicles. The amount of filling shows no consistent variation with depth, so the degree of mineralization must reflect local variations in the permeability of the rock or in the flow of hydrothermal solutions through the basalt. Two different types of amygdales are found in the drill core. Most frequent are one-chamber amygdales with an onion-like texture of concentric mineral layers. Less frequent are two chamber amygdales divided into an upper and a lower chamber by a horizontal floor that are filled by different minerals. Analysis of the physical conditions for formation of amygdales shows that the two-chamber amygdales are formed when the hydrostatic pressure of the mineral forming solutions was low compared to the internal gas pressure within the vesicle.The existence of two-chamber amygdales shows that the mineralization of the vesicles started when the lava was solidified, the temperature was below

the critical temperature of water (374°C) and a system of hydrothermal water streams had been established.

The Vágar Tunnel, Faroe Islands. Geological profile. Result of field work 2002

Madsen, T.
Jardfeingi Report 2006

The result of field work in the Vágar Tunnel performed immediately after the tunnel was drilled through is presented. A geological profile along the tunnel track is constructed based on this field work, geological logging by the engineering company Landsbyggifelagið and reports produced in connection with the Vágar Tunnel Project. The Vágar Tunnel drilled through the central part of the middle basalt series. The basalts show all characteristics of compound lava flows. The compound lava flows are sometimes separated by thin (10-20 cm) volcaniclastic sediments. 20 fracture zones were identified in the tunnel. Surprisingly the density of fracture zones is lower in the fiord section compared to the onshore sections. There does not seem to be a clear correlation between fracture zones and 'low velocity zones' defined from refraction seismics.

Rock physics analysis of sonic velocities in wells Lopra-1, Glyvursnes-1 and Vestmanna-1

Mavko, G. & Japsen, P.
GEUS Rapport **2005/17**

Summary. We have examined the sonic behaviour of basalts as estimated from log data from wells Lopra-1, Glyvursnes-1, and Vestmanna-1. In general we observe that the sediment facies have the highest gamma ray and the lowest velocities, while the basalt facies have the highest velocities. Data from Lopra-1 and Vestmanna-1 have similar velocities and Vp/Vs ratios, while Glyvursnes-1 indicates smaller Vp/Vs ratios. Comparison of the sonic data and porosity estimated from the neutron porosity log with rock physics ellipsoidal inclusion models suggests that there are slight mineralogical difference among the three wells, indicated by different mineral elastic moduli required for model consistency. It is not obvious how the introduction of quartz, calcite, clay, or zeolites can account for these differences in average mineral moduli. In the future analysis of the data, a correction of the neutron porosity values should be attempted to give a better estimate of the true porosity. Well Lopra-1 showed little correlation of velocity or pore stiffness with depth, though wells Glyvursnes-1 and Vestmanna-1 show a fairly systematic stiffening of the pore space with depth although Vestmanna-1 shows an abrupt change in the lower 100 m of the well.

Preliminary rock physics analysis of basalts in the Lopra-1 well

Mavko, G., Japsen, P. & Boldreel, L.O.
GEUS Rapport 2004/96

Summary. A preliminary investigation of the rock physics properties of flood basalt on the Faroes has been carried out based on the extensive logging data from the Lopra-1/1A well. Data from the extensive logging program have been used to establish a detailed stratigraphy for the flood basalt sequence between 200 m and 2500 m by dividing the lava flows into massive and porous parts. In addition several intervals with >1% potassium were mapped at the flow boundaries and interpreted as altered basalt or tuffaceous sediments. Two dolerite dikes intruding the basalt column were identified by having the highest values of density, P- and S-velocities and lowest values of the neutron porosity.

The high-density limit of the density log is nearly constant with depth, while the low density values are wildly fluctuating. We believe that the high bulk densities are asymptotically approaching the mineral density as the porosity approaches zero, while the low density values vary with porosity. The P-wave velocities have wide fluctuations between about 3000 m/s and 7000 m/s, though there are systematic differences among the various facies. The sediments have the lowest velocities; the topflows have slightly higher velocities; the massive basalts are higher still; and the dolerites have the highest velocities. Empirical upper bounds on density and velocity are taken as estimates of the mineral properties. The velocities and densities should asymptotically approach values appropriate for the minerals, as the porosity approaches zero.

We superimpose effective medium models for velocity vs. neutron porosity, computed using Berryman's (1980) formulation of the self-consistent approximation. For each of the four curves, the pores are assumed to take the shape of oblate spheroids, having aspect ratios 1, 0.3, 0.1, and 0.03, respectively. The mineral is assumed to have properties similar to pyroxene and the pores are assumed to be filled with water. The overall trends of the various lithological facies in the Lopra-1 well can be represented with pores that are nearly spherical (aspect ratio 1) or slightly flattened (0.3), as one might expect for vesicular basalts. Those data that fall at velocities significantly below these trends are consistent with the occurrence of micro or macro fractures, which can be represented with very low aspect ratios.

Crossplots of Vp vs. Vs for the four facies of the Lopra-1 well show that Vp and Vs are highly correlated. All facies have a nearly constant Poisson's ratio of 0.3. High-velocity points can be interpreted as approaching the mineral values, while porosity increases along the trend to the lower left. Empirical upper bounds on P- and S-wave velocities are taken as estimates of the mineral properties.

The preliminary analysis of log data from the flood basalts in the Lopra-1 well presented here suggests that the acoustic properties of these basalt flows are mainly controlled by

porosity and the high correlation between P- and S-velocities may be indicative of a constant mineralogical composition for the Lower Basalt Formation.

Special Core Analysis for the SeiFaBa Project. Ultrasonic velocity measurements on plug samples from the Vestmanna-1 and Glyvursnes-1 wells, Faroe Islands

Olsen, D.
Rapport 2005/10

Summary. GEUS Core Laboratory has carried out ultrasonic velocity measurements on a total of 31 plug samples from the Faroe Islands. 12 of the samples come from the Vestmanna-1 well and 19 from the Glyvursnes-1 well. 19 of the samples are classified as lava core, 6 as lava crust, 1 as lava breccia, and 5 as sediment. The porosity ranges from 0.8 to 34.0% for the lava samples and from 24.1 to 33.5% for the sediment samples. Permeability ranges from 0.003 to 5.8 mD for the lava samples and from 0.06 to 10.2 mD for the sediment samples.

For all samples the P- and S-wave velocities were measured at three different stress conditions, i.e. at hydrostatic confining pressures 100 bar, 200 bar and 300 bar. In addition, two of the samples from Vestmanna-1 were measured at a confining pressure of 500 bar. The measurement at the highest pressure step was repeated after 15 hours as an equilibrium check. All samples were measured in a water-saturated state. The Glyversnes-1 samples and two of the Vestmanna-1 samples were also measured in a gas saturated state.

For measurements in the water-saturated state, estimates of pore volume compression and length reduction were obtained by quantification of the amount of water expelled during sample loading.

Ultrasonic measurements were conducted with a centre frequency of 700 kHz at a temperature of 23°C.

The precision of the ultrasonic velocity determinations are considered to be 1% (1 σ level) for a large majority of the samples. This is based on control measurements on a velocity standard and uncertainty evaluation of the ultrasonic signals. For 5% of the measurements, however, the signal evaluation indicates that the precision is between 1 and 3%.

Well-defined negative correlations are present for V_P vs. porosity and V_S vs. porosity for both water-saturated and gas-saturated samples. Similarly, well-defined positive correlations are present for V_P vs. V_S for both water-saturated and gas-saturated samples. A weak positive correlation is present for V_P/V_S ratio vs. porosity for samples in water-saturated state, while a weak negative correlation is present for samples in gas-saturated state. V_P for water-saturated samples vs. V_P for gas-saturated samples shows a well-defined positive correlation shifted towards higher velocities for water-saturated samples. Similarly, V_S for water-saturated samples vs. V_S for gas-saturated samples shows a well-defined positive correlation but now clustered tightly around a 1:1 correlation, i.e. the saturation state of the samples has little effect on the S-velocity. In several of the correlations sample V10 behaves as an outlier, though the cause of this behaviour is not known.

The mean porosity reduction from 0 bar to 300 bar hydrostatic stress is 0.4 percent unit (p.u.) ranging from 0.03 p.u. for low-porosity lava samples to 2.5 p.u. for high-porosity sediment. Positive correlations of ultrasonic velocity with hydrostatic stress are present for most of the samples.

Special Core Analysis for the SeiFaBa Project. Ultrasonic velocity measurements on 12 plug samples from the Lopra-1, Vestmanna-1 and Glyvursnes-1 wells, Faroe Islands

Olsen, D., Jørgensen, M. & Guvad, C.
Rapport 2005/76

Summary. GEUS Core Laboratory has carried out ultrasonic velocity measurements on a total of 12 plug samples from the Faroe Islands. 5 of the samples come from the Lopra-1 well, 1 comes from the Vestmanna-1 well and 6 come from the Glyvursnes-1 well. 8 of the samples are classified as massive lava, 3 as vuggy lava, and 1 as tuff. The porosity ranges from 0.9 to 16.1% for the lava samples. The tuff sample has a porosity of 34.4%. Permeability ranges from 0.005 to 2.8 mD for the lava samples. The tuff sample has a permeability of 17.4 mD.

The present study is a supplement to the study reported in Danmarks og Grønlands Geologiske Undersøgelse Rapport 2005/76 and identical analytical procedures were used.

For all samples, the P- and S-wave velocities were measured at three different stress conditions, i.e. at hydrostatic confining pressures 100 bar, 200 bar and 300 bar. The measurement at 300 bar was repeated after 15 hours as an equilibrium check. All samples were measured in a water-saturated state. Four of the Lopra-1 samples were also measured in a gas-saturated state.

Ultrasonic measurements were conducted with a centre frequency of 700 kHz at a temperature of 23°C. For measurements in the water-saturated state, estimates of pore volume compression and length reduction were obtained by quantification of the amount of water expelled during sample loading.

The precision of the ultrasonic velocity determinations on the lava samples is considered to be better than 1% (1 σ level). This is based on control measurements on a velocity standard and uncertainty evaluation of the ultrasonic signals. For the tuff sample the uncertainty evaluation of the ultrasonic signals indicate an inferior precision between 1 and 3%.

Well-defined negative correlations are present for V_P vs. porosity and V_S vs. porosity for water-saturated. For the gas-saturated samples the porosity range is only 1.2% but a negative correlation is present. Similarly, positive correlations are present for V_P vs. V_S for both water-saturated and gas-saturated samples. Disregarding the tuff sample, the V_P/V_S ratio vs. porosity relationship does not show any clear correlation for neither the water-saturated sample nor the gas-saturated samples. V_P for water-saturated samples vs. V_P for gas-saturated samples shows a distinct shift towards higher velocities for water-saturated samples. Similarly, V_S for water-saturated samples vs. V_S for gas-saturated samples shows a shift towards higher velocities for the water-saturated samples, though the effect is less than for V_P.

The mean porosity reduction for the lava samples when increasing the hydrostatic stress from 0 to 300 bar is 0.2 percent unit (p.u.) with a range from 0.02 to 0.8 p.u. The tuff sample shows a large porosity reduction of 4.2 p.u. Positive correlations of ultrasonic velocity with hydrostatic stress are present for most of the samples.

Geology of Glyvursnes, Streymoy, Faroe Islands

Passey, S.R.
Jardfrødisavnid 2005

Summary. A geological map of the Glyvursnes area has been compiled in scale 1 : 10 000. Furthermore, a generalized stratigraphic column and a cross section showing the general relations of rocks along a WSW-ENE trending line across the area has been produced. Within the Glyvursnes area six lineaments have been identified from orthophotographs and from mapping in the field. The lineaments are characterised by being extremely straight and are commonly constrained to streams that transect the area. Only the Glyvursgil lineament is exposed where it meets the sea. Here it can be seen that there is little or no movement along the lineament and that it has not been subsequently infilled with a basaltic dyke.

Glyvursnes seismic experiment, summer 2002. Field report and preliminary data analysis

Petersen, U.K., Andersen, M.S. & Andersen, H.L.
University of the Faroe Islands 2003

Summary. In June 2002, a small experiment was carried out by University of Faeroe Islands and Aarhus University (Petersen et al. 2003). This experiment was mainly aimed at obtaining sufficient data to investigate problems related to acquisition of near-vertical incidence and wide-angle seismic data in the Glyvursnes area. Four different data sets were acquired.

- A 500 m long profile with 5 m geophone interval and 10 m shot interval using a 10 g dynamite source placed in 1.8 m deep holes.
- Two wide-angle seismic profiles with maximum offsets around 1400 m with a 375 m geophone string (5-m geophone interval) using a 130 cu. inches Halliburton slevegun cluster.
- A wide-angle seismic profile perpendicular to geophone string using the slevegun energy source.

During acquisition of all three data sets, an external radio source induced a high frequency signal of unacceptable amplitude. The radio source was identified as 500 MHz ground waves originating from the Loran-C transmitter at Eide. These waves occurred in a notch on the analog antialias filters on the Geometrix acquisition system. The further analysis of the data was severely hampered by this noise source.

During the near-vertical incidence experiment most coherent energy in both shot and receiver gathers was related to the direct arrivals and reverberations of direct arrivals. Refractions through the basalt were also evident. However, due to the low signal/noise ratio caused by the noise from the Loran-C transmitter at Eide, the near-vertical incidence data were not of sufficient quality to study reflections from the basalts. A larger source and removal of the radio noise was deemed necessary to provide data suitable for the study of reflections from the basalts below Glyvursnes.

The slevegun data recorded a good, repeatable signal with significant penetration, and it was considered suitable as the source for a P-wave azimuthal VSP-survey in Glyvursnes. However, a larger energy source was considered preferable. New antialias filters were designed in consultation with Geometrix and tested in the field during the winter 2002-2003. The new filters performed as expected and removed the Loran-C noise to a level below detection.

Preliminary processing of the seismic data acquired in the vicinity of wells Glyvursnes-1 and Vestmanna-1

Petersen, U.K., Andersen, M.S., White, R.S., Worthington, M.H., Mohammed, N.G., Shaw, F., Normark, E. & Trinhammer, P.
University of the Faroe Islands 2005

Summary. Following the drilling of well Glyvursnes-1, an array of 45 Guralp (6TD) seismometers, various lines of geophones and a hydrophone streamer were deployed within the immediate vicinity of the well. A large number of air-gun shots at sea and dynamite shots on land were fired. 2-D and 3-D reflection seismic images were obtained from these data. In addition, a VSP and two offset VSP surveys were carried out, using a three component clamped downhole geophone. Up-going wavefields have been extracted from the vertical VSP data. Earthquake data have been acquired with the Guralp array over a six month period from June to December 2003.

A geophone receiver line and a line of Guralp seismometers were also deployed within the vicinity of the Vestmanna-1 well. Air-gun shots were fired in a stream and from a small vessel in a nearby harbour. Walkaway and azimuthal surveys were carried out with a downhole geophone fixed at 100, 200, 300, 400 and 500 metres depth. In addition, one zero offset and two offset VSP surveys were performed. A boomer survey was carried out in the harbour to obtain accurate information on the nature and thickness of the sediments. Preliminary processing of these data includes the extraction of the up-going wavefield from the vertical VSP data.

All these data have been sorted, edited, documented and safely archived in the Universities of The Faroe Islands, Cambridge, Oxford and Aarhus. The analysis and interpretation of these processed data will be described in the final project report.

Well completion report: Glyvursnes-1 and Vestmanna-1, Faroe Islands

Regin Waagstein (GEUS) and Claus Andersen (JFS)
Rapport 2003/99

Summary. A new 700 m deep scientific well (*Glyvursnes-1)* with continuous coring was successfully drilled autumn 2002 near Tórshavn through the Upper and Middle Basalt Formation boundary and the existing *Vestmanna-1* well was reamed prior to running an extensive logging programme.

The Glyvursnes-1 well, located on the headland 2 km southeast of Tórshavn with the top of the surface casing at 16.56 m above sea level, was drilled by the Finnish drilling contractor SMOY. The drilling method was diamond core drilling with fresh water flushing. The 51.5 mm diameter core was partly described visually on-site and later fully using a set of high quality digital core photos. The observed structural and petrographic features allowed the drilled succession to be subdivided into flow-units based on abundance and size of vesicles and presence of chilled surfaces and sediments.
The existing 660 m deep Vestmanna-1 borehole penetrating the lower part of the Middle Basalt Formation with TD 100 m into the Lower Basalt Formation was originally drilled in 1980. It had to be reamed prior to logging due to partly blocking by precipitation of white tufa along the wellbore. The reaming operation was terminated at 615 m due to stuck pipe.

An extensive suite of slim hole wire-line logs was run in both wells by Robertson Geologging (RG). The logging programme comprised acquisition of the following logs: optical televiewer (OPTV), three arm caliper (3ACS), formation density ((FDGS), dual neutron (DNNS), focussed electric (GLOG), full waveform/compensated sonic (FWVS), natural gamma spectroscopy (SGAM) and temperature/conductivity (TCDF). The log quality is generally acceptable except for the spectral gamma logs due to lack of proper calibration. The full wave logs recorded with a tool with only two receivers are affected by high frequency noise causing difficulties to pick the shear waves. As the processing results from RG of the full wave sonic logs were considered unsatisfactory time-consuming additional processing passes to enhance results were undertaken both by the Norwegian company Logtek and by GEUS.
The logging runs were made with only one tool at a time. As a good integration of wire-line log and core data is paramount to the project a tedious task of depth matching was carried out. It was carried out in two steps. First the formation density runs were chosen as the master run to which the depths of all other runs were compared. Afterwards the wire-line log runs were compared and adjusted with the drill cores. The depth shifts have been applied to the composite logs and composite LAS-files.

A full documentation of the work-flow during and after the field operations is given in the report with four fold-out enclosures containing composite logs and full wave sonic logs, and a data DVD. The DVD contains the complete report in electronic format including core descriptions, core photos and all raw and processed logs from both wells.

The well results are highlighted in the composite logs in the scale 1:500 showing all log runs together general lithology and petrography of the cores. For simplicity only a distinc-

tion between sediments, brecciated lava crust, vesicular lava crust and massive lava core is made in the lithology column. The wire-line logs reflect clearly the bedding and other features seen in the core. For example the massive core of thicker flow-units comes out clearly with high bulk density, high sonic velocities, high resistivity and low neutron porosity. Details on the lava succession in Vestmanna-1 wells are given in Waagstein and Hald (1984). Therefore only the preliminary results from the new Glyvursnes-1 well is summarized. The boundary between the Upper (UBF)and Middle Basalt formations (MBF) was picked at a depth of 355 m. It is picked at the base of 9 m simple flow of aphyric basalt with a very low gamma ray response morphologically and lithological similar to the so-called C-horizon exposed some 6 km west of the well-site. It overlies a 0.8 m thick very fine-grained reddish sediment. The drilled succession consists dominantly of compound lava flows of thin flow-units of plagioclase-phyric basalts with vesicular crusts characteristic to pahoehoe lava. 150 complete flow-units have been identified in MBF and 99 in UBF. The mean thickness of the flow-unit is 2.2 m in MBF increasing to a mean thickness of 3.4 m in UBF. Thick flow-units above 10 m are only present in the upper 300 m of the well section. Sediments make up 1.3 % of the drilled succession. Most sediment layers are thin and increase in