DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2003/99

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

Contribution to the SeiFaBa project funded by the Sindri Group

Regin Waagstein (GEUS)
Claus Andersen (JFS)

(1 DVD included)

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MINISTRY OF THE ENVIRONMENT

G E U S

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GEUS

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2. The logging report of Robertson Geologging exclusive the processed OPTV logs (stored under the individual boreholes).

Glyvursnes-1

1. *Composite-log:* Composite log in LAS, pdf and WellCad format plus single curve data in ASCII format in subfolder. All depths are fitted to the core.
2. *Core-descriptions:* Excel spreadsheet files.
3. *Core-photos:* 3 sets, including (a) medium resolution digital core photographs taken before marking of the Glyvursnes core (raw jpg format), (b) high resolution digital core photographs, Glyvursnes-1 (raw jpg format) and (c) high resolution digital core photographs, Glyvursnes-1 (tiff format, adjusted colours).
4. *LAS-10cm-Robertson:* Files with 10-cm depth increments provided by Robert Geologging.
5. *LAS-1cm-fitted-to-core:* Files exported with 1-cm increments from the Winlogger program of Robertson Geologging without filtering, then imported and depth shifted to the core in WellCad and re-exported in LAS format. An exception is the NPHI data, which were exported from Winlogger with 10-cm increments in order to avoid excessive scattering. The unfiltered 1-cm logs are provided for comparison and generally should not be used.
6. *LAS-1cm-raw:* The same data as above without depth shifting.
7. *Logs-binary-Robertson:* Contains the binary raw log data files and ASCII text header files from Robertson (except the optv logs).
8. *OPTV:* Contains (a) raw optical televiewer logs in RG proprietary format with free viewer software and (b) processed data from Robertson Geologging including ASCII data and pdf-files of hole deviation data, azimuth and inclination of selected visible features.

9. *Sonic-processed:* Contains various sets of processed data from Robertson Geologging, GEUS and LogTek as explained in the read-me files plus the original waveform data in ASCII format and the industry standard file format called LIS.

Vestmanna-1

1. *Composite-log:* Composite log in LAS, pdf and WellCad format plus single curve data in ASCII format in subfolder. All depths are fitted to the core.
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INTRODUCTION

Project

This report is part of the scientific project '*Petrophysical and Seismic Properties of Faroes Basalts (SeiFaBa)*' under the theme '*Relevant technologies for imaging within basalt-covered areas*' of the Future Exploration Issues Programme of the Faroese Continental Shelf. The programme, called SINDRI, was officially established by the Minister of Petroleum on 17 August 2001 as part of the stipulated work programmes for hydrocarbon exploration licenses within the Faroese area. The programme is funded by the Sindri Group comprising the following companies:

Eni
DONG
Amerada Hess
Enterprise Oil
Anadarko Faroes Company
Føroya Kolvetni
Atlantic Petroleum
bp-Amoco
Phillips
BG-group
Petro-Canada
Statoil
Shell

Further information about Sindri may be found from the official home page on the internet www.sindri.fo.

During the first half year of the SeiFaBa project, a new well Glyvursnes-1 was core drilled and an old one (Vestmanna-1) was reopened on the island of Streymoy in the Faroe Islands. Afterwards an extensive suite of wire-line logs was run in both wells. The present report describes the drilling and wire-line logging work and presents the first geological results. The new well has since (summer 2003) been used for a number of seismic experiments described elsewhere.

Organisation

The SeiFaBa project is co-ordinated by the Geological Survey of Denmark and Greenland (GEUS) based on a contract with Atlanticon Sp/f, a Faroese consulting company, which as an agent undertakes the administration of the SINDRI Programme on behalf of the SINDRI Committee. GEUS selected the Finnish drilling Company Suomi Malmi OY (SMOY) as a subcontractor of all drilling work and Robertson Geologging in Wales as a subcontractor for the wire-line logging of the boreholes. GEUS undertook the on-site geological work in collaboration with the Faroes Geological Survey, Jarðfrøðisavnið. The present data will form the basis for a number of planned studies by the authors and other scientific partners working on the present data.

Intellectual property rights

The following agreement between GEUS and Atlanticon applies to the content of the present report:

The intellectual property rights in respect of all Pre-existing Know-how, including, without limitation, any copyright in all maps, reports and data furnished by either Party in performance of this Agreement shall remain the property of the Party introducing the same. Pre-existing Know-how may include data which is subject to confidentiality towards third parties, and any such obligation of confidentiality shall be respected.

The resulting intellectual property rights including without limitation the copyright of the Project Data and Knowledge arising out of any work under this Agreement shall be the property of GEUS. Distribution of intellectual property rights to Knowledge and Project Data between the Scientific Partners shall be defined in the respective collaboration agreement.

The members of the SINDRI Committee shall have the right to use the Project Data and/or Knowledge in furtherance of the objectives of the SINDRI Programme and/or their legitimate hydrocarbon exploration interests on an unrestricted and royalty-free basis, subject only to the undertaking that nothing shall be published or otherwise made public which pre-empts the rights of GEUS as set out in the agreement.

Organisation of report

The present report consists of a printed text, four foldout enclosures containing the composite logs and full wave sonic logs for the Glyvursnes and Vestmanna wells at the scale 1:500, and a data DVD.

The DVD contains the complete report in electronic format including all raw and processed logs. The data are organised in a folder tree and the general content is listed on pages 5 to 6. Some folders contain a read-me file with more details. The raw logs are in Robertson Geologging proprietary format and require special software for handling. However, all conventional log data are also provided in the general log ASCII format called LAS with a sampling rate of 10 cm, while the sonic full waveform data have been converted to the widely used LIS format. The raw optical televiewer logs can be viewed with a free viewer included on the disk together with the OPTV logs.

All tables are numbered consecutively. In order to save space only one-page tables are printed in the report, but all tables may be found as Excel spreadsheets in the 'Report' folder of the DVD. Tables on separate sheets of the same Excel file have a letter suffix. Tables not printed are referred to in the report by the table number with the note: '(on the DVD)'. Wire-line logs, core logs and other tabular data on the DVD are referred to by the name of the sub-folder or file.

Drilling and logging

Tasks

The new well was drilled near Tórshavn taking a continuous core sample with a diameter of about 51.5 mm and reached a depth of 700 m, 100 m deeper than originally planned. The existing 660 m deep Vestmanna-1 hole was reamed down to about 615 m, where drilling problems were encountered. The Icelandic National Energy Authority originally drilled this well in 1980 as part of a scientific deep drilling project (Berthelsen et al. 1984). The hole had since been partly blocked by tufa (deposits of calcite). Immediately after the completion of the drilling work a suite of petrophysical logs were run in both wells.

Locations

Glyvursnes-1

The Glyvursnes-1 well is located on the headland of Glyvursnes two kilometres southeast of Tórshavn. Glyvursnes is part of the Kirkjubøur municipality south of Tórshavn and belongs to farmer Sjúrður Patursson from the village of Kirkjubøur. Glyvursnes is shown on Figure 1.a. The map is taken from the photogrammetric map 1:20,000 of the Faroes, sheet No. 508 and has a contour interval of 10 m and a grid spacing of 1 km. The map was checked in the field in 1987 and shows the large quarry on Glyvursnes and the small landing used some years ago for the transport of rocks for the construction of a new harbour area in Tórshavn. The quarry is now in little use and the Glyvursnes landing is destroyed by the surf. A new unpaved road has been made from Tórshavn to Glyvursnes since 1987 and is seen on the orthophoto map of Glyvursnes in Fig. 1.c.

The Glyvursnes-1 well is located on an existing level area above the rock escarpment at the former landing of Glyvursnes, about 30 m from the shore line. The area is approximately 20 m times 80 m and has direct road access. The top of the casing is 0.08 m above ground level and 16.56 m above sea level. The geographical co-ordinates are 61° 58.965493' N, 6° 44.592609' W (WGS84 datum). The well is almost vertical with a mean deviation of 0.92° to N224 corresponding to a horizontal deviation of 11.2 m at 687.2 m (maximum depth of optical televiewer log).

The Glyvursnes-1 well site is located within the lower part of the Upper Basalt Formation (Figs. 1.b and 1.d). The geological prognosis made prior to drilling (Fig. 2) suggested that the base of the Upper Basalt Formation would be penetrated at a depth of about 390 m. However, it was already penetrated at a depth of about 355 m. The drilling was terminated 345 m within the Middle Basalt Formation at TD 700 m (MDbGL).

Vestmanna-1

The Vestmanna-1 borehole is located in the small town of Vestmanna in the backyard of a timber store right at the outlet of the Heljareyga River (Fig. 3). The top of the casing is 1.52 m above sea level and has the geographical co-ordinates 62°09.079757' N, 7°08.786178' W (WGS84 datum). The well is almost vertical with a mean deviation of 0.56° to N264 corresponding to a horizontal deviation of 5.6 m at 570.3 m (maximum depth of optical televiewer log).

The borehole penetrates the lower part of the Middle Basalt Formation and extends 100 metres into the Lower Basalt Formation.

Drilling method

The drilling method at Glyvursnes was diamond core drilling with fresh water flushing. The water was taken from a nearby creek. The flushing water pumped into the hole was clean and additives were not used at any time. The water consumption was approximately 500 litres per hour or 150 – 200 m^3 in total for the 700-m hole. Normally, at least part of the water returned to the surface. A sedimentation pool was dug in the ground to separate cuttings from the returning water. The cutting of the rock was carried out by a ring shaped bit with industrial diamonds impregnated in the bit matrix. Two bits were used for the drilling operations at Glyvursnes. The core sample was collected in a core barrel hoisted by a wire line. The drill pipes were of steel and in three-meter lengths coupled by threads.

Drilling rig

The SMOYdrilling rig was a BKS Boyles 20S, a diesel driven hydraulic unit mounted on a bogey trailer with rubber wheels (Figs. 4 and 5). The unit, which can be pulled by a 4WD agricultural tractor, has a total length of 7.5 m, width 2.6 m and height in transport 3.1 m. The weight of the unit is about 7 tons. The power of the diesel engine is 125 kW. The consumption of diesel oil was about 200 litres per day. The diesel oil was stored in a rented tank at the well-site.

The crew

The crew on each shift consisted of a driller and an assistant driller. The work on Glyvursnes was performed nominally in two ten hours' shifts six days per week. The total number of crewmembers was four. In addition drilling supervisor Esko Hartikainen from SMOY was present during the first week of operations. The reaming of the existing Vestmanna-1 well was carried out in one shift per day. All crewmembers were Finnish nationals.

Drilling operations

A summary of drilling operations is given below. Detailed information on drilling progress shift by shift including further information on day to day operational issues can be found in Tables 1 and

2. Table 1 is compiled from the daily reports of the drilling contractor made for invoicing purposes. Table 2 (on the DVD) is compiled from the driller's records of the length and position of the drill string at the end of each 3-m coring interval and the time of beginning and end of the drilling of core. The average daily penetration rate in Glyvursnes -1 is illustrated in Fig. 6.

Glyvursnes-1 operations summary

Date

13-10: SMOY drilling rig arrived at Tórshavn harbour from Gothenburg.

14-10: Drilling rig cleared through customs and drilling crew arrived from Finland. The hook for pulling the rig was broken during sea transport.

15-10: Hook-up repaired and rig pulled by lorry to the Glyvursnes drilling site. Preparations to spud initiated.

16-10: The core barrel (new, directly delivered from supplier) proved 5 cm to short. New core barrel ordered from Atlas-Copco in Sweden.

17-10: The existing core barrel was modified at the workshop of Tórshavn Skipasmiðja and made ready for temporary use. Well spudded at 14.00 hrs and a surface steel casing was drilled to a depth at 2.90 m below ground level into massive basalt below a thin cover of loose overburden. The casing (type: 90/77 CS-J GD2) has an outer diameter of 90 mm and an inner diameter of about 84.5-85.0 mm. Core recovered from 1.81 m.

19-10: Round trip performed to check modified core barrel. Drilling operations stopped for weekend at 18.00 hrs at 114 m.

21-10: While drilling at 140 m no return of drilling fluid was recorded. The LC-zone was identified to an approximate 2 m broken interval between 120.5 - 122.5 m with joints in a slow drying reddish basalt with void vesicles. Drilling was continued to 143.6 m without return of water to surface and preparations were made to carry out a cementing job. A packer was set at 125 m and 50 kg of cement was pumped into the hole.

22-10: The first cement job failed and a second cement job also using 50 kg cement was attempted. After drilling 2 m lost circulation occurred again. A third attempt was made, this time using 100 kg of cement.

23-10: Drilling was resumed without problems. Cement was drilled from 119.7 to 128 m.

24-10: New core barrel arrived; this time is was 3 cm too long. Drilling resumed with old 'modified' core barrel without problems.

28-10: Diamond bit change at 320.9 m. 5 cm core stuck in core catcher.

01-11: Attempts to make a round trip for change of drill pipe and bit. Attempt aborted due to strong winds. Bit # 2 used without problems to TD.

07-11: TD reached at 700 m and drilling pipes were pulled. Gradually reduced water return occurred at 663 m and the TD section was drilled without any return to surface.

08-11: Water level had stabilised at 4.8 m b.GL (measured with a wooden stick on a string). Drilling rig was packed and pulled to Vestmanna. The well was secured and drill-site cleaned.

Vestmanna-1 reaming operation

08-11: Rig arrived at Vestmanna- site at 16.00 hrs.

09-11: Rig positioned over existing borehole and preparations to ream. Reaming operations initiated at 14.00 hrs using bit #1 from Glyvursnes.
12-11: Stuck pipe at both 590 m and 615 m. Decided to stop reaming and terminate operations. White tufa returned to surface from 27 to 350 m; thereafter clean hole to 590 m when white tufa reappeared and return water turned reddish (level corresponds to a several m thick tuffaceous horizon with slickensided fractures).
13-11: Demob of drilling rig.
14-11: Drill-site cleaned and drilling rig plus container pulled to Tórshavn harbour.

Well completion

Glyvursnes-1

A 4 mm steel flange measuring 98 * 98 mm was welded on top of the 3 m long surface casing in the Glyvursnes borehole. The flange was covered with a steel lid of similar dimensions. The lid and flange have a hole in each corner and the casing is closed and secured with two bolts and two padlocks using the holes (Fig. 7).

The casing is surrounded by a platform of concrete. The platform has an inner rectangular opening of about 45 * 52 cm and is covered with a 8 mm thick steel plate measuring 50.7 * 61.2 cm positioned in a rabbet. The top of the platform is about 14.25 cm above ground level based on a mean of 15.5 cm and 13.0 cm measured between 1 to 2 m east-southeast and west-northwest of the platform, respectively. The same distance is approximately 14 cm when measured around the casing inside the platform. The top of the flange on the casing is 62-63 mm below the top of the platform and thus about 8 cm above ground level. Driller's depths were measured relative to ground level, whereas the loggers used the top of the flange of the casing as zero reference level.

Vestmanna-1

The old Vestmanna well was spudded Sept. 17th 1980 and TD at 659.7 m was reached Oct. 28th 1980. It started as tricone-drilling (6½") down to 4 m, and then normal NQ wire line drilling was performed to a depth of 20 m. After reaming a 5 1/8" conductor pipe was run to app. 20 m. Normal NQ wire line drilling then continued down to the bottom of the well. The drilling fluid was always fresh water from Heljareyga (app. 2 litres/sec.). The well head is shown in Fig. 8. It is covered beneath a steel lid.

Handling and marking of the Glyvursnes core

The cores retrieved at the well-site were placed in wooden boxes capable of storing 5 core lengths of 1 m each. A small wood block with driller's depth annotated separates each core section of approximately 3 m length. Each core box number and top-bottom annotation was properly marked.

The core boxes were on a regular basis transported to the core storage facilities at Jarðfrøðisavnið to be inspected, marked and photographed.

The core pieces were fitted (locked) together and supplied with a continuous central line with a permanent marker in order to orientate the core in a relative sense. The length or the core was subsequently re-measured and a new 'corrected' depth was annotated on the core pieces at least every integral meter. A small difference (usually a few cm) exists between the corrected core depths and the original driller's depths. Differences can e.g. occur when core pieces do not break exactly at TD when pulling the core, and a small piece is left in the hole.

When the continuity of the core could not be established due to core loss, the colour of the central line was changed and a new depth reference was taken from 'driller's depth' annotation on the first wood block on top of or within the new core interval. Arrow marks have been put on part of the core pieces. Arrows point downwards.

The contents of each core box are given in Table 3 (on the DVD). The depths are corrected core depths. The locations of the blocks and the depth corrections applied relative to driller's depths are shown.

Core photographs

Two sets of digital core photos were taken. The first set was acquired in Tórshavn as soon as the cores had dried and when light and weather conditions permitted. A simple camera and an improvised set-up with two core boxes (10 m of core) per photo were used. This set of photos was only used for back-up purposes and to establish a fast early overview of the down-hole lithologies. A second set of high quality core photos were acquired at GEUS in Copenhagen with a 5 MB Olympus E20 digital camera with the optical zoom set at a focal length of about 105 mm. Four electronic flashes were used as a light source (see example of photos in Figs. 9 and 10). Both sets are provided on the enclosed DVD without any corrections in the original compressed format (jpg). An additional copy of the latter is provided with minor colour adjustment and sharpening and stored in uncompressed TIFF format for direct display.

Core descriptions

Glyvursnes-1 core

The upper 355 m of core corresponding to the Upper Basalt Formation were preliminary described at the core storage facilities at Jarðfrøðisavnið by the well-site geologists during the drilling and logging operations. The descriptions were partly made before the marking of the core thus requiring a later check of precise depths. The work was carried in more or less detail depending on time available using a lithological classification scheme similar to that of the Ocean Drilling Program (Shipboard Scientific Party 2002). The noted features were written directly into an Excel spreadsheet in order to ease later additions and revisions. The lava sequence was divided into flow-units (lava lobes) based on the abundance and size of vesicles and the presence of chilling surfaces and sediments (Fig. 11). Flow-units were classified structurally into intervals of massive, vesicular and auto-brecciated (rubbly or inhomogeneous) basalt, and the abundance and size distribution of vesicles and degree of vesicle-fill were often noted. Petrographic parameters including basalt type, groundmass colour, phenocryst content (plagioclase and/or olivine), phenocryst shape and size were likewise noted. Intra-basaltic sediments were described in terms of grain-size, colour and sedimentary structure (if any). Transitions between descriptive intervals were recorded as gradational, sharp or irregular.

The lower half of the Glyvursnes core was later described and the upper half re-described by the senior author at GEUS. The new visual description was made from the set of high quality digital core photographs taken at GEUS. The photo interpretation was primarily focussed on the bedding and vesicularity of the basalt lava (Fig. 11). The core photos were displayed on a standard notebook PC in Adobe PhotoShop at maximum resolution equivalent to the actual pixel size of the screen. The resulting image was at a scale of 1:1.6 close to the physical size with each pixel representing 0.5 mm of core. The actual document size in Adobe PhotoShop was set to the true width of the area imaged (122 cm) to allow distances to be read directly in cm with the on-screen rulers. A set of colour prints on A4 size paper at a scale of 1:4.5 was used for overview. Bedding planes were defined by their intersection with the vertical line marked on the core and read to the nearest centimetre. All observations were as before written directly into an Excel spreadsheet. The spreadsheet was run simultaneously on the same screen as the core photos.

The use of photographs makes it easy to compare core sections from different depths visually in order to secure maximum consistence of the descriptions. This was considered of prime importance for later comparisons of the core with the petrophysical parameters obtained from the wire-line logs. The main disadvantage is the limited resolution of details and colours. It makes it difficult to distinguish zeolite or clay filled vesicles smaller than about 2 mm from alteration products occurring in the basalt groundmass. The same minerals thus replace interstitial glass or voids within the framework of the primary minerals of plagioclase, pyroxene and iron-titanium oxides and they also replace olivine. Likewise it may be difficult to distinguish between silica minerals, zeolites, calcite and plagioclase, which have similar colours, or to distinguish empty vesicles with a lining of black clay from vesicles filled with black clay. Interpretation of core photos therefore very much relies on the experience of the observer with similar rocks. However, the same also applies to visual observations of the core itself.

The basalt was classified according to the abundance of vesicles or amygdales as highly vesicular (>25% vesicles), moderately vesicular (5-25% vesicles), sparsely vesicular (1-5% vesicles) and massive (<1% vesicles). The depth intervals assigned were somewhat subjective, not only because of the difficulties of seeing the vesicles, especially when very small, but also because the vesicle content often varies considerably within a distance of a few centimetres or tens of centimetres, sometimes forming bands. Auto-brecciated basalt and chilled skin of altered glass or very fine-grained basalt were classified as such disregarding the vesicle content. The brecciated basalt is generally of welded type and often shows a gradual transition into homogeneous basalt. Both brecciated and chilled basalt show large variations in vesicularity. Segregation veins, larger fracture fillings, and megavesicles were likewise noted by depth.

The elaborate subdivision of the cored sequence has made it possible to split the sequence into flow-units with a relatively high degree of confidence and to identify the core and crust of individual flow-units. Lava crust is generally vesicular or brecciated due to the high cooling rate and is usually defined as having more than about 5% vesicles, while the lava core is typically sparsely vesicular or non-vesicular. This 5% vesicle limit has been used as a guide for distinguishing between crust and core during the construction of the lithological profile, which is presented graphically as part of the composite log. It is important to note however that thin intervals of non-vesicular basalt may occur in lava crust and likewise that vesicle horizons may be present in the lava core. The abundance of vesicle often increases and the size decreases towards the base of a flow-unit defining a basal zone or crust, which is generally much thinner than the top crust. The basal crust is characterised by the presence of pipe vesicles (in addition to smaller round vesicles) and the pipe vesicles have sometimes been used to identify flow-unit boundaries in the absence of clear signs of chilling. Unfortunately, pipe vesicles often do not show up in a piece of core because of the small core diameter. Thus, no attempt has been made to distinguish between the two types of crust except by the position indicated relative to the top and base of the flow-units. In thin flow-units, the core is often missing and the top and basal crusts form a single unit.

Almost all flow-units seem to form part of compound lava flows. Most of the units are of pahoehoe type, which are characterised by a continuous crust and a relatively smooth top (Fig. 11). Other units are auto-brecciated in the upper part and sometimes also at the base, which characterises flows of aa type. However, they are almost always compound and have less rubbly tops than typical aa. They should therefore probably be considered of a transitional type.

The flow-units have tentatively been grouped into 37 individual lava flows in the composite log based on the size and overall abundance of plagioclase phenocrysts and natural gamma ray activity and the presence of sediment beds. Individual flows are considered to represent a single volcanic eruption of limited duration and often have a unique chemical composition, which distinguish it from those erupted immediately before or after.

The data files used for the generation the lithological columns in the composite log are included on the DVD.

Vestmanna-1 core

Very detailed lithological descriptions already existed for the more than 20-year-old Vestmanna core (Waagstein 1983; Waagstein & Hald 1984). Like the Glyvursnes core it was divided into massive basalt, vesicular basalt, brecciated basalt and tuffaceous sediments and individual flow-units were identified. A large number of rock chemical analyses were subsequently made and used to delimit a number of magmatic units, which probably represent different eruptions or compound flows (Waagstein & Hald 1984). During the present study a lithological profile similar to that of Glyvursnes has been compiled from the original core sheets drawn at the scale of 1:10 (down to 350 m) or 1:100. The profile is presented graphically on the composite log as well as digitally on the DVD. All depths are rounded to multiples of 0.1 metre.

Wire-line logging

An extensive suite of wire-line logs was run in Glyvursnes-1 and Vestmanna-1 as planned. The logging was carried out under a subcontract between GEUS and Robertson Geologging (RG) in November 2002 immediately after the completion of the drilling work. It was based on the quotation included with our original project proposal. The rig was kept on stand-by in the harbour of Tórshavn during the 11 days of logging in case of hole problems, but was fortunately not needed. The following logs were run in both holes:

(1) Optical Televiewer
(2) Three arm caliper
(3) Formation Density Probe
(4) Dual Neutron Probe
(5) Focussed Electric
(6) Full waveform / compensated sonic
(7) Natural Gamma Spectroscopy Probe
(8) Temperature and Conductivity

Details on wire-line logging and tools are summarised in Tables 5 to 7. The tools run by Robertson Geologging and measured parameters are summarised in Table 5 (from log headers). Table 6 is a list of log runs and raw data files and Table 7 contains sonde calibration data provided by Robertson Geologging. Technical specifications of the tools and a description of the logging operations are given in the logging report of Robertson Geologging included on the DVD.

Robertson Geologging was selected for the job because this was the only company that offered to run the complete suite of logs. Logging companies working for the petroleum industry like Schlumberger do not have tools for slim hole logging. RG mainly logs shallow geotechnical boreholes and is not used to the same strict QC procedures as logging contractors working for the petroleum industry. However, the logs from Vestmanna and Glyvursnes seem acceptable except for the spectral gamma logs. The latter logs are useless due to lack of calibration. The full wave sonic logs are much affected by high frequency noise, but give clear first arrivals of the compression wave at most depths. The shear wave is more difficult to pick, especially in intervals of low velocity. This seems, however, to be a general problem with slim hole tools with only two receivers.

Only the gamma ray sondes associated with the resistivity and temperature/fluid conductivity tools were calibrated into API units, while the GR activities of the remaining runs are given in CPS (counts per second). The GR curve of the temperature/fluid conductivity tool shows a slight increase in the uppermost 200 – 250 m of both wells. This increase is not recorded by the other GR sondes and is therefore probably not real.

RG uses non-standard proprietary file formats and markets different software packages for working with their standard full wave sonic and image logs, respectively. They have only developed a single export filter. This converts their standard logs to the widely accepted ASCII format called LAS.

RG delivered all logs electronically on CD's in proprietary format with measurements every 10-mm. RG also provided a complete set of LAS files of the standard logs with 10-cm depth increments plus a free viewer for inspecting the optical televiewer logs. RG later processed the optical televiewer and full wave sonic logs using their standard procedures, which unfortunately turned out not to give results of much use (see later). RG delivered the raw and processed logs in a final log report for each well together with a description of the tools, logging operations and a few notes on the processing. The complete reports were delivered in two hard copies and the text and data files also electronically. The hard copies are extremely bulky due to the inclusion of a poor colour printout of the interpreted optical televiewer logs at a scale of 1:10. GEUS has corrected a number of mistakes in the report text and scanned the enclosures related to the televiewer logs in pdf-format. The report text is included in the report folder of the DVD as a file named RG-Logging-report.doc. The two pdf files with a size of 600-650 MB each are included on the DVD in the relevant data folders as:
Glyvursnes-1\GL1-OPTV\RG-processed\Glyv_composite\GL1-optv.pdf and
Vestmanna-1\VM1-OPTV\RG-processed\Vest_composite\VM1-optv.pdf.

GEUS has previously encountered difficulties using software from RG (optical televiewer). GEUS therefore purchased a single-user licence of WellCad from Advanced Logic Technologies for the present project. The new version 3.2 of this programme can import and process all types of RG files.

Sonde calibration

When calibration of any log channel is made by Robertson Geologging using their WinLogger software, the data gathered is recorded in an ASCII file. This file has a name composed of the sonde acronym and the serial number of the sonde plus the extension 'CAL' and is stored in the WinLogger subdirectory 'Calibration'. The file is in two parts: a coefficient matrix for transforming the six channels of raw log units to calibrated units, and information on data gathered for calibration. The file will only record the most recent calibration run - and not the full history of calibration. Robertson Geologging also appends the new data to a separate 'history' file. The CAL file does not include calibration - it only remembers the transformations required to make the raw data into the real units. Some RG log recordings are transmitted from the sonde in calibrated units with a fixed transformation to be applied in the logging unit (e.g. Focussed Electric log, where Ohm-m = log reading X 0.1). This allows greater precision in the result when the raw data are sent as an integral value. There is no calibration history of such a measurement.

The Logging report of Robertson Geologging contains extracts of the CAL files of all sondes except the Caliper and Spectral Gamma Sondes. These are the only data on sonde calibration that Robertson Geologging has been willing to provide. They are compiled in Table 7. The data for each sonde are explained in some detail below with assistance from an independent expert and also include the philosophy of the calibration.

Three-arm Caliper Sonde (3ACS)

The sonde was calibrated immediately before each run using a jig carried with the logging truck.

Spectral Gamma Sonde (SGAM)
Pads at BGS are logged as part of the sonde manufacture. K, U, Th and blank pads are logged for 10-15 minutes - maybe longer. Plots of gamma ray intensity against energy are made, which allows the position of the characteristic peaks of the emitters to be defined. These energy windows, 5 in number, are set into the controller ROM programme. After that, the channels of output from the sonde are the count rates in the windows, plus gross-gamma which is all gamma rays counted EVEN IF THEY ARE OUTSIDE ALL OF THE WINDOWS. At the same time as calibration, a set of linear equations are solved to relate K, U and Th concentrations to count rates in 3, 4 or 5 windows according to the model preferred (usually 4 as in the Faroes). The computation of concentration of emitters from the windows counts is done by a 'user function' which runs in real time, so no trace of the calibration process is visible in the log data. Maybe calibration of gross-gamma in API is visible in the calibration file, but we have not been able to obtain this file. No field jig is used because the sonde is controlled very carefully by the microcontroller on board, which adjusts the PM tube voltage to compensate for temperature.

Optical Televiewer (OPTV)
There is no calibration procedure in the field. The tabulated data are used only to correct for different magnetometer vector set-ups. The orientation package is a sealed unit, which reads out the sonde heading automatically.

Full Wave Sonic (FWVS)
The coefficients in Table 7 are simply conversions from the internal clock rate of 2 MHz, with a fixed offset of 50 microseconds, which is the 'dead' time to protect the receivers from the electrical noise of the transmitted pulse. There is no calibration on site, since the crystal oscillators are very stable. Sonde operation is checked by observing the correct compression wave slowness in steel casing, which may be a problem in small diameter boreholes as in Vestmanna-1 (casing above water table in Glyvursnes-1).

Temperature / Conductivity Sonde (TCDS)
Table 7 shows the original calibration created in manufacture under temperature-controlled conditions. The circuitry includes a solid state temperature sensor of great stability, and no calibration is carried out on site. The absolute temperature is seldom important with great precision and small differentials are detected well. The data shows that the gamma channel was calibrated on 21st Sept. 2002. The points used are background in air and then in the pit which gives 800 API. The increase over background is used to calculate the detector slope. The 'NextCalibration' entry is an entry to allow the logging software to warn that calibration is overdue. It is not used, but the software uses a default value of 90 days for the interval. Robertson Geologging has a portable natural gamma calibrator with a source of 137-Cs, which can be carried by the service trucks. However, this is not common practice and the calibrator was not offered for the Faroes job.

Guard Log or Focussed Electric (GLOG)
The sonde prototype was calibrated in manufacture by immersing the electrodes in an infinite conductive medium (a lake in North Wales) and a precision resistor chosen that incorporates

the geometrical correction factor. The electrical performance is stable, so the only requirement is to be able to connect this resistor as a simulator of a formation of known resistivity. At the start of each log, a command to the sonde switches a relay to connect the calibration resistor. The sonde controller software computes the necessary factor to make the output equal to the theoretical resistivity (100 ohm-m). For 50 samples the output is held at this value, so the operator can see that the log value is correct. The resistor is disconnected automatically after this time, and real formation resistivity is then recorded. A log should therefore include the 'tail' that shows the normalisation process in the borehole. Natural gamma is done in the home pit as above.

Dual Neutron-Neutron Sonde (DNNS)
The calibrator is simply a sleeve that is made of coaxial polythene tubes and a filler of foamed plastics, which thermalise the neutrons from the source. The intensity of radiation at the detectors is used as a ratio in the real-time porosity 'user function'. At manufacture the sleeve has its thermalisation characteristic compared with the prototype, and any difference in ratio between the sonde under calibration and this characteristic value is simply removed by multiplying ONE channel of the detectors by a value which causes normalisation of the ratio. The calibrator is about 70cm X 30cm and must be supported 1.5m above ground to prevent thermalisation by the ground. The last calibration was carried out on 24 October 2002.

Formation Density / Gamma ray Sonde (FDGS)
The FDGS has three channels requiring calibration: Caliper, Density (long spacing gamma-gamma) and Natural gamma. It is a feature of the WinLogger software that only the most recent calibration data is held in the header file of the log. (The header file is a separate ASCII text file stored together with binary log data file and with the same name, but the extension "HED" instead of "LOG"). There is thus no record of density or caliper calibration in the log supplied to the costumers - the other data will be in the calibration history file and could be recovered. The density channel is taken into a real-time 'user function' to perform a complex calculation involving logarithms to convert to gm/cc. The sonde response to a large aluminium cylinder and a large water tank are used in a normalisation routine to correct for detector change and source decay. These standards are not transportable. The caliper calibrator is a small plate that is used to hold the spring arm at a set of fixed distances. It is easily and normally carried, but there is no record of its use on site. Natural gamma was calibrated on 24 October in the home pit.

Depth match of wire-line log runs

The Robertson Geologging sondes sample standard curve logs with a depth increment of 0.01 m. The data are stored by the RG WinLogger software in a proprietary binary file format, but can be exported in the popular ASCII format LAS. The present report is based on a set of LAS files provided by Robertson Geologging with a sampling rate of 0.1 m. They performed the resampling with a running average filter using the default filter widths. These are 51 cm for the channels of the spectral gamma sonde and between 7 and 21 cm for the channels of the other sondes. The filter settings are shown in Table 5 and in the log headers. The original logs sampled every 0.01 m are effected by low counting rates and large statistically scatter, so it is normally better to use resampled data.

The logging runs were made with only one tool at a time. The Robertson Geologging tools are not constructed to be run in combination. This is because they are mainly intended for logging shallow holes using thin cables. However, the formation density, neutron porosity, resistivity and temperature tools have a build-in gamma ray unit at one end.

A good integration of wire-line log and core data is considered paramount to the present project. A detailed examination of match of the wire-line logs and cores has therefore been carried out. The logs and cores have been compared at many depths, not just near the top and bottom. This has been a tedious task because of the many log runs involved. The task has been carried out in two steps. First the formation density run were chosen as the master run to which the depths of all other log runs were compared. Afterwards the wire-line log runs were compared with and adjusted to the drill cores. The depth shifts have been applied to the composite logs and composite LAS files. All other log data in the report are presented with their original depths.

The porosity, resistivity and temperature runs were matched with the density run based on the accompanying gamma ray curves. The three-arm caliper runs were matched directly with the one-arm caliper readings of the density tool. The sonic log runs were matched with the master density curve using processed first arrivals because the full wave sonic tool had no gamma ray unit.

The rather low gamma ray activity of the volcanic rocks makes it difficult to distinguish real lithological differences from random statistical fluctuations and safely correlate deflections observed on different gamma curves with each other. The problem is especially acute in the Vestmanna well, which shows no well-defined gamma ray peaks at all. Therefore, a ghost matching process was applied on all logs. It is based on comparison of depth intervals rather than single curve points. Each depth interval was usually chosen to include a number of deflections in order to obtain a convincing match and to increase the precision of the match. During this process, it became apparent that distinct deflections may appear on one or more gamma ray curves, while they are missing on the remaining ones. When seen on more than one curve the deflections most likely reflect an increase of the abundance of radioactive isotopes. Their absence on other curves therefore suggests that the gamma sondes do not always sample exactly the same part (volume) of the formation.

The depth matching was performed in WellCad. Short sections of the master log curve were copied at an appropriate scale and superimposed as a ghost on the selected log curve. When a satisfactory fit was obtained the top and bottom depths of that section were automatically stored for both logs. The process was repeated for all visible matches covering the whole length of the logs. Based on all matches a new depth scale was automatically generated. This made it possible to export the depth matches in ASCII format and import them in a spreadsheet. The whole process was usually repeated adding a note on the quality of each match in the open spreadsheet. The two sets of depths were averaged and poor fits excluded before the depth shift relative to the master was estimated. Tables 8.A and 9.A summarise the results and Tables 8.A to 8.G and 9.A to 9.F on the DVD show all data). In Glyvursnes-1 the estimated shifts relative to the master vary from about + 0.7 m to –0.4 m, and in Vestmanna-1 the estimated shifts vary from about +0.1 to –0.3 m. The shift of Individual wire-line logs show no systematic variations with depth. All logs can therefore be adjusted by simple block shifting without compressing or stretching the curves to match the depths of the master run. The estimated depth shifts have been rounded to multiples of the 0.1-m depth increment before block shifting. This makes it possible to compile all wire-line logs from each well in a single ASCII file with the same depth increment in the standard LAS format without resampling.

The density master log has been compared to the core description in a similar way. The detailed lithological description of the core was first converted to a step curve by assigning simple numeric values to each lithology downward from 1.0 ranked approximately after estimated densities. (In the order massive lava, sparsely vesicular lava, moderately vesicular lava, highly vesicular lava, brecciated lava, sediment, chilled margins, fracture fillings and megavesicles for Glyvursnes-1 and in the order massive lava, vesicular lava and sediment for Vestmanna-1).

The optical televiewer sonde does not provide any gamma ray or other log curves for a match with other wire-line logs. Instead features visible on both the OPTV log and the core were matched using core photographs from Glyvursnes-1 and the old graphic core log and photos from Vestmanna-1. Matches below 615 m in Glyvursnes are uncertain because of minor oil on the OPTV tool window in the beginning of the log run, which drastically reduced the quality of the image. The OPTV log from Vestmanna-1 is of poor quality down to about 300 m because encrustations of tufa were not completely removed during the reaming, the remains often forming a partly transparent layer on the wall of the well.

The matches of density and OPTV logs with core are shown in Figs. 12 and 13 and in Tables 8.F, 8.G, 9.E and 9.F on the DVD. The matches of OPTV image and core can be made with a precision of a few centimetres or better. However, the measuring points show a scattering of up to 0.2 m from a smooth curve. As sticking of tools was not experienced during logging this scattering most likely reflects errors on core depths. When the 3-m core barrel is full and is hauled the core will sometimes break a short distance above TD. The stub left in the hole will usually be recovered with the next section of core resulting in an overestimate of the top depth of that core section. This is because the driller's assumes that the top depth is the same as the depth of the drill bit at the beginning of the coring session. Other errors are due to the process of fitting core pieces into continuous sections of core and the depth marking of the core. The latter errors shows a tendency to accumulate in long sections of continuos core, but may go in either direction as seen in the Glyvursnes well (Fig. 12).

The core from the old Vestmanna well could be fitted into even longer continuous sections. Furthermore, it was sometimes possible to identify an elevated edge on the last piece of core drilled. This shoulder indicated that the core was detached from the very bottom of the hole thus exactly matching driller's depth and made it possible to obtain a good depth control for long intervals of core (Nielsen 1983). Nevertheless, the core depths in Vestmanna-1 show a similar scatter as in Glyvursnes-1 when compared to the OPTV log (Fig. 13).

The matches of the density and OPTV logs with the Glyvursnes core show a large scatter but clearly show that the depth of both wire-line logs increases faster than driller's depth. The depth of density master run seems to increase faster than the OPTV depth, but the former run is poorly constrained. A simple linear correction of all log depths has therefore been estimated based on both data sets (Tables 9.F and 9.G) by choosing a line approximately centred between the regression lines for the density and OPTV runs in Fig. 12. The linear equation consists of a conversion factor of 0.9993 (-0.7 m per 1000 m) and a constant of –0.08 m. The constant is poorly constrained, but is taken as the difference between ground and top of casing as the driller used the former level and the logger the latter one as a zero point (reference level). The conversion has been applied to all log curves of the composite after depth shifting to the master run (Tables 8.A, 8.B). The conversion was made in WellCad by converting the master depth scale. Resampling the log curves subsequently restored the sampling rate of 0.1 m.

The matches of the density and OPTV logs with the Vestmanna core likewise show a large scatter, but little variation with depth. The OPTV log depths are constantly within -0.25 to +0.15 m of the core depths and the average does not deviate statistically from zero. The density master log seems to be 0.2 m too short compared to the core, but the depth trend is uncertain because of the scatter of points. A simple block shift of 0.1 m has therefore been applied to the density and gamma ray curves of the master run displayed in the composite log (attachment) and the remaining wire-line curves have been shifted accordingly. No depth shift is necessary for the OPTV log (not displayed).

No corrections have been made for hole deviation in the Glyvursnes and Vestmanna wells, as they are both almost vertical. Total vertical depth (TVD) is thus only 0.09 m and 0.03 m less than total drilling depth (TD) in Glyvursnes-1 and Vestmanna-1, respectively.

The above differences of log and core depths are quite small in both wells and it is therefore difficult to unravel their cause. The logging engineers lined the shoulder of the sondes with the top of the casing with great care at the beginning of each log run and set the depth counter to the length of the sonde. They stopped in the same position at the end of each run and according to them the end depth was always within a few centimetres of the start depth. The logging wire (a 6.35-mm co-axial cable) passed the measuring wheel under tension and logging depths should therefore be little affected by cable stretch. Both wells were logged with the same cable starting and ending in Glyvursnes-1 and without experiencing tool sticking at any time. Anyway, cable stretch not compensated for should result in an underestimate of depth, whereas the logging depths in Glyvursnes increase too fast compared to the driller's depth. The drilling rod is as the logging cable stretched by its own weight. The drill pipes used in Glyvursnes were of NQ2 type and came directly from the manufacturer. They had a length of 3 m, an outer diameters of 69.9 mm an inner diameter of 60.3 mm and weighted 23.4 kg. Using a Young's Modulus of elasticity for steel of $30*10^6$ psi a 1000-m rod submerged in water will stretch 33 cm by its own weight. Drilling depths were computed from the number of pipes added to the drill string and thus do include stretch. This could possibly explain part of the differences observed in Glyvursnes. However, the drilling of the old Vestmanna well was performed with a similar rod (NQ) and the depths recorded during drilling in Vestmanna are similar to the new logging depths (Fig. 13).

Processing of logs

Processing of optical televiewer logs

The optical televiewer logs were recorded in 102-m long sections with an overlap of 2 m, which gives a file size of about 100 MB. This size can be fairly easily handled using a fast PC with a standard amount of RAM, while larger files may cause difficulties. Thus, no later attempts were made merging the individual log sections. As part of their standard presentation package, Robertson Geologging performed '*a basic interpretation of Optical televiewer, defining features in the hole*'. It turned out to be taken quite literally. RG classified all measurements as '*features*' disregarding their appearance or origin (fractures, veins, bedding planes, vesicle bands or non-horizontal streaks). They neither made any attempt to distinguish between measurements made in zones with obvious magnetic disturbances from those made in little or not disturbed intervals. The RG processing thus mainly gives a hint on the distribution of measurable structures. They may also be used as a check that the raw azimuthal data are correctly converted when imported into other software packages.

Processing of full wave sonic logs

The processing of the full wave sonic logs from the Glyvursnes-1 and Vestmanna-1 wells has been much more difficult than anticipated in the approved scientific work plan. The task was first handed to Robertson Geologging, who knew the tool and was used to process their own logs, but the result was unsatisfactory. It was subsequently decided to ask LogTek, a small Norwegian company specialised in sonic log processing, for assistance. The processing at LogTek was made between March and November 2003 in close collaboration with GEUS using various software packages and routines until an optimal result was obtained. The transit time of the compressional wave computed from the LogTek/GEUS sonic data from Glyvursnes is within about one percent of the result of a check shot analysis conducted in Sept. 2003 (F. Shaw, pers. comm. 2003). All processings are listed in Table 10 on the DVD and the results are displayed in Figs. 14.a to 14.n. The procedures are summarised below.

Robertson Geologging

The full wave sonic tool from Robertson Geologging was the first slim hole tool of this type on the market and seems to have a good reputation. It has two transmitters and two receivers enabling borehole compensation of first arrivals, but it only records the full waveforms from the lower transmitter. This reduces the amount of data to be transmitted through the cable allowing a logging speed of 3 m/min. When first tested in the Glyvursnes-1 well, it turned out to be slightly too wide to be run with centralisers as recommended. It therefore had to be run without. The same was the case in Vestmanna-1. The lack of centralisers causes destructive interference of the signal received from different directions and causes road noise from the tool when sliding along the borehole wall.

Immediately after the logging, we asked Robertson Geologging to make a standard processing of both sonic logs based on a separate quotation. We received the final result in February 2003 based on the Direct Phase Determination method. This is one of the two semblance processing methods that Robertson Geologging has implemented in their own processing software package and the one they recommend. RG wrote that: '*Direct Phase Determination (DPD) is a waveform processing technique for accurate determination of compressional and shear slowness. It involves the setting of windows on the compressional and shear wavelets of the two signals. The time difference between corresponding windows on the two signals, i.e. the moveout, provides a first estimate of slowness. The phase difference between the two windowed sections of the signals is then converted to time, according to the dominant frequency, and used to refine the initial moveout estimate, hence obtaining a better estimate of slowness.*'

However, the processing gave a wide variation in V_p/V_s ratio unrelated to lithology and thus probably not real (Figs. 14.a and 14.g). A statistical analysis of the tabulated transit times and slownesses further suggested that RG used a receiver spacing of about 406.3 mm (= 16.0 inches) rather than the standard spacing of 400 mm reported. A similar analysis of the compensated V_p data displayed during logging using first arrivals showed that these were based on an even longer spacing of about 432 mm (= 17.0 inches). GEUS has a similar version of the RG tool. RG says in the user manual that small differences in the make of the tool may give slightly different compensated velocities and recommends that for precise work an automatic compensation is made by changing the receiver spacing in the equation used. We also detected that RG had shifted the depths of the Glyvursnes sonic data non-linearly with up to 2 m without reporting this. GEUS requested velocities with their original depths and five months later (July) we got a new processing of both sonic logs dated May 8th.

The accompanying note from their processing expert reads as follows:
'*The Glyvursnes and Vestmanna FWVS/FDGS logs have been completely reprocessed using improved software. The following procedure was followed:*

1. *Browse completely through the VDL waveforms, in the DPD Processing program, displaying 1st arrival times from the LOG file on the waveforms and correcting these where necessary. Results are saved in file CMP.*
2. *The STC processing program, automatic and faster than interactive DPD processing, was used to calculate compressional, shear and Stoneley velocities, using 1st arrival times from the CMP file to seed the search for compressional peaks on the semblance map. Calculated compressional velocity and fluid velocity are used as constraints for locating the shear peak.*
3. *Dynamic modulae were calculated using a new version of the program. Previous versions read calibrated density data from a PCL2-style merge file, this version reads the FDGS LOG file and does its own caliper and density calibration. A calibrated caliper plot has been added to the density channel in the output log and forms a new column in the tabulated results. Both caliper and density results are on-depth with WinLogger replay.*'

In a report from February the same RG expert stated: '*1. STC is a relatively rapid, fully automatic method, but produces results as a series of discrete values dependent on the 4 µs sampling and the Tx1-Rx1, Tx1-Rx2 distances. 2. DPD is a time-consuming, partially-interactive method, but provides more accurate results. It can only be used on high quality waveforms. Windowed sections of the signals are used to calculate complex spectral density functions, from* *which dominant frequencies and phase differences can be calculated. These enable much finer estimates of velocity to be obtained than those from STC processing.*'

The new data were like the earlier ones presented in two different tables for each well: one with velocity and semblance values and the other one with velocity, density and mechanical parameters. Unlike earlier, the velocities were different in the two tables. The velocities in the later table was increased with a factor of about 1.117 and used for derivation of mechanical parameters. The same difference of velocities exists between two different types of log plots delivered (see pdf files on the DVD). The adjustment of velocities is not explained and has therefore been ignored. Both tables showed the same erroneous depths as before and V_p of the first table was in large intervals copied from the old DPD processing. The remaining V_p and all V_s values formed series of discrete values confirming derivation by STP. The STP results are poor as judged from the scatter of V_p/V_s ratios (Figs. 14.c and 14.h), but slightly better than the DPD results.

We have asked RG repeatedly to explain the use of different receiver spacings for the same run and to provide all relevant calibration data, but without success. However, in December 2003, twelve months after the logging they finally told that due to manufacturing (problems?) the receiver spacing was 41 cm in the particular sonde used in the Faroes.

LogTek

As the full wave sonic logs seemed difficult to process, it was decided at the PCC meeting March 18th 2003 to send the data to the Norwegian company LogTek specialised in sonic logs. RG does not offer any export filter for their FWS logs. In order to be able to read the raw sonic data from Robertson Geologging we therefore acquired the WellCad sonic processing module from Advanced Technologies.

The FWS logs were re-exported in the WellCad ASCII text format (WAF) for processing at LogTek. We initiated a discussion with LogTek, who first made some test processing. They told that the data quality was good to fair at most depths and that they could improve the processing of Robertson Geologging, which we had sent for comparison. We made an agreement with LogTek and received processings of the complete full wave sonic logs from Glyvursnes-1 and Vestmanna-1 in June-July.

LogTek processed both logs with two different methods, which they explained as follows.
Cross-Correlation: We take a pre-determined number of samples (window) and slide it across the second array at every step. The slowness is where the maximum correlation is found. This same process is repeated for the next point. Where more than two waveforms are present, we use the maximum entropy to determine the optimum slowness for a point.
Moveout: Is the time difference between two first break events. In this case, we track the two events and let the software reposition the time event to zero crossing and calculate the time difference between two receivers, calculate slowness from RR spacing. In our software, when more than two receivers are present a Hodges-Lehmann average is used to determine the slowness.

Software package used is Expert Acoustic Logging System, owned by Partha Biswas in Houston. Partha Biswas has been associated with LogTek since 1998.

LogTek usually recommends the cross-correlation method for precise work, but we found that in this case moveout gave slightly more consistent results in many intervals. However, neither data set fulfilled our expectation to data quality for the planned scientific work (Figs. 14.b, 14.i and 14.j).

Depths are during import in WellCad automatically corrected for the tool offset specified in the RG header file. This is not documented in the manual, but means that the wave forms from the two receivers of the RG sonic tool are assigned different depths by WellCad corresponding to the mid point between the transmitter and receiver (i.e. TX1-RX1 and TX1-RX2 depths). The above offset corrections made during the WellCad import was not properly understood when re-exported and LogTek used the first channel (i.e. TX1-RX1) as a depth reference, which depth is 0.56 m deeper than the mid point between the two receivers. More seriously, a mismatch of waveforms of 0.2 m occurred in the Glyvursnes log because of a missing first record from the near receiver.

In order to sort out the various depth problems an attempt was made to read the FWS logging depths using the RG WinLogger program. However, the depths displayed turned out to be dependent on the playback speed. In August 2003 it was consequently decided to process both logs at GEUS using the Full Wave Sonic Module of WellCad for comparison with the results from RG and LogTek. The WellCad module contains a semblance process, which requires that waveforms recording the same pulse must have the same depth. Depth were therefore shifted to a common RX1-RX2 midpoint depth, but rounded to multiples of 0.2 m. The WellCad results were better than any previous data (Figs. 14.d and 14.k).

LogTek sent new depth corrected processings of Vestmanna-1 and Glyvursnes-1 between September and November 2003 and the final reports in Dec. 2003. This time they used a guided pick-finding routine, which they now considered more suitable for the Robertson Geologging logs with only two receiver channels. The first result from Vestmanna-1 only showed an moderate improvement (Fig. 14.l), but final processings showed a clear improvement compared to the earlier ones as seen from a better correlation between V_p, V_s, density and porosity. The final results from LogTek include three types of results: receiver-array, transmitter-array and pseudo borehole compensated (see below). The receiver-array and borehole compensated sets are displayed in Figs. 14.e, 14.f, 14.m and 14.n). The receiver-array velocities are used in the present report because they are most simple. The borehole compensated data show a better correlation in Vestmanna, but a poorer one in Glyvursnes.

The following is an merged extract of the final reports from LogTek Dec. 2003 (the full reports are on the DVD).

Data quality

Glyvursnes: *Waveform data quality was good, but there was some noise, possibly caused by impacts between non-centralised logging instrument and low-clearance borehole wall. Shear* *features generally had greater amplitude than compressional features: with good contrast within dense sections of clean massive basalt, but lower contrast near bed boundaries.*

Vestmanna-1: *Waveform data quality was good enough to make frequency filtering unnecessary. Shear features generally had greater amplitude than compressional features: with especially good contrast within dense sections of clean massive basalt.*

Processing Methodology

Glyvursnes: *Efforts were made to track compressional and shear features in waveforms from both receivers using judgements to find early compressional and shear cycles and a guided peak-finding routine applied to waveform amplitudes in time-domain to find signal minima closely associated in time with compressional and shear arrivals. These efforts were successful for receiver 1 compressional and shear features and for receiver 2 compressional features but more difficult for receiver 2 shear features, which were sometimes hard to distinguish from compressional features. For receiver 2 a pseudo shear was calculated using a good compressional and shear relationship established from transmitter 1 and compressional time from transmitter 2.*

Vestmanna: *Compressional and shear features in waveforms from both receivers were tracked using judgements to find early compressional and shear cycles and a guided peak-finding routine applied to waveform amplitudes in time-domain to find signal minima closely associated in time with compressional and shear arrivals. Final results where used to produce times for corresponding compressional and shear features propagating from formation near receiver 1 to formation near receiver 2. Dividing time differences (of receiver 2 times minus receiver 1 times) by inter-receiver spacing yields slowness results.*

Results

There are three groups of results presented in spreadsheet files gly1-peaks-rev2.xls and vm1.xls as follows:

1. *Receiver-array type results based on common-transmitter-depth phase differences, for which waveforms 1 and 2 both have a depth shift of +0.2 metres. (Aim here is for 'as acquired' simultaneous receiver times... i.e. one pair for each transmitter firing with a single depth value for each such pair. This should allow investigation of extra time taken to travel from formation near receive 1 to formation near receiver 2.)*
2. *Transmitter-array type results based on common-receiver-depth time differences, for which waveform 1 has a depth shift of +1.4 metres and waveform 2 has a depth shift of +1.0 metres. (This should allow investigation of extra time taken to travel across formation traversed by transmitter firing to receiver 2 at deep station and to receiver 1 at shallower station while logging instrument ascends approximately same 0.4-m distance that separates both receivers).*
3. *Pseudo-borehole-compensated type results based on average of compressional and shear slownesses from result groups 1 and 2 on a depth-matched basis within nearest depth increment of 0.2 metres.*

Uncertainties are probably lowest where results from groups 1 and 2 show good agreement.

In a later communication LogTek confirmed that the V_s data reported from Glyvursnes do not include the shear curve of the receiver 2, but were computed from the V_p/V_s ratio of receiver 1 and Vp of receiver 2. They tested this procedure with the Vestmanna data and compared the result with the V_s data reported from Vestmanna, all of which were based on both shear curves. The test showed that the error introduced by using one instead of both shear-curves was small. In both wells, V_p was usually picked with the automatic peak-finding routine. However, in a few intervals V_p was digitised manually in order to obtain a correct pick. None of the waveform logs was frequency filtered before use.

GEUS

Both sonic logs have also been processed at GEUS as said above. The processing was made by the senior author using the full wave sonic module of WellCad. It works with only two receiver channels although the manual recommends at least three. Both logs are disturbed by high frequency noise peaking at about 14 kHz close to the transmitter frequency of 23 kHz. The built-in frequency filter of the WellCad was used to improve the 23 kHz signal by removing frequencies below 18 kHz and above 34 kHz, which is similar to the filtering first applied by LogTek. Then the process for velocity analysis was run, which uses a semblance algorithm to check the trace coherence. It is possible to change both the number of samples and the time window, but the default settings of 15 samples and 50 µs, respectively, were accepted. The process returns a three-dimensional depth-slowness-trace semblance matrix conveniently displayed as a bitmap with depth and slowness along the vertical and horizontal axis, respectively, and the trace semblance values shown by a range of colours (see pdf files in the Sonic-processed\GEUS folders on the DVD). The compressional and shear wave first arrivals were picked from peaks of high semblance values and traced manually with depth. In case of doubt, other logs like density, porosity and caliper were use to pick slownesses at semblance maxima that gave the best correlation with these other parameters. The C and S arrivals were further chosen such that Poisson's ratio was generally falling between 0.2 and 0.5, which is not too far from the normal ratio of about 0.3 for basalts. After the manual picking the resulting slowness curves were adjusted to fit exactly the semblance maxima for all depths using the automatic fitting process of WellCad and the slownesses and associated semblance values were extracted. The resulting velocities attain a series of discrete values reflecting the sampling rate of 4 µs (as for the STC processing of Robertson Geologging). The limited number of values available give many overlapping points forming a grid in ordinary cross plots, which make it difficult to perceive dense distributions. However, the processing seems to give accurate results (Figs. 14.d and 14.k; Table 11). The semblance values further provide a hint on the probability of a correct pick, at least when having similar high values at consecutive depths. There is a tendency in zones of abrupt changes that the P and S curves move in opposite directions across a single depth increment (0.2 m). This may be a processing artefact. No smoothing has been applied to the results, which are stored on the DVD in the Sonic_processed\GEUS folders in LAS and pdf format based on a receiver spacing of 40 cm.

Results

Stratigraphy

Regional

The Faroe Islands consist of Paleogene flood basalts with an exposed thickness of more than 3 km and is divided into three basalt series of formations (Rasmussen & Noe-Nygaard 1969, 1970; Waagstein 1988). The lavas are subaerial and consist of tholeiitic basalt. The Glyvursnes-1 and Vestmanna-1 wells sample all three basalt formations (Fig. 1.b and 1.d). Including an 500 m undrilled section in between they span about 60% of the exposed lava succession. They supplement the Lopra well which was drilled in the southern island, Suðuroy, to a depth of 2.2 km in 1981 and deepened to 3.65 km in 1996. The Lopra well samples the hidden part of the Faroes volcanic succession.

The drilling at Lopra shows that the Lower Basalt Formation consists of about 3.3 km of basalt lavas underlain by a hyaloclastite sequence of at least 1.2 km (Fig. 1)(Hald & Waagstein 1984; Waagstein 1997, 2002). The Lower Basalt Formation formed during magnetochrons C26r to C24r and is K-Ar and Ar-Ar dated to 56-59 Ma (Waagstein 1988; Riisager et al. 2002; Waagstein et al. 2002). The Faroes Lower Basalts are stratigraphically equivalent to lavas of the Upper Vandfaldsdalen Formation/'Nansensfjord formation' in East Greenland (Larsen et al. 1999; Nielsen et al. 2000), which have a similar chemical composition. The Lower Formation is capped by the about 10 m thick coal-bearing sequence, also called the A-horizon (Fig. 1.d). The sequence mainly consists of claystones and minor coal, but basaltic sandstones and conglomerates of fluvial origin occur locally at the top. It is in turn overlain by the tuff-agglomerate zone along a presumed NW trending eruption fissure (Rasmussen & Noe-Nygaard 1969, 1970).

The 1.4 km thick Middle Basalt Formation and the 0.9 km thick Upper Basalt Formation formed rapidly during the final continental break-up between the Faroes and Greenland in magnetochron C24r. Two Ar/Ar ages of between 55.5-56 Ma have been obtained from plagioclase phenocrysts separated from one lava sample from each formation (Larsen et al. 1999). The Faroes Middle and Upper basalts are stratigraphically and geochemically equivalent to the lavas of the Milne Land Formation in East Greenland (Larsen et al. 1999).

The Middle Basalts are different from the Lower Basalts in chemical composition as shown e.g. by their higher Ti/Fe ratio at similar Fe/Mg levels and they mark a change of magmatic regime (Waagstein 1988). The formation is dominated by plagioclase-phyric lavas, but olivine-phyric or almost aphyric lavas are present at several levels, especially in the lowermost part (Fig. 1.d). The phenocryst mineralogy is reflected in the composition of the basalt lavas, which show a general progression up-section from one high or rather high in magnesium to one high in iron and titanium (Waagstein 1988). An exception is some of the younger aphyric or olivine-phyric flows, which have a markedly different composition and are similar to mid-ocean ridge basalts (e.g. B-horizon/Eidi member; Fig. 1.d).

The Upper Basalts are dominantly plagioclase-phyric and relatively rich in Fe and Ti in the central part of the Faroes as the underlying Middle Basalts. However, phenocryst-poor lavas of mid-ocean ridge type low in Ti and Fe become increasingly abundant to the north and northeast towards the opening line between the Faroes and Greenland (Waagstein 1988; Larsen et al. 1999). The Upper Basalt section of the Faroes main profile was collected on the northeastern island Viðoy (Noe-Nygaard & Rasmussen 1968; Rasmussen and Noe-Nygaard 1970) and is dominated by these MORB type lavas, but the Viðoy section is far from representative of the Faroes Upper Basalt Formation as a whole. The base of the Upper basalts is defined by a group of MORB lavas (C-horizon/Kollafjörður member; Fig. 1.d), which are widely exposed forming large lava shields in the northern and central Faroes (Noe-Nygaard 1968).

Glyvursnes

The 700 m deep Glyvursnes-1 well ranges stratigraphically from 355 m above the base of the Upper basalt Formation and 345 m into the Middle Basalt Formation (Fig. 2). Both formations are dominantly plagioclase-phyric. The Upper Basalt succession of Glyvursnes contains a number of thick plagioclase-phyric flow-units in the interval 70 to 300 m, which probably belong to the group of thick lava flows seen in and around the town of Tórshavn.

The Middle-Upper Basalt boundary occurs at a depth of 355.13 m in the Glyvursnes well. The basal flow of the Upper Basalt Formation is a 9 m thick simple flow of aphyric basalt with a very low gamma ray activity of 4-5 GAPI (API gamma ray units) in the central part. It is morphologically and lithological similar to the extensive C-horizon flows that define the base of the Upper Formation in large parts of the Faroes. The C-horizon flows consist of a mid-ocean ridge type basalt (MORB) low in titanium, potassium and other so-called incompatible elements. The C-horizon flows are exposed 10 km NW of Glyvursnes, but are missing in exposures at the same stratigraphic level 6 km to the west of Glyvursnes and on the islands of Hestur and Sandoy farther to the south. It was therefore uncertain if they would be present in the well. The C-flow drilled in Glyvursnes probably belong to a group of flows or a flow field, which attains a maximum thickness of at least 55 m near the presumed eruption site in central Streymoy (Noe-Nygaard 1968). The mid-ocean ridge type of basalt is the dominant basalt type of the Upper Basalt Formation in the northernmost Faroes.

A 0.78 m thick sediment bed underlies the aphyric flow. The sediment is very fine-grained, dusky red with an indistinct, irregular bedding or lamination. The gamma ray activity increases sharply downward to a maximum of about 70 GAPI at or just below the base of the sediment bed, which shows that it is relatively high in potassium. It suggests that the bed mainly consists of reworked clay-rich weathering products of the underlying flow. It has therefore been grouped with the Middle Basalt Formation.

The plagioclase-phyric Middle Basalt succession of Glyvursnes contains a few macroscopic aphyric or almost aphyric lava flows. One of these is a typical MORB flow with a low gamma ray activity of about 5 GAPI in the least altered parts. The flow is an about 20 m thick compound flow made up of nine flow-units and occurs near TD (664 - 684 m). MORB flows are uncommon in the Middle Basalt Formation and none have been found so far in the exposed parts of the Faroes that can be correlated stratigraphically with the lower Glyvursnes MORB. It is not possible either to match any other Middle Basalt unit in the well with a particular exposed flow.

Vestmanna

The Vestmanna-1 well was spudded at a stratigraphic level about 500 m below TD in Glyvursnes and samples the lowermost 555 m of the Middle Basalt Formation, the uppermost 100 m of the Lower Basalt Formation and an intervening 2.8-m thick sedimentary succession. The sediments consist of a 0.7 m thick coarse bottom conglomerate of basalt overlain by 2.1 m of sandy to silty volcaniclastites showing cross-bedding in the upper part (Waagstein & Hald 1984). The sediments are stratigraphically equivalent to the coal-bearing sequence (A-horizon) separating the Lower and Middle Basalt formations in the exposed part of the Faroes (Rasmussen & Noe-Nygaard 1969, 1970).

The upper 104-m Middle Basalt interval is plagioclase-phyric, while the lower 450-m interval is dominantly olivine-phyric (Fig. 1.d; Waagstein & Hald 1984) and informally called the Vestmanna member (Waagstein 1988). The member is thicker at Vestmanna than elsewhere in the Faroes. The top of the member is exposed in the sea cliffs north of Vestmanna.

The 100-m topmost section of the Lower Basalts represented in Vestmanna-1 consists of basalt lavas, which are aphyric to sparsely plagioclase-phyric and relatively evolved (low in magnesium)(Hald & Waagstein 1984). The lavas are of C25n to C24r age and a fresh basalt sample has given a K-Ar age of 56.5±1.3 Ma (Waagstein et al. 2002).

Interbasaltic sediments

The number and thickness of interbasaltic sediment beds in the Faroes lava pile vary considerably with stratigraphical level (Waagstein 1988). The sediments are tuffaceous, fine- to coarse-grained, massive, bedded or laminated. They usually have a reddish or greyish colour and consist of reworked weathering products of the lava tops and altered volcanic ash (Waagstein & Hald 1984). The abundance of sediments seems to be reversely correlated with lava accumulation rates (Waagstein 1988).

Sediments are most abundant in the uppermost part of the Lower Basalt Formation. The 100-m section of Lower Basalts drilled in Vestmanna contains six sediment beds ranging in thickness from 0.3 to 4.5 m that make up 14.6% of the section. In contrast, the overlying 551-m cored interval of Middle Basalts only contains 0.5% sediments. These are distributed among twelve thin beds that range in thickness from <1cm to 90 cm (Waagstein 1983; Waagstein & Hald 1984). The uppermost bed occurs at a depth of 236 m and is only a few millimetres thick. The 345 m thick uppermost section of the same formation drilled in Glyvursnes is less poor in sediments (present report). Including the top layer it contains eight beds ranging in thickness from 0.07 to 2.29 m with an average of 0.56 m. They make up 1.3% of the total thickness. The longest interval without sediments is 108 m (464 – 572 m). The amount of sediments shows a further increase in the 355-m top section in Glyvursnes representing the lower part of the Upper Basalt Formation (present report). This section contains 15 beds ranging in thickness from 0.01 to 5.03 m with an average of 0.62 m comprising 2.6% of the drilled section of Upper Basalts.

The sediments of the Lower Basalt Formation are generally clay-rich, fissile and probably mainly composed of reworked weathering products of the lava tops. The thin sediments in the Middle Basalts in Vestmanna are generally less fine-grained and harder. Many are true tuffs, i.e. rich in altered volcanic ash. A few beds thus contain almost fresh volcanic glass (Waagstein, unpublished). The sediments in Glyvursnes have not been examined in detail. A 0.16 m thick dark grey bed on top of the C-horizon flow possibly contains some fresh volcanic glass. Several other thin beds are probably also tuffs, whereas the thicker beds in Glyvursnes most likely represent reworked weathering products. The 5 m thick volcaniclastic interval at about 38.8 - 43.8 m consists of coarse sandy to silty material locally with distinct bedding and lamination. The 1.9 m thick interval at 296.7 – 298.6 is a sandy to silty, generally massive volcaniclastite but with distinct bedding in the upper 0.8 m.

Lava morphology

The lava successions in the Glyvursnes and Vestmanna well dominantly consist of compound lava flows made up of thin flow-units (lobes). The flow-units may be identified based on variation of the abundance, size and form of the vesicles in the lava (see section on 'Core descriptions'). The boundaries are often clearly seen due to the presence of an about one cm thick dark clay-rich layer, which replaces the original glassy skin of the lava. In the Glyvursnes well, 99 complete lava flow-units (lobes) have been identified in this way in the Upper Basalt section and 150 complete units have been identified in the Middle Basalt section. In the Vestmanna well, 244 complete units have been recorded in the Middle Basalt section and 11 in the Lower Basalt section (Fig. 15; Waagstein 1983). The flow-units range in thickness from tiny lava tongues or toes with a thickness of a few centimetres and up to almost 40 m thick lobes (max. 37.7 m). The thickness distribution is approximately normal Gaussian on a logarithmic scale. Median thicknesses are therefore lower than the arithmetic means. The flow-units in the 100-m Lower Basalt section in Vestmanna have a median thickness of 4.2 m. The flow-units in the lower and upper part of the Middle Basalt Formation drilled in Vestmanna and Glyvursnes, respectively, have a much smaller median thickness of about 1.50 m. There is a minor difference between the mean thicknesses of the two sections (2.24 versus 2.17 m), but the difference is possibly partly due the fact that beds in the Vestmanna core thinner than about 5 cm have been rounded to zero or have not been described. The Upper Basalt section in Glyvursnes shows a larger spread in flow-unit thicknesses than the Middle Basalt section resulting in a lower median thickness (1.31 m), but a much higher mean thickness (3.42 m). This accords with the classification of the Upper Basalt Formation as a mix of lavas of different thicknesses (Rasmussen and Noe-Nygaard 1969, 1970).

The majority of flow-units in the two wells have a vesicular crust consisting of continuous lava as characteristic to pahoehoe lava. The pahoehoe units have a smooth top at the scale of the core, but often show a distinct dip suggesting that many are of small horizontal extent. However, 7 out of the 11 Lower Basalt flow-units drilled in Vestmanna have an upper crust, which is more or less auto-brecciated (rubbly) and welded as characteristic to aa lava. In the Middle Basalt succession in Vestmanna, about 31% of the flow-units have similar auto-brecciated tops, while the percentage of auto-brecciated tops is about 21 and 26, respectively, in the Glyvursnes Middle and Upper Basalt sections. 'Pahoehoe' and 'aa' are generally accepted terms for lava, which were first used by the natives of Hawaii. Here the former type often gradually converts to the latter one downslope from the volcanic vent due to an increase of viscosity and shear, whereas a conversion from aa to pahoehoe has rarely been observed. Most of the brecciated lavas in Glyvursnes and Vestmanna seem to be transitional between pahoehoe and aa.

The percentage of lava core increases with total flow-unit thickness (Fig. 16). Lava core is uncommon in flow-units thinner than about 0.5 m, while flow-units thicker than 2 m usually possess a central core of massive basalt. The disproportional rapid increase of lava core indicates that the flow-units have grown in thickness by inflation, which means that additional magma has been flowing into the liquid core of the lava after the formation of the lava crust (Self et al. 1997).

Flow groups

The flow-units in the Glyvursnes well have tentatively been combined into 37 groups based on the general size and abundance of plagioclase phenocrysts, gamma ray log response and the presence of intercalated sediments. The groups are numbered downward from F1 to F37 and are shown diagrammatically in the petrography column of the attached composite log as uniform beds disregarding within-group petrographical variations. Each group possibly represents an individual compound lava flow formed during a single volcanic eruption. They range in thickness from 0.4 to 78 m with a mean of about 20 m and are made up of between 1 and 29 flow-units.

The flow-units of the Middle Basalt Formation in the Vestmanna well were grouped by Waagstein & Hald (1984) into 16 chemical units based on whole-rock major element analysis. The units were numbered a1 to g4 from below and range in thickness from 3.3 to 108 m with a mean thickness of 37 m (excluding the incomplete unit g4). The Lower Basalt Formation was similarly divided into 5 units based on chemistry, but not numbered. In the present report these have been numbered LBF1 to LBF5 starting from the top of the formation. LBF1 (558.5-586.9 m) is made up of six flow-units. It contains a 0.3 m thick bed of tuffaceous sandstone between the two uppermost units and is thus divided into an upper simple flow and a lower compound flow. The underlying four units LBF2 to LBF5 are all simple flows (made up of a single flow-unit) and are separated by tuffaceous sediments. All chemical units in the Vestmanna well are shown in the attached composite log. Each unit probably represents a unique basalt magma and therefore presumably formed during a single volcanic eruption of shorter or longer duration. Most of the units are presumably made up of a single compound flow or flow field (Self et al. 1997).

Petrography

Glyvursnes-1

The far majority of flow-units in the Glyvursnes well are plagioclase-phyric with between 1 and 40% phenocrysts. The plagioclase phenocrysts attain a maximum size within different units of between a few millimetres and up to about 2 cm. The phenocrysts often form part of larger glomerocrysts. Phenocrysts of olivine up to a few millimetres in size are common and are often intergrown with the plagioclase, but only form a small part of the phenocryst assemblages. The olivine is completely altered and usually replaced by black clay. Phenocrysts of pyroxene are rare.

The content of phenocrysts often varies within individual flow-units. Generally, the highest content is found within the massive core of the flow-units, while the overlying vesicular or brecciated crust may be completely aphyric. The underlying thin basal zone is usually also less porphyritic than the core. The variation is most pronounced in flows with large phenocrysts and is beautifully displayed in for example F19 (437-461 m). The transition from highly porphyritic to almost aphyric basalt may occur abruptly with no signs of chilling. The large phenocrysts must have crystallised slowly in a magma chamber and the predominance of phenocrysts in the lava cores with no sign of in-situ crystal settling (or buoyancy) therefore suggests that they were mainly concentrated in magma feeding and inflating the still liquid central core of the flows during the later part of a volcanic eruption.

A few flows are mostly aphyric or near-aphyric with less than 1% phenocrysts (F2, F4, F15, F18, F21 and F35) or contain only minor plagioclase-phyric intervals (F23). Two aphyric flows have a gamma ray activity of only 4-5 API units in the most massive parts, which is less than half of the activity recorded in other flows of the Middle Basalt sequence. The low gamma ray activity indicates that the basalt is low in potassium and it resembles the mid-ocean ridge type of basalts (MORB) found elsewhere in the Faroes both in this respect and in terms of the dark grey colour, fine grain size, texture of the groundmass and the appearance of vesicles. The upper flow F15 is simple and belongs to the C-horizon, which defines the base of the Upper Basalt Formation. The other (F35) is compound and occurs near TD. It cannot be correlated with any specific exposed lava.

Vestmanna-1

The lavas of the Lower Basalt Formation succession in Vestmanna are aphyric or sparsely plagioclase-phyric. The majority of the Middle Basalt lavas in the well are olivine-phyric and many show large within-flow variations in phenocryst abundance with the highest abundance usually occurring in the lower part of the massive lava core. This suggests that crystal settling has taken place partly after the extrusion of the lavas (Waagstein & Hald 1984). The Vestmanna member is overlain by a succession of plagioclase-phyric lavas at the depth of 0 to 104 m and is exposed in the mountains around Vestmanna. The plagioclase-phyric lavas also commonly display internal variations in phenocryst abundance.

Log stratigraphy

The distribution of physical properties with lithology and depth in Glyvursnes-1 and Vestmanna-1 are shown in the attached composite logs at a scale of 1:500, and at a highly condensed scale of about 1:5,600 in Figs. 17.a and 17.b. The condensed log curves are shown in grey with coloured dots superimposed reflecting the four main lithologies. The minor basal lava zones and basal breccias and units thinner than about 0.4-0.5 m are omitted for clarity (se below). The main grouping of lavas after petrography (Glyvursnes) or chemistry (Vestmanna) is shown with black horizontal lines and group numbers, while formation boundaries are shown in red. The top of the Vestmanna well is stratigraphically about 500 m below TD of the Glyvursnes well.

The standard wire-line logs reflect the bedding and other features seen in the core. Gradual changes of physical properties are clearly seen on the wire-line logs, while small details are smoothed out or lost. The massive core of thicker flow-units comes out clearly with high bulk density, high sonic velocities, high resistivity and low neutron porosity. The lava crust and basal zone have a distinctly lower density, sonic velocity and resistivity and a higher porosity. The basal zone is usually thin and just seen as a zone of rapid deflection of the log curves toward the base of the flow-unit. The upward change from core to lava crust is usually gradual. Likewise, the crust itself generally shows an upward decrease of density, sonic velocity, resistivity and decrease of porosity, albeit it is often quite inhomogeneous with local minima or maxima. The lava core is more uniform than the lava crust, but typically most dense in the lower part. When present, top breccia usually shows a lower density, sonic velocity, resistivity and higher porosity than continuous lava crust. Top breccia sometimes directly or almost directly overlies lava core and in such cases the change of log parameters may be very abrupt (e.g. at 33.0 m, 133.9 m and 268.9 m in Glyvursnes-1 and at 225.3 m and 315.8 m in Vestmanna-1). The sediments between the lava flows are variable, but generally have the lowest densities, sonic velocities, resistivities and the highest porosities.

Thin flow-units appear as small-scale fluctuations of the log curves. It is thus generally not possible on wire-line logs to distinguish intervals of thin flow-units forming part of a compound flow from the crust of a single thick flow-unit. Similarly thin sediment beds may be difficult to see.

Fracture fillings and open fractures also influence the log responses. This is best seen in massive lava core, for example within the intervals 336.8 – 337.4 m and 685 – 685.4 m in Glyvursnes-1. Fractures may be confused with bed boundaries on logs, but large fractures or veins with a clear log response are not very common in the two wells.

The density and porosity curves show the best correlation with lithological classification. The sonic curves also generally show a good correlation. However, some lava cores have local sonic maxima associated with non-vesicular basalt that is less altered than usual. The low alteration is apparent from the low neutron porosity and light colour of the basalt (for example at about 340 – 341 m, 502 – 505 m and 663 m in Glyvursnes-1 and at about 420 m, 507.5 m and 510 m in Vestmanna-1).

The gamma ray (GR) curve is generally below 20 GAPI (API gamma ray units). The curve has been smoothed by a relatively wide running average filter of 17 cm (Table 5 on the DVD), but is nonetheless much affected by high-frequency variations. These variations are partly due low counting statistics and partly real, reflecting an irregular distribution of gamma ray emitting isotopes of potassium, uranium and thorium. The short-range variation of radioactivity is mainly due to mobilisation and redistribution of potassium and uranium during low-temperature alterations of the basalt, whereas thorium is relatively immobile. The lowest radioactivity is recorded in massive lava core and the GR curve often show a well-defined level of minimum values in such intervals recording the most fresh basalt. Within individual flow-units, there is a slight tendency of increasing radioactivity from the massive core to the vesicular or brecciated crust and basal zone.

The highest gamma activities are found within and close to the inter-basaltic sedimentary beds in the Glyvursnes well. Five or six sediment beds have more than 30 GAPI (7.1 – 8.0 m?, 38.8 – 43.8 m, 296.7 – 298.6 m, 355.1 – 355.9 m, 591.2 – 591.9 m and 604.7 – 607.0 m). The highest value of 70 API is recorded in the relatively thin bed at 355 m that separates the Middle and Upper Basalts. In contrast, the 5-m thick bed around 40 m, a coarse sandy to silty volcaniclastite, is relatively low, but variable in GR (7 – 33 GAPI).

There are fewer sediments and no distinct gamma peaks at all in the Middle Basalts of the Vestmanna well and only one small peak of 23 GAPI in the underlying 30-m logged section of the Lower Basalts. It is associated with a thin tuffaceous bed at 564.2 – 564.5 m. A GR core scan (Andersen & Clausen 2001) shows no additional gamma peaks down to TD 660 m in spite of the presence of five tuffaceous beds with thicknesses between 1.6 and 4.5 m. It is noteworthy that even the fine-grained volcaniclastics and the strongly altered basalt conglomerate of the A-horizon are low in gamma activity. The low gamma ray activities in the Vestmanna succession reflect the chemical composition of the rocks. More than 100 basalts and sediments have been analysed (Waagstein & Hald 1984). They have a mean K_2O content of only 0.20%. Minimum and maximum values are 0.04 and 1.14%, respectively, both measured in tuffaceous sediments. The tuffaceous sediments in Vestmanna mainly consist of smectite, a low-potassium clay. This is very likely also the case in Glyvursnes as smectite is the main clay type formed during low-temperature alteration of basalt. This means that GR is generally not a safe indicator of volcaniclastites of basaltic origin, although used in geothermal wells in Iceland to identify K-rich rhyolitic tuffs (cf. Nielsen et al. 1984).

The chemical or petrographical groups of flow-units are more or less visible in the log curve pattern like the individual flow-units, most clearly in the GR and resistivity curves. In Glyvursnes the two flows of mid-ocean ridge basalt (MORB) have the lowest GR (about 5 GAPI) and highest resistivity (about 50,000 Ohm-m) and are clear-cut on the condensed composite log of Fig. 17.a. The upper MORB flow at 346.2 – 355.1 m consists of a single flow-unit. It has a central low-velocity and low-resistivity zone at 351 m probably associated with fractures. The lower MORB flow at 664.5 – 684.2 m is compound with nine flow-units, four of which are clearly seen on the log pattern. The petrographic groups F18 – F31 form another interval of low, but slightly higher GR values. The resistivity curve in Glyvursnes often shows an asymmetric pattern with values first steeply increasing and then gently decreasing up-section. This pattern is not only seen in thick flow-units, for example in the upper major units of flow groups F6, F11 and F12. A similar pattern also appears as a superimposed trend ranging across groups of flows (F34 – F33, F32 – F28, F27 – F26, and F21 – F18).

In the Vestmanna well, the GR curve is generally <15 GAPI. GR is very low in the thick chemical units b and c of the Middle Basalt Formation characterised by a high olivine and MgO content (up to 23% MgO; Waagstein & Hald 1984) but somewhat higher in the lower few units (a1-a4) of the formation and in later units. The resistivity curve partly follows the chemical classification. The resistivity is relatively low in the short Lower Basalt section (Fig. 17.b). It increases up through the lower units a1 – a4 in the Middle basalts and is strongly fluctuating but generally high in the high MgO units b and c, which are characterised by large variations in the content of olivine phenocrysts. The resistivity is more constant, but still high in the overlying units d1 and d2. Units e to f3 have distinctly lower, but upward slightly increasing resistivities, while the plagioclase-phyric units g1 to g4 again show relatively high resistivities. Interestingly, the resistivities in the upper 500 m of the well seem to show some correlation with the FeO/MgO ratio and titanium content of the lavas (see Fig. 6 in Waagstein & Hald 1984).

Finally, some general trends are seen on the scale of the formation or well. The various log curves of the Upper Basalt Formation show large fluctuations, but no general trend with depth. The Middle Basalt section, in contrast, show a clear trend of increasing resistivities and sonic velocities with depth, while neutron porosity and density are fluctuating at fairly constant levels down-section. The Vestmanna well shows a very slight general increase of porosity with depth, but no systematic trend of other physical properties.

Physical properties

The relationships between the various rock physical properties logged in the Glyvursnes and Vestmanna wells are shown in bi-axial diagrams in Fig. 18 grouped after lithology. The variation of properties by depth are shown in Fig. 17.a and b using the same lithological grouping, while Table 11 shows the mean and standard deviation of properties grouped after both lithology and stratigraphic division (formation). In order to minimise mixed log responses all data sampled within 0.2 m of a lithological boundary are excluded in the diagrams in Figs. 17 and 18 and in Table 11. This means that all beds thinner than 0.4-0.5 m are excluded (exact limit dependent on the relative position of data points). For clearness, the diagrams only display the four main lithologies lava core, lava crust, top breccia and sediments, thus in addition excluding the few intervals of basal crust and basal breccia >0.4-0.5 m. However, all six lithologies are included in Table 11. The sediments between the Lower and Middle Basalt formations (A-horizon) are only shown in Fig. 17.b.

The sonic data presented in the diagrams are the receiver-array set of results from the final processing of full waveforms made at LogTek by guided pick-finding. Table 11 for comparison also includes the pseudo borehole compensated data set from LogTek and the results of the semblance processing performed on the same wave form data at GEUS. The three sets of mean velocities are with a few exceptions very similar. GEUS gets a mean V_p and V_s within 0-3% of that of LogTek for the main lithologies lava core and lava crust in Glyvursnes and for all lithologies from Vestmanna represented by at least 10 sonic data points (sampled at a 0.2-m depth increment). The V_p and the V_p/V_s ratio from GEUS are on average about 1% higher than the values from LogTek and this may be an effect of the different processing methods. The remaining minor lithologies from Glyvursnes show larger differences in velocities by the two processing methods, especially in the Upper Basalt well section. In the Upper Basalt Formation in Glyvursnes-1 GEUS thus gets about 30% higher velocities for sediments and 20% higher velocities for top breccia than LogTek, but the same V_p/V_s ratio. Similarly, GEUS gets about 20% and 6% higher velocities, respectively, for the same rocks in the Lower basalt section of the well. These low velocity intervals give a very poor sonic response and the waveforms are swamped by high frequency noise. It is noteworthy however that the low receiver-array and borehole compensated values from LogTek are quite similar forming a continuation of the trend seen from densities and porosities (Figs. 18.c and e), which suggests that they are real.

The V_p/V_s ratio in two wells is almost constant 1.8, which is typical of basalt and basaltic sediments. The mean receiver-array type velocities from LogTek in Table 11 thus show a ratio of 1.79-1.83 (1.79) for lava core, 1.79-1.85 (1.81) for continuos lava, 1.82-1.87 (1.82) for top lava breccia and 1.60-1.94 (1.82) for sediments (weighted means in parenthesis). Because of the constant velocity ratio, mainly V_p velocities are mentioned below.

There is a clear relationship between lithology and rock physical properties. In the order lava core, lava crust, lava breccia and sediments the formation show decreasing sonic velocities, bulk density and resistivity and increasing neutron porosity (Fig. 17.a and b, Fig. 18.a to f and Table 11). Basal lava zone is similar to lava crust and basal lava breccia similar to top lava breccia, respectively. The various properties show a continuos distribution with a considerable overlap between the different lithologies.

Ignoring a few outliers, the formation in both wells shows a maximum density of about 2.9 g/cm^2, a maximum V_p of about 6.7 km/s and a minimum neutron porosity of 2-5%. This represents the most fresh, non-vesicular parts of the lavas. The neutron porosity sonde measures the amount of hydrogen ions present (calibrated to a limestone matrix) and the small porosity recorded is probably mainly due to water residing in clay. Almost all Faroes basalts contain some clay or other secondary minerals replacing the residual glass phase (chilled melt) of the matrix. The content of interstitial clay is often around 5 to 15% in lava core (Waagstein et al. 2002; unpublished data). Massive basalt in the deep Lopra well shows a maximum density of about 3.1 g/cm and a maximum V_p of about 7 km/s (Japsen et al. in press a, b). The lower figures in the Glyvursnes and Vestmanna may reflect that the strata have been less deeply buried than in Lopra. However, lava morphology and petrography almost certainly also play a role. The small flow-unit thickness in Glyvursnes and Vestmanna gives thinner lava cores and therefore probably less massive and more altered lava. The lavas also contain abundant phenocrysts of plagioclase (both wells) or highly altered olivine (Vestmanna-1) probably reducing the sonic velocity, while the basalts in the Lopra well are dominantly aphyric or near-aphyric.

Although there may be some uncertainty about the exact minimum velocities in Glyvursnes (see above) the Upper Basalt Formation in Glyvursnes clearly exhibits much larger velocity contrasts than the Middle Basalt Formation or the Middle and Lower Basalt formations in Vestmanna. The low velocities recorded in lava crust, lava breccia and sediments in the Upper Basalts of Glyvursnes-1 are likely partly related to the lower stratigraphic depth, i.e. depth of burial. The low sonic velocities of the Faroes Upper Basalts were first noted by Palmason (1965) based on seismic refraction studies.

Temperature - conductivity logs

Glyvursnes-1

Continuous temperature-conductivity logs were run in Glyvursnes-1 on Nov. 28th some 20 days after termination of drilling operations. The rationale to run these logs was to locate possible zones of inflow/outflow that may be associated major fractures.

The time-lapse had been sufficient to allow the borehole fluids to approximate an equilibrium with the formation with respect to temperature. The fluids have a temperature of 8°C near the surface gradually increasing (with a close to constant gradient of 2.5°C/100m) to 25°C at TD (700 m).

However, a number of conductivity 'breaks' indicate that the fluid column is not uniform but composed of separate fluids of differing salinity suggesting that flow into or out of the borehole has happened or is still happening. A gradual drop in conductivity from 0.25 to 0.17 mS/cm is recorded from the top of the water table at about 7.5 m to 12.5 m. The latter level corresponds to a major wash-out on the caliper log located in a heavily crushed and oxidised zone at the top of a rubbly interval. Even a subtle decrease in fluid temperature is recognised in the 5-m interval above the crushed zone.

A small but distinct increase in conductivity from 0.18 to 0.20 mS/cm is recorded at a caliper-log deflection at 122.5 m. This level corresponds to a broken interval with low and high angle fractures in slowly drying vesicular reddish basalt. Lost circulation occurred at this level during drilling, and it was necessary to perform several cement-jobs before return of drilling fluid to surface could be re-established (Fig. 6 and 10).

A high salinity fluid body exists over a 55 m interval from 631 to 686 m near the base of the hole. The conductivity rises from about 26 to 40 mS/cm over a 1 m interval and reaches a maximum of 50 mS/cm at a level about 665 m. Downwards there is gradual decrease in conductivity to 40 mS/cm until the lower shoulder at about 685 m where it drops back to the original value of 0.26 mS/cm over a 2 m interval. The position of the lower shoulder corresponds to a minor washout recorded on the caliper-log. It is noted that return of drilling fluid to the surface while drilling was reduced from about 663 m until total loss of circulation occurred at 685 m. No obvious tectonic fractures are observed on the core material at these levels, however, zones with irregular zeolite-filled veins and cm-large amygdales are abundant.

Vestmanna-1

The existing Vestmanna-1 borehole had to be reamed prior to logging due to partly blocking by precipitation of white tufa along the wellbore. A caliper-log acquired in year 2000 in conjunction with unsuccessful attempts to run a suite of logs by GEUS showed a downward gradual decrease of hole diameter to about 50 mm at a depth of about 300 m (Andersen & Clausen 2001). At this level, the borehole was almost totally blocked preventing further caliper logging. Since the original borehole was drilled, continuous flow of water to the surface has been noticed. In weather conditions with sub-zero temperatures and heavy snowfall, the area around the wellhead remained wet and free of snow. Before start of the reaming operation, the flow was estimated to a few litres per minute. This is a reduction compared to the flow rate reported by Balling et al. (1984) of about 25 l/min.

The temperature-conductivity logs were run by RG some 14 days since last circulation with the purpose to locate levels of inflow and to evaluate borehole conditions. Deepest recorded level is 586 m.

The recorded temperature profile of the borehole fluid column fairly closely resembles the temperature profiles reported by Balling et al. (1984). They have obtained several temperature logs, three of them acquired from one to two years after the original drilling was completed. The fluid temperature rises from 16.5°C at surface to 20.5°C at 302 m with gradual decreasing gradient. An abrupt 2°C increase occurs at this level together with a sharp rise in conductivity from 0.3 mS/cm to 1.0 mS/cm. This point of water inflow corresponds to a 0.5 wide broken interval with steeply inclined fractures. The fractured interval in the core is hardly recognised on the caliper log.

From 302 m to last recording at 586 m the fluid temperature rises with an almost constant gradient of 0.3°C/100m from 22.5°C to 31°C. Following the argumentation put forward by Balling et al. (1984) the temperatures in this part of the borehole approximate equilibrium. It is noteworthy that the hole appeared clean below 350 m and until stuck pipe occurred at 590 m.

Two conductivity 'breaks' occur at 511.5 m and 521 m with an increase in conductivity of 0.5 mS/cm and 0.7 mS/cm, respectively. The breaks are associated with very subtle increases in fluid temperature but hardly any deflections on the caliper. An irregular vein or megavesicles filled with white material crosses the core at the upper break. An irregular steeply inclined fracture exists at the lower break.

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Table 1. *Compilation of daily drilling reports from Suomen Malmi OY in English translation.*

Day	Date	Start	End	Shift No.	m/e/n	Hole depth	Result	Move	Overburd.	Bedrock	Miscell.	Mainten.	Total hours	Driller	Ass. d.	Man hours	Driller	Ass. d	Information for invoicing etc.
Mon	14-10-2002			1	e						3		3	6		6	EL	JM	Fixing damaged hook on rig.
Tue	15-10-2002	06:00	14:00	2	m			4			4		8	8	8	16	EL	JM	Moving rig to well-site.
Tue	15-10-2002	14:00	22:00	3	e						8		8	8	8	16	AE	AN	Moving container to well-site; preparing to spud.
Wed	16-10-2002	06:00	14:00	4	m				1		7		8	8	8	16	EL	JM	Fixing core barrel.
Wed	16-10-2002	14:00	22:00	5	e						8		8	8	8	16	AE	AN	Fixing core barrel.
Thu	17-10-2002	06:00	22:00	6	m	2.80	2.80		1	1	7		9	9	9	18	EL	JM	Modifying core barrel.
Thu	17-10-2002			6	m	2.45	0.75												
Thu	17-10-2002	14:00	22:00	7	e	23.15	20.70			8			8	8	8	16	AE	AN	
Fri	18-10-2002	06:00	14:00	8	m	50.80	27.65			8			8	8	8	16	EL	JM	
Fri	18-10-2002	14:00	22:00	9	e	80.80	30.00			8	8		16	16	16	32	EL+AE	JM+AN	Getting replacement from airport.
Sat	19-10-2002	06:00	12:00	10	m	98.70	17.90			5	1		6	6	6	12	EL	JM	Lifting rods to shift part.
Sat	19-10-2002	12:00	18:00	11	e	113.65	14.95			4	2		6	6	6	12	AE	AN	Getting gas, winter dryers and fuses.
Mon	21-10-2002	06:00	14:00	12	m					8			8	8	8	16	EL	AN	
Mon	21-10-2002			12	m	140.65	27.00				5		5	5	5	10	AE	JM	Getting core barrel through costums.
Mon	21-10-2002	14:00	22:00	13	e	143.60	2.95			2	6		8	8	8	16	AE	JM	Hole cemented (50 kg), at 13:00 hour.
Tue	22-10-2002	06:00	14:00	14	m						8		8	8	8	16	AE	AN	Hole cemented (50 kg), at 09:00 hour.
Tue	22-10-2002	14:00	22:00	15	e						8		8	8	8	16	EL	JM	Hole cemented (100 kg), at 18:00 hour.
Wed	23-10-2002	06:00	14:00	16	m	146.60	3.00			2	4	2	8	8	8	16	AE	AN	
Wed	23-10-2002	14:00	22:00	17	e	173.45	26.85			8			8	8	8	16	EL	JM	Changing part on core barrel.
Thu	24-10-2002	06:00	14:00	18	m	188.45	15.00			5.5	2.5		8	8	8	16	AE	AN	New core barrel doesn't work!
Thu	24-10-2002	14:00	22:00	19	e	215.85	27.40			8	1		9	9	9	18	EL	JM	
Fri	25-10-2002	06:00	14:00	20	m	242.90	27.05			8			8	8	8	16	AE	AN	
Fri	25-10-2002	14:00	22:00	21	e	263.85	20.95			7	1		8	8	8	16	EL	JM	Lifting rods to shift part.
Sat	26-10-2002	06:00	14:00	22	m	275.90	12.05			5	1		6	6	6	12	AE	AN	
Sat	26-10-2002	14:00	22:00	23	e	293.90	18.00			6			6	6	6	12	EL	JM	
Sun	27-10-2002	06:00	14:00	24	m	308.90	15.00			6			6	6	6	12	EL	AN	
Sun	27-10-2002	14:00	22:00	25	e	320.90	12.00			5			5	5	5	10	AE	JM	
Mon	28-10-2002	06:00	14:00	26	m	338.90	18.00			6	2		8	8	8	16	EL	JM	Bit 002.
Mon	28-10-2002	14:00	22:00	27	e	362.90	24.00			8			8	8	8	16	AE	AN	
Tue	29-10-2002	06:00	14:00	28	m	386.90	24.00			8			8	8	8	16	EL	JM	
Tue	29-10-2002	14:00	22:00	29	e	411.00	24.10			8			8	8	8	16	AE	AN	
Wed	30-10-2002	06:00	14:00	30	m	425.90	14.90			5	3		8	11	11	22	EL+AE	JM+AN	
Wed	30-10-2002	14:00	22:00	31	e	447.00	21.10			8			8	8	8	16	AE	AN	
Thu	31-10-2002	06:00	14:00	32	m	465.00	18.00			8			8	8	8	16	EL	JM	
Thu	31-10-2002	14:00	22:00	33	e	485.90	20.90			8			8	8	8	16	AE	AN	
Fri	01-11-2002	06:00	14:00	34	m	503.90	18.00			7	1		8	8	8	16	EL	JM	Attempted to pull to change bit, but too much wind.
Fri	01-11-2002	14:00	22:00	35	e	524.90	21.00			8			8	8	8	16	AE	AN	
Sat	02-11-2002	06:00	14:00	36	m	539.90	15.00			6			6	6	6	12	EL	JM	
Sat	02-11-2002	14:00	22:00	37	e	554.90	15.00			6			6	6	6	12	AE	AN	
Sun	03-11-2002	08:00	14:00	38	m	566.90	12.00			5	1		6	6	6	12	EL		Fixing roof on rig.
Mon	04-11-2002	06:00	14:00	39	m	587.90	21.00			8			8	8	8	16	AE	AN	
Mon	04-11-2002	14:00	22:00	40	e	607.30	19.40			8			8	8	8	16	EL	JM	
Tue	05-11-2002	06:00	14:00	41	m	624.85	17.55			8			8	8	8	16	AE	AN	
Tue	05-11-2002	14:00	22:00	42	e	642.00	17.15			8			8	8	8	16	EL	JM	
Wed	06-11-2002	06:00	14:00	43	m	659.90	17.90			8			8	8	8	16	AE	AN	
Wed	06-11-2002	14:00	22:00	44	e	680.80	20.90			9			9	9	9	18	EL	JM	
Thu	07-11-2002	06:00	14:00	45	m	698.90	18.10			8			8	8	8	16	AE	AN	
Thu	07-11-2002	14:00	22:00	46	e	700.30	4.40			3	5		8	10	10	20	EL+AE	JM+AN	Lifting rods.
Glyvursnes-1										201 5	17.5		219	224	224	448			
Fri	08-11-2002	06:00	18 00	1	m			4					4	8	8	16	EL+AE	JM+AN	Packing and move to Vestmanna.
Sat	09-11-2002	06:00	18:00	2	m	93.00	93.00	6		4			10	20	20	40	EL+AE	JM+AN	Positioning the rig.
Sun	10-11-2002	06:00	18:00	3	m	243.00	150.00			10	6		16	20	12	32	EL+AE	JM+AN	Construction of cover on Glyvursnes-1
Mon	11-11-2002	06:00	18:00	4	m/e						12		12	12	12	24	AE	JM	Waiting 2 hours for replacement of car.
Tue	12-11-2002	06:00	18:00	5	m/e	615.00	372.00			15	15		30	15	15	30	AE	JM	Reaming. Stuck pipe.
Wed	13-11-2002	06:00	18:00	6	m/e						14		14	14	14	28	AE	JM	Finishing reaming 6:15; demob.
Thu	14-11-2002	06:00	18:00	7	m						9		9	9	9	18	AE	JM	Moving rig and container to Tórshavn harbour.
Vestmanna-1										29			95	98	90	188			

EL: Erkko Lehtonen, drill foreman; AE: Arto Enqvist, senior driller; JM: Jari Määttälä, assistant driller; AN: Arto Nurmi, assistant driller.

Table 5. *Wire-line sondes and measured parameters (from log headers).*

Sonde	Data Channel	Physical Channel	Long name	Short name	Visible	Default Filtering
OPTV	0		Depth	DPTH		
OPTV	1		Borehole View	OPTV		
OPTV	2		Orientation	ORI		
OPTV	3		Rotation	ROT		
OPTV	4		Inclination	INC		
OPTV	5		Spare	AUX	no data	
3ACS	0	2	Borehole Diameter	CALP	x	11
3ACS	1	1	Casing Collar Locator	CCL	no data	3
DNNS	0	5	Casing Collar Locator	CCL	no data	3
DNNS	1	6	Natural Gamma	NGAM	x	17
DNNS	2	1	Near count rate	Near	x	17
DNNS	3	2	Far count rate	Far	x	17
DNNS			Porosity	Pors	x	
FDGS	0	1	Natural Gamma	NGAM	x	17
FDGS	1	2	Temperature	TEMP		11
FDGS	2	3	Caliper	CALP	x	11
FDGS	3	4	Formation Density	DENS	x	17
FDGS	4	5	High Res Density	HRD	x	17
FDGS	5	6	Bed Res Density	BRD	x	17
GLOG	0	1	Formation Resistivity	RES	x	11
GLOG	1	4	Natural Gamma	NGAM	x	17
FWVS	0	1	Transit Time TX1-RX1	TA		7
FWVS	1	2	Transit Time TX1-RX2	TB		7
FWVS	2	3	Transit Time TX2-RX1	TC		7
FWVS	3	4	Transit Time TX2-RX2	TD		7
FWVS	4	5	Interval Transit Time	SVEL	x	21
FWVS	5	7	Near Receiver Waveform	NEAR		0
FWVS	6	8	Far Receiver Waveform	FAR		0
TCDS	0	2	Fluid Conductivity	COND	x	11
TCDS	1	1	Fluid Temperature	TEMP	x	11
TCDS	2	3	Natural Gamma	NGAM	x	17
SGAMM	0	1	POT	POT	x	51
SGAMM	1	2	URAN	URAN	x	51
SGAMM	2	3	THOR	THOR	x	51
SGAMM	3	5	GROS	GROS	no data	51
SGAMM	4	6	GROS	GROS	x	51

Table 6. *Wireline log runs and raw data files from Glyvursnes-1 and Vestmanna-1 November 2002.*

Well	Sonde	Run	Start Depth metres	End Depth metres	Date	Start	End	Trailer end depth metres	Logging time minutes	Mean logging speed metres/min.	Field print	Sonde ID	Header file name	Header file date	Header file time	Header file size byte	Data file name	Data file date	Data file time	Data file size byte	Wave form file name	Wave form file date	Wave form file time	Wave form file size byte
Glyv-1	OPTV	M	690.00	644.00	18-11-2002	09:44	10:30		46			3815	690_644.HED	19-11-2002	17·19	2,609	690_644.otv	19-11-2002	17:16	50,047,224				
Glyv-1	OPTV	M	644.00	550.00	18-11-2002	10:36	12:10		94			3815	644_550.HED	19-11-2002	17:18	2,610	644_550.otv	19-11-2002	17:19	102,661,752				
Glyv-1	OPTV	M	552.00	450.00	18-11-2002	12:18	14:00		102			3815	552_450.HED	19-11-2002	17:18	2,583	552_450.otv	19-11-2002	17:18	110,841,504				
Glyv-1	OPTV	M	452.00	350.00	18-11-2002	14:08	15:50		102			3815	452_350.HED	19-11-2002	17:17	2,583	452_350.otv	19-11-2002	17:18	110,876,256				
Glyv-1	OPTV	M	352.00	250.00	19-11-2002	08:58	10:40		102			3815	352-250.HED	19-11-2002	17:17	2,583	352-250.otv	19-11-2002	17:17	110,926,212				
Glyv-1	OPTV	M	252.00	150.00	19-11-2002	10:48	12:30		102			3815	252_150.HED	19-11-2002	17:16	2,583	252_150.otv	19-11-2002	17:17	110,813,268				
Glyv-1	OPTV	M	152.00	50.00	19-11-2002	12:38	14:20		102			3815	152_50.HED	19-11-2002	17:16	2,579	152_50.otv	19-11-2002	17:16	111,010,920				
Glyv-1	OPTV	M	52.00	0.00	19-11-2002	14:28	15:20		52			3815	52_0.HED	19-11-2002	17:55	2,571	52_0.otv	19-11-2002	17:55	53,376,900				
Glyv-1	3ACS	M	700.27	2.37	19-11-2002	15:56	17:24	2	88	7.93	x	1703	3ACSM.hed	23-11-2002	17:10	3,248	3ACSM.LOG	23-11-2002	17:10	977,074				
Glyv-1	FDGS	M	700.31	2.92	20-11-2002	09:55	12:13	2	138	5.05	x 511	5294 GQ	FDGSM.hed	23-11-2002	17:10	4,767	FDGSM.log	23-11-2002	17:10	976,360				
Glyv-1	FDGS	R	20.11	3.05	20-11-2002	12:26	12:30	3	4	4.27		5294 GQ	FDGSR.hed	23-11-2002	17:10	4,766	FDGSR.log	23-11-2002	17:10	23,898				
Glyv-1	DNNS	M	699.54	1.98	20-11-2002	13:22	15:38	1	136	5.13	x	2167 N 502	DNNSM.hed	23-11-2002	17:10	3,992	DNNSM.log	23-11-2002	17:10	976,598				
Glyv-1	DNNS	R	20.03	2.04	20-11-2002	15:48	15:52	2	4	4.50		2167 N 502	DNNSR.hed	23-11-2002	17:10	3,991	DNNSR.log	23-11-2002	17:10	25,186				
Glyv-1	GLOG	M	700.26	12.45	21-11-2002	09:26	11:38	12	132	5.21	x	2324	GLOGM.hed	23-11-2002	17:10	3,230	GLOGM.log	23-11-2002	17:10	962,948				
Glyv-1	GLOG	R	33.29	12.45	21-11-2002	11:45	11:49	12	4	5.21		2324	GLOGR.hed	23-11-2002	17:10	3,219	GLOGR.log	23-11-2002	17:10	29,190				
Glyv-1	FWVS	R	70.64	38.41	21-11-2002	12:04	12:15	38	11	2.93	x	652	FWVSR.hed	23-11-2002	17·10	4,827	FWVSR.log	23-11-2002	17:10	44,730	FWVSR.VDL	23-11-2002	17·10	159,750
Glyv-1	FWVS	M	700.30	7.46	21-11-2002	12:50	16:39	7	229	3.03	x	652	FWVSM.hed	23-11-2002	17:10	4,824	FWVSM.log	23-11-2002	17:10	969,234	FWVSM.VDL	23-11-2002	17:10	3,461,550
Glyv-1	SGAM	M	700.31	2.66	22-11-2002	09:29	c. 20:30		661	1.06	x	3305	SGAMM.hed	28-12-2002	18:17	5,100	SGAMM.LOG	23-11-2002	17:14	976,710				
VM-1	OPTV	M	590.00	500.00	23-11-2002	10:00	c. 11:30		90			3815	590_500.HED	23-11-2002	17:19	2,579	590_500.otv	23-11-2002	17:20	97,874,664				
VM-1	OPTV	M	502.00	400.00	23-11-2002	11:38	c. 13:20		102			3815	502_400.HED	23-11-2002	17:19	2,579	502_400.otv	23-11-2002	17:19	110,811,096				
VM-1	OPTV	M	402.00	300.00	23-11-2002	13:28	c. 15:10		102			3815	402_300.HED	23-11-2002	17:19	2,579	402_300.otv	23-11-2002	17:20	110,871,912				
VM-1	OPTV	M	302.00	200.00	24-11-2002	08:58	c. 10:40		102			3815	302_200.HED	28-11-2002	10:05	2,579	302_200.otv	28-11-2002	10:05	110,969,652				
VM-1	OPTV	M	202.00	100.00	24-11-2002	10:40	c. 10:40		0			3815	202_100.HED	28-11-2002	10:04	2,577	202_100.otv	28-11-2002	10:04	19,400,304				
VM-1	OPTV	M	202.00	100.00	24-11-2002	10:48	c. 12:30		102			3815	202_100A.HED	28-11-2002	10:04	2,605	202_100A.otv	28-11-2002	10:05	110,863,224				
VM-1	OPTV	M	102.00	68.00	24-11-2002	12:36	c. 13:10		34			3815	102_68.hed	28-11-2002	10:04	2,575	102_68.otv	28-11-2002	10:04	36,007,416				
VM-1	OPTV	M	70.00	20.00	24-11-2002	13:20	c. 14:10		50			3815	70_20.HED	28-11-2002	10:04	2,572	70_20.otv	28-11-2002	10:04	54,667,068				
VM-1	3ACS	M	594.20	2.33	24-11-2002	14:24	15:48	2	84	7.05	x	1703	3ACSV1M.hed	28-11-2002	10:04	3,247	3ACSV1M.log	28-11-2002	10:04	828,632				
VM-1	FDGS	M	589.61	3.05	25-11-2002	09:29	11:26	3	117	5.01	x 511	5294 GQ	fdgsV1M.hed	28-11-2002	10:05	4,771	fdgsV1M.LOG	28-11-2002	10:05	821,198				
VM-1	FDGS	R	40.03	15.98	25-11-2002	11:42	11:49	15	7	3.44	x 511	5294 GQR	fdgsV1R.hed	28-11-2002	10:05	4,773	fdgsV1R.LOG	28-11-2002	10:05	33,670				
VM-1	DNNS	M	588.61	1.98	25-11-2002	12:44	14:39	1	115	5.10	x	2167 N 502	DNNSV1M.hed	28-11-2002	10:05	3,996	DNNSV1M.log	28-11-2002	10:05	821,296				
VM-1	DNNS	R	20.16	1.98	25-11-2002	14:45	14:49	1	3.4	5.35		2167 N 502	DNNSV1R.hed	28-11-2002	10:05	3,995	DNNSV1R.log	28-11-2002	10:05	25,466				
VM-1	GLOG	M	588.63	15.08	25-11-2002	15:19	17·10	16	111	5.17	x	2324	GLOGV1M.hed	28-11-2002	10:05	3,233	GLOGV1M.log	28-11-2002	10:05	802,984				
VM-1	GLOG	R	37.26	15.94	25-11-2002	17:17	17:22	15	4.4	4.85		2324	GLOGV1R.hed	28-11-2002	10:05	3,232	GLOGV1R.log	28-11-2002	10:05	29,862				
VM-1	FWVS	M	590.64	14.85	26-11-2002	11:57	15:07	14	190	3.03	x	652	FWVSV1M.hed	28-11-2002	10:05	4,832	FWVSV1M.log	28-11-2002	10:05	806,120	FWVSV1M.VDL	28-11-2002	10:05	2,879,000
VM-1	FWVS	R	40.25	4.19	26-11-2002	15:14	15:27	4	12.7	2.84		652	FWVSV1R.hed	28-11-2002	10:05	4,829	FWVSV1R.log	28-11-2002	10:05	50,498	FWVSV1R.VDL	28-11-2002	10:05	180,350
VM-1	TCDS	M	0.00	586.15	26-11-2002	09:09	10:54	586	105	5.58	x	1365	TCDSV1M.hed	28-11-2002	10:05	3,609	TCDSV1M.log	28-11-2002	10:05	820,610				
VM-1	TCDS	R	507.03	525.62	26-11-2002	11:00	11:03	525	3.5	5.31		1365	TCDSV1R.hed	28-11-2002	10:05	3,614	TCDSV1R.log	28-11-2002	10:05	25,858				
VM-1	TCDS	R	297.91	308.82	26-11-2002	11:15	11:17	308	2.3	4.74		1365	TCDSV1R1.hed	28-11-2002	10:05	3,615	TCDSV1R1.log	28-11-2002	10:05	15,288				
VM-1	SGAM	M	588.00	1.60	27-11-2002	09:23	c. 19:00		577	1.02	x	3305	SGAMV1.hed	28-12-2002	22:25	5,100	SGAMV1.LOG	28-11-2002	10:05	820,960				
Glyv-1	TCDS	M	0.01	698.04	28-11-2002	08:50	11:48	698	178	3.92	x	1365	TCDSM.hed	27-12-2002	16:06	3,566	TCDSM.log	28-11-2002	11:48	977,256				
Glyv-1	TCDS	R	679.83	692.12	28-11-2002	11:53	11:56	692	3	4.10		1365	TCDSR.hed	18-12-2002	14:08	3,609	TCDSR.log	28-11-2002	20:56	17,220				
Glyv-1	TCDS	R	117.59	130.24	28-11-2002	12:18	12:21	130	3	4.22		1365	TCDSR1.hed	18-12-2002	11:06	3,608	TCDSR1.log	28-11-2002	21:21	17,556				

Note: Logging times are derived from the ticks marked every minute on field prints counting from the time stored with the header file.

Tool acronyms:

OPTV Optical televiewer
3ACS Three-arm Caliper Sonde
FDGS Formation Density/Gamma Ray Sonde
DNNS Dual Neutron-Neutron Sonde
GLOG Guard Log (focussed resistivity)
FWVS Full Wave Sonic
SGAM Spectral Gamma
TCDS Temperature/Conductivity Sonde

Table 7. *Sonde calibration data provided by Robertson Geologging (Jan. 2003).*

Optical Televiewer Calibration	Full waveform / compensated sonic calibration	Temperature / Conductivity Calibration	Focussed Electric Calibration	Dual Neutron Probe Calibration	Formation Density Probe Calibration
[Probe Information] hx_off=0.0 hy_off=0.0 hz_off=0.0 gx_off=0.0 gy_off=0.0 gz_off=0.0 hx_span=-1.0 hy_span=-1.0 hz_span=1.0 gx_span=1.0 gy_span=1.0 gz_span=1.0	[Channel1] LastCalibration=26/07/02 NextCalibration=26/07/03 CalibrationInterval=0 CalibrationMethod=CONST Coefficient0=50 Coefficient1=0.5 Coefficient2=0.0 Coefficient3=0.0 [Channel2] LastCalibration=26/07/02 NextCalibration=26/07/03 CalibrationInterval=0 CalibrationMethod=CONST Coefficient0=50 Coefficient1=0.5 Coefficient2=0.0 Coefficient3=0.0 [Channel3] LastCalibration=26/07/02 NextCalibration=26/07/03 CalibrationInterval=0 CalibrationMethod=Const LastCalibration=26/07/02 NextCalibration=26/07/03 CalibrationMethod=Const CalibrationInterval Coefficient0=50.0 Coefficient1=0.5 Coefficient0=50.0 Coefficient1=0.5 Coefficient2=0.0 Coefficient3=0.0 [Channel4] LastCalibration=26/07/02 NextCalibration=26/07/03 CalibrationInterval=0 CalibrationMethod=Const LastCalibration=26/07/02 NextCalibration=26/07/03 CalibrationMethod=Const CalibrationInterval Coefficient2=0.0 Coefficient0=50.0 Coefficient1=0.5 Coefficient0=50.0 Coefficient1=0.5 Coefficient2=0.0 Coefficient3=0.0	[Channel1] LastCalibration=26/09/02 NextCalibration=26/12/02 CalibrationInterval=0 CalibrationMethod=Polynomial Coefficient0=-8.8079615989e+000 Coefficient1=4.8432864577e-003 Coefficient2=0.00000000e+000 Coefficient3=0.00000000e+000 [Channel2] LastCalibration=26/09/02 NextCalibration=26/12/02 CalibrationInterval=0 CalibrationMethod=Polynomial Coefficient0=1.2809736118e+000 Coefficient1=8.8148705977e-001 Coefficient2=3.0943086658e-006 Coefficient3=0.00000000e+000 [Channel3] LastCalibration=21/09/02 NextCalibration=21/12/02 CalibrationInterval=0 days CalibrationMethod=Polynom Coefficient0=0 Coefficient1=1.454545455 Coefficient2=0 Coefficient3=0 JigCount=2 ReferencePoint0=18 CPS at 0 API Cs. ReferencePoint1=568 CPS at 800 API Cs.	****** CALIBRATION-HISTORY FILE ****** File created: 18/09/02 LastModified=18/09/02 Sonde=GLOG SerialNo=2324 channel=NGAM CalibrationMethod=Polynom Coefficient0=0 Coefficient1=1 Coefficient2=0 Coefficient3=0 JigCount=2 ReferencePoint0=20 CPS at 0 API Cs. ReferencePoint1=486 CPS at 800 API Cs.	CALIBRATION FILE GENERATED BY RG - WINLOGGER [General] LastModified=24/10/02 Sonde=DNNS SerialNo=2167 [Channel1] LastCalibration=24/10/02 NextCalibration=24/01/03 CalibrationInterval=100 days CalibrationMethod=Polynom Coefficient0=0 Coefficient1=0.850774555 Coefficient2=0 Coefficient3=0 JigCount=2 NEAR=Count rate: 6560 in sleeve with ratio of 0.148000 FAR=Count rate: 826 in sleeve with ratio of 0.148000	CALIBRATION FILE GENERATED BY RG - WINLOGGER [General] LastModified=24/10/02 Sonde=FDGS SerialNo=511 [Channel1] LastCalibration=24/10/02 NextCalibration=24/01/03 CalibrationInterval=100 days CalibrationMethod=Polynom Coefficient0=0 Coefficient1=1.473296501 Coefficient2=0 Coefficient3=0 JigCount=2 ReferencePoint0=19 CPS at 0 CPS ReferencePoint1=562 CPS at 800 CPS

Compilation of data included with the logging report from Robertson Geologging Jan. 2003.
The data are extracted by Robertson Geologging from the "CAL" files stored with the WinLogger program.
Note: No data received on Tree-Arms Caliper or Spectral Gamma Tools.

Table 8A. *Depth shifts in Glyvursnes-1 measured relative to the formation density log run (master run) and corrected to core depths.*

Log run	Tool acronym	No. of fits ¤	Median of shifts (metres)	Mean of shifts (metres)	Std. dev. of shifts (metres)	Std. error of shifts (metres)	Shifts, rounded (metres)	Fit of master run to core at top casing (metres) §	Fit of master run to core at TD=700 m (metres) §
Formation Density/Gamma Ray Sonde (Master run)	FDGS						0.00	-0.08	-0.57
Three-arm Caliper Sonde	3ACS	11	-0.21	-0.23	0.04	0.01	-0.20	-0.08	-0.57
Dual Neutron-Neutron Sonde	DNNS	7	0.00	0.00	0.07	0.02	0.00	-0.08	-0.57
Guard Log (focussed resistivity)	GLOG	7	-0.18	-0.18	0.06	0.02	-0.20	-0.08	-0.57
Temperature /Conductivity Sonde	TCDS	6	-0.40	-0.39	0.05	0.02	-0.40	-0.08	-0.57
Spectral Gamma	SGAM	6	-0.10	-0.12	0.04	0.02	-0.10	-0.08	-0.57
Full Wave Sonic (processed log from LogTek)	FWVS	18	0.47	0.43	0.12	0.03	0.50	-0.08	-0.57
Full Wave Sonic (processed log from GEUS)	FWVS	14	0.66	0.65	0.12	0.03	0.70	-0.08	-0.57
Optical televiewer	OPTV	92	0.33	0.31	0.12	0.01	0.30	-0.08	-0.57
Core		41	0.22	0.25	0.20	0.03		0.00	0.00

¤ Number of depth intervals or depths matched (see Tables 8C to 8G).
§ The wire-line logs in the composite well log are first depth shifted to the depth of the formation density log (master run).
Subsequently master log depths "X" are shifted to fit core depths "Y" using the equation Y = 0.9993*X - 0.08 (in metres).

Table 9A. *Depth shifts in Vestmanna-1 measured relative to the formation density log run (master run) and corrected to core depths.*

Log run	Tool acronym	No. of fits ¤	Median of shifts (metres)	Mean of shifts (metres)	Std. dev. of shifts (metres)	Std. error of shifts (metres)	Shift rounded (metres)	Shift relative to core (metres)
Formation Density/Gamma Ray Sonde (Master run)	FDGS						0.00	0.10
Three-arm Caliper Sonde	3ACS	15	0.09	0.10	0.05	0.01	0.10	0.20
Dual Neutron-Neutron Sonde	DNNS	15	0.02	0.01	0.16	0.04	0.00	0.10
Guard Log (focussed resistivity)	GLOG	8	-0.05	-0.03	0.25	0.09	0.00	0.10
Temperature /Conductivity Sonde	TCDS	7	-0.30	-0.24	0.15	0.06	-0.30	-0.20
Spectral Gamma	SGAM	23	-0.06	-0.08	0.10	0.02	-0.10	0.00
Full Wave Sonic (processed log from LogTek)	FWVS	28	-0.14	-0.16	0.09	0.02	-0.10	0.00
Full Wave Sonic (processed log from GEUS)	FWVS	29	0.03	0.03	0.11	0.02	0.00	0.10
Optical televiewer	OPTV	64	-0.08	-0.07	0.08	0.01	-0.10	0.00
Core		27	-0.13	-0.11	0.11	0.02	-0.10	0.00

¤ Number of depth intervals or depths matched (see Tables 9B to 9F).

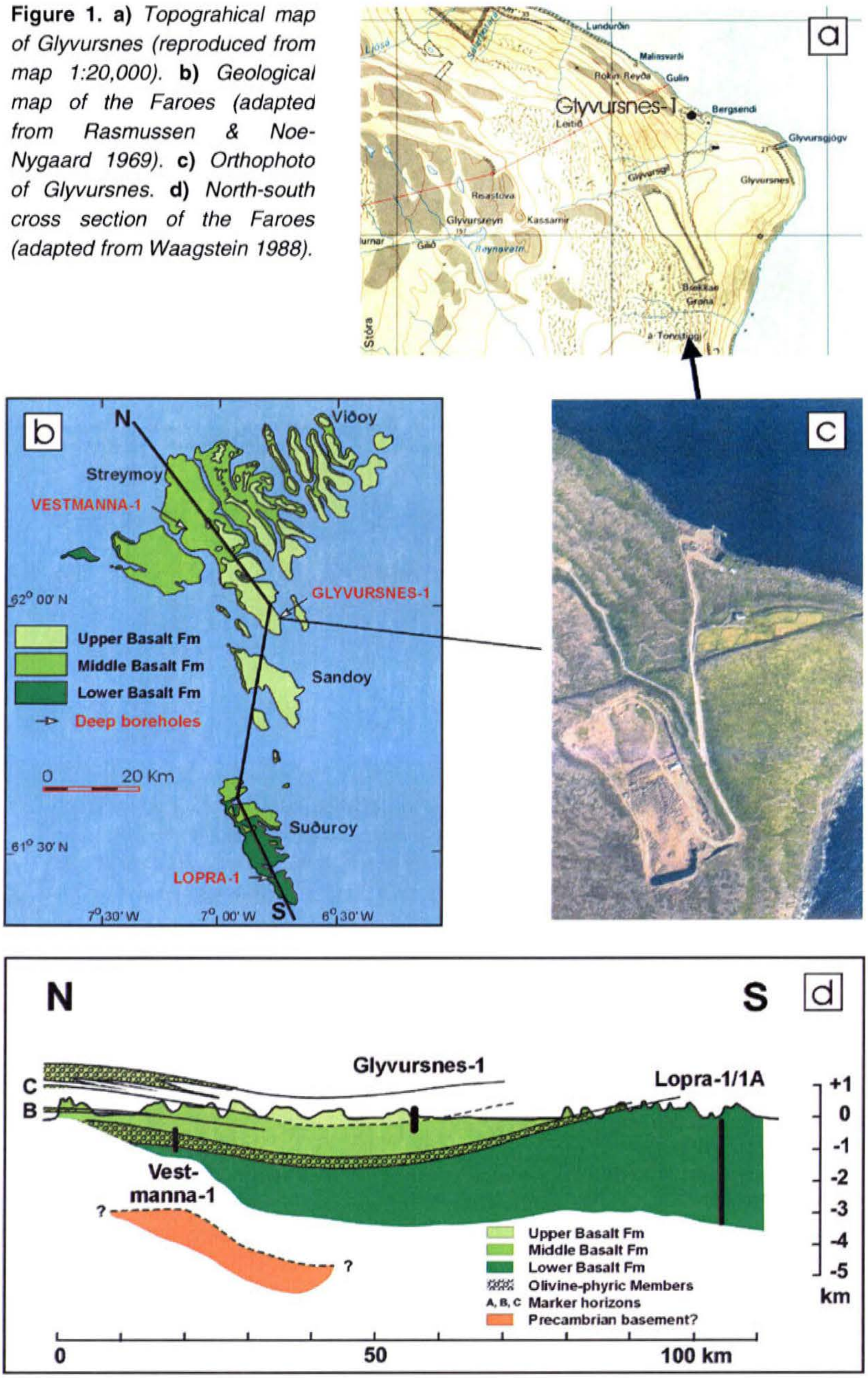
Table 11. *Variation of log parameters with lithology and stratigraphic depth in Glyvursnes-1 and Vestmanna-1.*

			No. of standard		Caliper		Gamma ray		NPHI porosity		log10 Resistivity		Density		Vp LogTek (1)		Vp LogTek (2)	
Well	FM	Lithology	log samples		inch		API units		LPU		Ohm-m		g/ccm		km/s		km/s	
			min.	max.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.
GL-1	UBF	Lava core	1669	1722	3.12	0.02	9.4	3.3	12.1	5.1	3.23	2.66	2.79	0.06	4.90	0.71	4.91	0.71
GL-1	MBF	Lava core	1394	1403	3.11	0.02	9.5	3.4	17.9	4.4	3.14	2.64	2.73	0.07	4.62	0.56	4.61	0.53
VM-1	MBF	Lava core	1514	1538	3.09	0.02	6.3	2.4	14.2	4.0	3.55	2.72	2.81	0.05	5.64	0.46	5.63	0.44
VM-1	LBF	Lava core	49	50	3.10	0.07	6.9	2.4	14.5	1.4	3.23	2.73	2.82	0.02	5.33	0.26	5.32	0.23
GL-1	UBF	Lava crust	420	422	3.14	0.04	9.8	2.9	23.5	4.2	2.93	2.59	2.65	0.06	3.73	0.49	3.70	0.50
GL-1	MBF	Lava crust	573	574	3.12	0.01	10.9	4.0	25.6	3.9	2.99	2.56	2.63	0.07	3.92	0.50	3.91	0.47
VM-1	MBF	Lava crust	1277	1289	3.10	0.03	7.3	2.7	24.8	4.2	3.41	2.54	2.69	0.06	5.07	0.32	5.07	0.31
VM-1	LBF	Lava crust	60	65	3.10	0.02	6.4	2.2	19.0	3.5	2.97	2.52	2.78	0.03	4.78	0.27	4.77	0.27
GL-1	UBF	Top lava breccia	285	286	3.22	0.15	11.6	3.1	25.9	5.9	3.08	2.71	2.58	0.09	3.41	0.65	3.37	0.66
GL-1	MBF	Top lava breccia	11	11	3.13	0.03	15.1	6.2	30.3	2.1	3.15	3.05	2.50	0.07	3.70	0.56	3.65	0.62
VM-1	MBF	Top lava breccia	245	247	3.10	0.01	7.7	2.8	27.7	4.4	3.20	2.59	2.64	0.06	4.74	0.31	4.76	0.30
VM-1	LBF	Top lava breccia	7	7	3.10	0.00	9.7	2.4	35.1	2.4	2.50	2.43	2.67	0.02	3.37	0.02	3.40	0.04
GL-1	UBF	Sediment	50	55	3.26	0.08	23.6	8.5	45.7	10.6	2.66	2.37	2.33	0.07	2.52	0.19	2.54	0.25
GL-1	MBF	Sediment	18	18	3.12	0.02	47.7	13.8	41.3	8.7	2.67	2.51	2.39	0.05	2.60	0.53	2.64	0.56
VM-1	MBF	Sediment	10	10	3.09	0.00	10.2	1.8	33.2	4.0	2.72	2.60	2.57	0.04	3.68	0.14	3.75	0.26
VM-1	LBF	Sediment	1	16	3.27	0.14	12.0	0.0	63.2	15.4	2.69	2.15	2.40	0.10	2.82	0.07	2.73	0.07
GL-1	UBF	Basal lava breccia	4	4	3.18	0.02	12.4	1.9	28.5	1.7	3.07	3.06	2.60	0.04	3.17	0.25	3.57	0.38
VM-1	MBF	Basal lava breccia	21	21	3.16	0.14	6.3	1.8	32.7	4.7	3.11	2.72	2.68	0.05	4.92	0.33	4.94	0.30
VM-1	LBF	Basal lava breccia	2	2	3.10	0.00	11.6	3.2	29.0	1.9	2.47	2.46	2.66	0.02	3.83	0.00	3.86	0.00
GL-1	UBF	Basal lava zone	15	18	3.18	0.09	12.8	4.4	25.3	2.8	2.89	2.74	2.61	0.05	3.56	0.69	3.67	0.50
GL-1	MBF	Basal lava zone	25	26	3.11	0.01	10.6	3.6	25.5	5.7	3.10	2.61	2.65	0.09	4.29	0.60	4.31	0.58
VM-1	MBF	Basal lava zone	115	116	3.10	0.02	6.7	2.6	25.5	4.4	3.32	2.73	2.70	0.05	5.06	0.30	5.08	0.29
VM-1	LBF	Basal lava zone	3	3	3.10	0.00	5.4	1.6	16.5	1.6	2.76	2.73	2.79	0.01	4.99	0.00	5.02	0.00

			Number of sonic	Vp GEUS (3)		Vs LogTek (1)		Vs LogTek (2)		Vs GEUS (3)		Vp/Vs LogTek (1)		Vp/Vs LogTek (2)		Vp/Vs GEUS (3)	
Well	FM	Lithology	log samples (1)	km/s		km/s		km/s		km/s							
				mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.
GL-1	UBF	Lava core	844	4.99	0.75	2.73	0.48	2.74	0.49	2.75	0.42	1.80	0.10	1.81	0.12	1.82	0.10
GL-1	MBF	Lava core	700	4.72	0.59	2.59	0.37	2.58	0.37	2.62	0.31	1.79	0.06	1.79	0.08	1.80	0.07
VM-1	MBF	Lava core	766	5.79	0.54	3.16	0.28	3.17	0.26	3.18	0.29	1.79	0.09	1.78	0.05	1.82	0.08
VM-1	LBF	Lava core	24	5.36	0.23	2.92	0.14	2.92	0.12	2.88	0.12	1.83	0.05	1.83	0.04	1.86	0.05
GL-1	UBF	Lava crust	215	3.76	0.52	2.03	0.31	2.02	0.31	2.05	0.31	1.85	0.09	1.84	0.11	1.84	0.15
GL-1	MBF	Lava crust	278	3.97	0.50	2.17	0.31	2.17	0.31	2.20	0.30	1.81	0.05	1.81	0.07	1.81	0.09
VM-1	MBF	Lava crust	645	5.12	0.40	2.81	0.21	2.80	0.21	2.82	0.19	1.81	0.08	1.81	0.07	1.82	0.06
VM-1	LBF	Lava crust	31	4.78	0.31	2.67	0.22	2.64	0.22	2.68	0.19	1.79	0.09	1.81	0.09	1.79	0.06
GL-1	UBF	Top lava breccia	141	3.99	0.70	1.87	0.35	1.86	0.35	2.11	0.33	1.82	0.12	1.82	0.14	1.89	0.14
GL-1	MBF	Top lava breccia	6	3.91	0.56	1.99	0.40	1.93	0.52	2.12	0.31	1.87	0.09	1.94	0.21	1.85	0.11
VM-1	MBF	Top lava breccia	124	4.76	0.37	2.62	0.24	2.63	0.21	2.64	0.24	1.82	0.12	1.82	0.09	1.81	0.10
VM-1	LBF	Top lava breccia	4	3.20	0.24	1.81	0.12	1.82	0.11	1.83	0.08	1.87	0.12	1.88	0.10	1.75	0.07
GL-1	UBF	Sediment	29	3.26	0.44	1.37	0.09	1.38	0.10	1.84	0.19	1.84	0.09	1.84	0.10	1.78	0.21
GL-1	MBF	Sediment	9	3.09	0.33	1.43	0.26	1.48	0.32	1.74	0.17	1.81	0.08	1.78	0.06	1.78	0.15
VM-1	MBF	Sediment	5	3.61	0.15	1.90	0.13	1.95	0.10	2.01	0.13	1.94	0.06	1.92	0.10	1.81	0.18
VM-1	LBF	Sediment	4	2.82	0.15	1.76	0.07	1.70	0.11	1.49	0.12	1.60	0.02	1.60	0.10	1.90	0.11
GL-1	UBF	Basal lava breccia	2	4.18	0.14	1.78	0.17	1.78	0.22	2.19	0.15	1 78	0.03	2.01	0.03	1.91	0.20
VM-1	MBF	Basal lava breccia	11	4.89	0.28	2.77	0.18	2.73	0.22	2.69	0.14	1.78	0.10	1.82	0.07	1.82	0.05
VM-1	LBF	Basal lava breccia	1	3.84	0.00	1.87	0.00	1.88	0.00	2.21	0.00	2.05	0.00	2.05	0.00	1.74	0.00
GL-1	UBF	Basal lava zone	9	3.97	0.81	1.98	0.45	2.03	0.36	2.08	0.26	1.81	0.13	1.82	0.11	1.91	0.26
GL-1	MBF	Basal lava zone	13	4.32	0.60	2.39	0.40	2.39	0.37	2.38	0.37	1.80	0.05	1.81	0.07	1.83	0.09
VM-1	MBF	Basal lava zone	57	5.05	0.34	2.81	0.15	2.81	0.15	2.78	0.16	1.80	0.06	1.81	0.04	1.82	0.05
VM-1	LBF	Basal lava zone	1	4.91	0.12	2.76	0.00	2.78	0.00	2.74	0.04	1.81	0.00	1.81	0.00	1.79	0.02

Specifications:
Sampling rate is 10 cm for standard logs and 20 cm for sonic logs.
In order to minimize boundary effects samples of log data acquired within a distance of +/- 0.2 m of lithological boundaries (cutoff distance) are excluded.
This means that a bed should be between 0.4 to 0.5 m thick to provide a single depth point.
Thin flow-units consisting of lava crust throughout have been merged with adjoining lava crusts of other units (but not with overlying basal zones).
Samples from a few intervals with a borehole diameter >20% larger than the nominal diameter of 3" are excluded (very few samples).
Log data <0 are excluded (to avoid missing values of '-999.25').
Number of standard log samples used is shown as a range. The variations mainly reflect that the logs do not have exactly the same start and end depths.
Different depth coverage of the logs is mainly a problem near TD in Vestmanna-1.
The number of sonic log samples (from LogTek receiver-array data set) is half the values of the standard logs due to the lower sampling rate of 0.2 m.
Three sets of sonic data are shown based on different processings of the same full wave sonic logs:
(1) Receiver-array type data based on results of LogTek using a guided peak finding method.
(2) Pseudo borehole compensated type data based on results of LogTek using a guided peak finding method.
(3) Receiver-array type data based on the results of GEUS using a WellCad semblance process.

Figure 1. a) *Topograhical map of Glyvursnes (reproduced from map 1:20,000).* **b)** *Geological map of the Faroes (adapted from Rasmussen & Noe-Nygaard 1969).* **c)** *Orthophoto of Glyvursnes.* **d)** *North-south cross section of the Faroes (adapted from Waagstein 1988).*



Glyvursnes-1 well

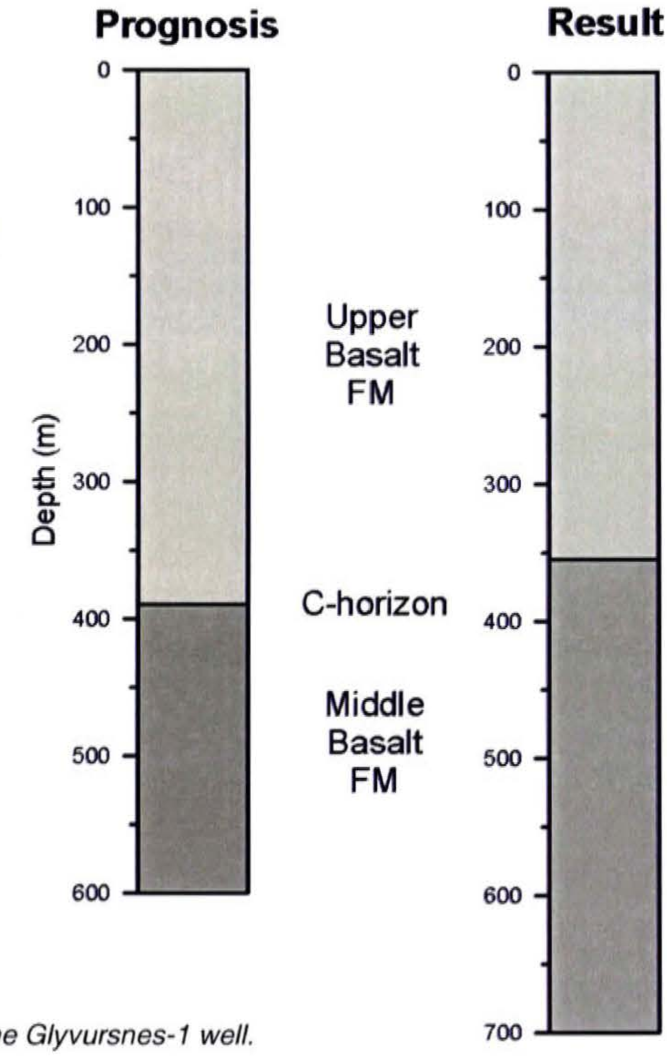


Figure 2. *Lithostratigraphy of the Glyvursnes-1 well.*

Upper Basalt Formation: *The 355 thick Upper Basalt section contains 15 volcaniclastic beds with a mean thickness of 0.62 m. The lava succession consists of compound lava flows made up of flow-units (lopes) with a mean thickness of 3.4 m. The Upper Basalt Fm. is dominantly plagioclase-phyric as in the exposed areas of central Faroes and similar to the underlying Middle Basalts. This is in contrast to the NE Faroes, where aphyric or olivine-phyric lava flows or mid-ocean ridge type are common in the Upper Formation.*

The C-horizon: *The lowermost lava flow of the Upper Basalt formation in the well consists of an aphyric, dark grey basalt with low gamma ray activity typical of the C-horizon flows. This is the southernmost known occurrence of these flows, which define the base of the Upper Basalts in exposures father north. The flow is underlain by a 0.78 m thick bed of a reddish, fine-grained volcaniclastic sediment.*

Middle Basalt Formation: *The 345 m long section only contains 8 volcaniclastic beds with a mean thickness of 0.56 m. The succession consists of compound lava flows made up of flow-units with a mean thickness of 2.2 m. The thicker flow-units have a non-vesicular core and a vesicular crust, which is sometimes auto-brecciated, while the thinner units are vesicular throughout. The far majority of flows are sparsely to highly plagioclase-phyric with the plagioclase phenocrysts ranging in size from a few millimetres up to 2 cm, often gathered in larger glomerocrysts together with minor olivine (altered). The phenocrysts are often concentrated in the lava core, while the crust may be almost devoid of phenocrysts.*

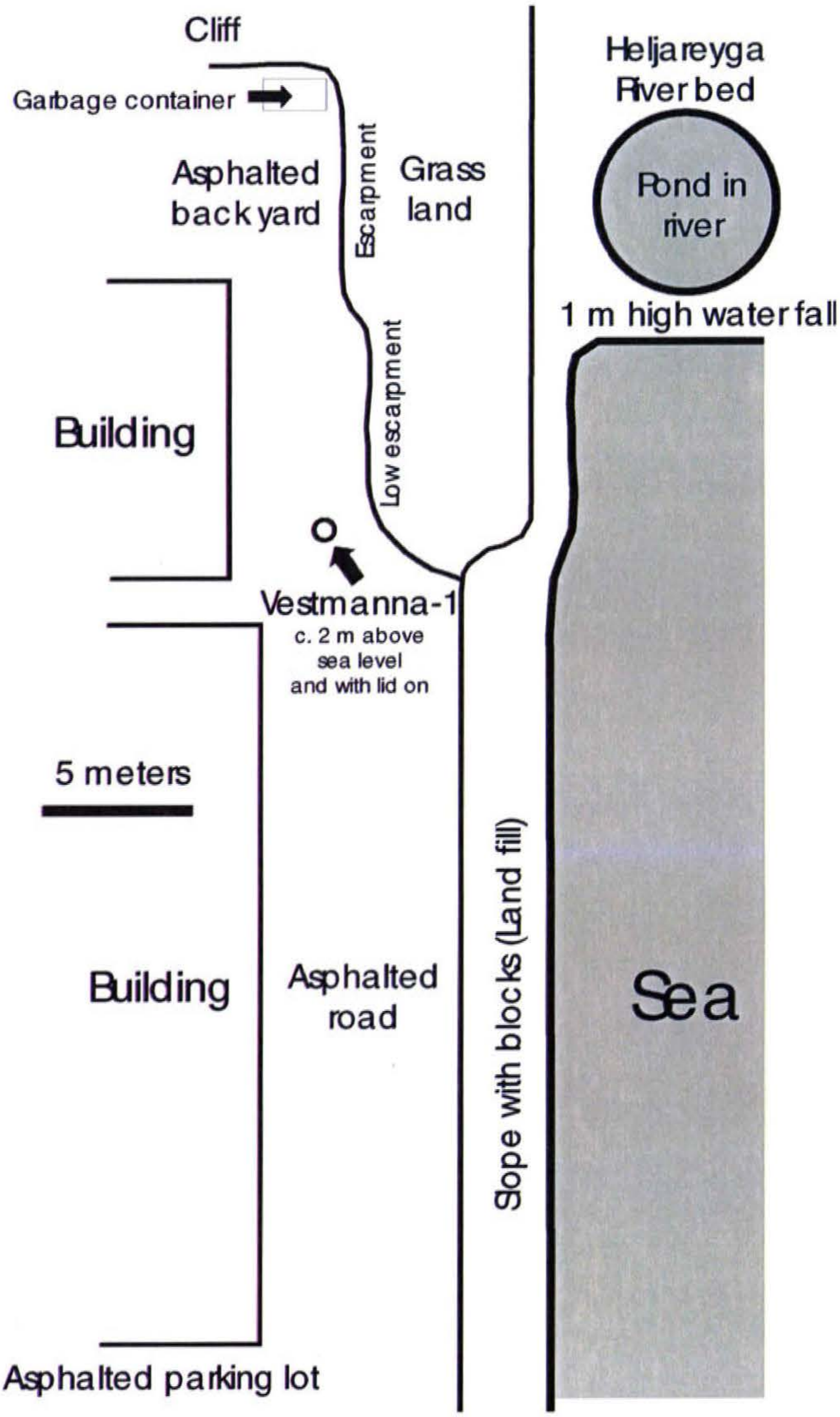


Figure 3. *Sketch map of Vestmanna-1 well site 1:200 measured by foot stepping during a short in visit in January 2002.*

Figure 4. *The drill rig at the Glyvursnes-1 well site with Nolsoy in the background.*

Figure 5. *The drill rig at the Glyvursnes-1 well site with Tórshavn in the background.*

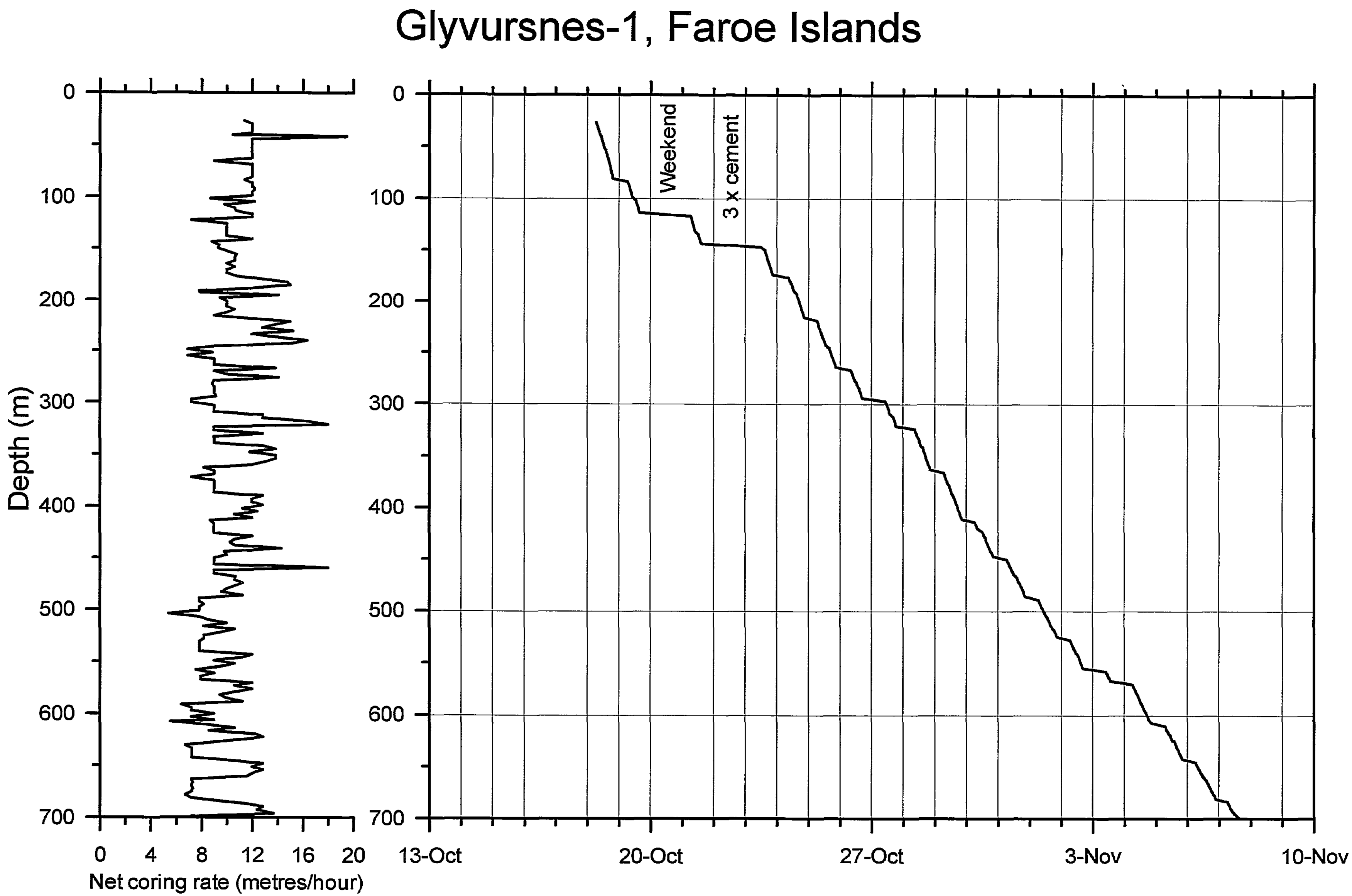


Figure 6. Penetration rate in Glyvursnes well.

Figure 7. *Water covered well head of Glyvursnes-1 with steel lid removed.*

Figure 8. *Well head of Vestmanna-1with steel lid removed.*

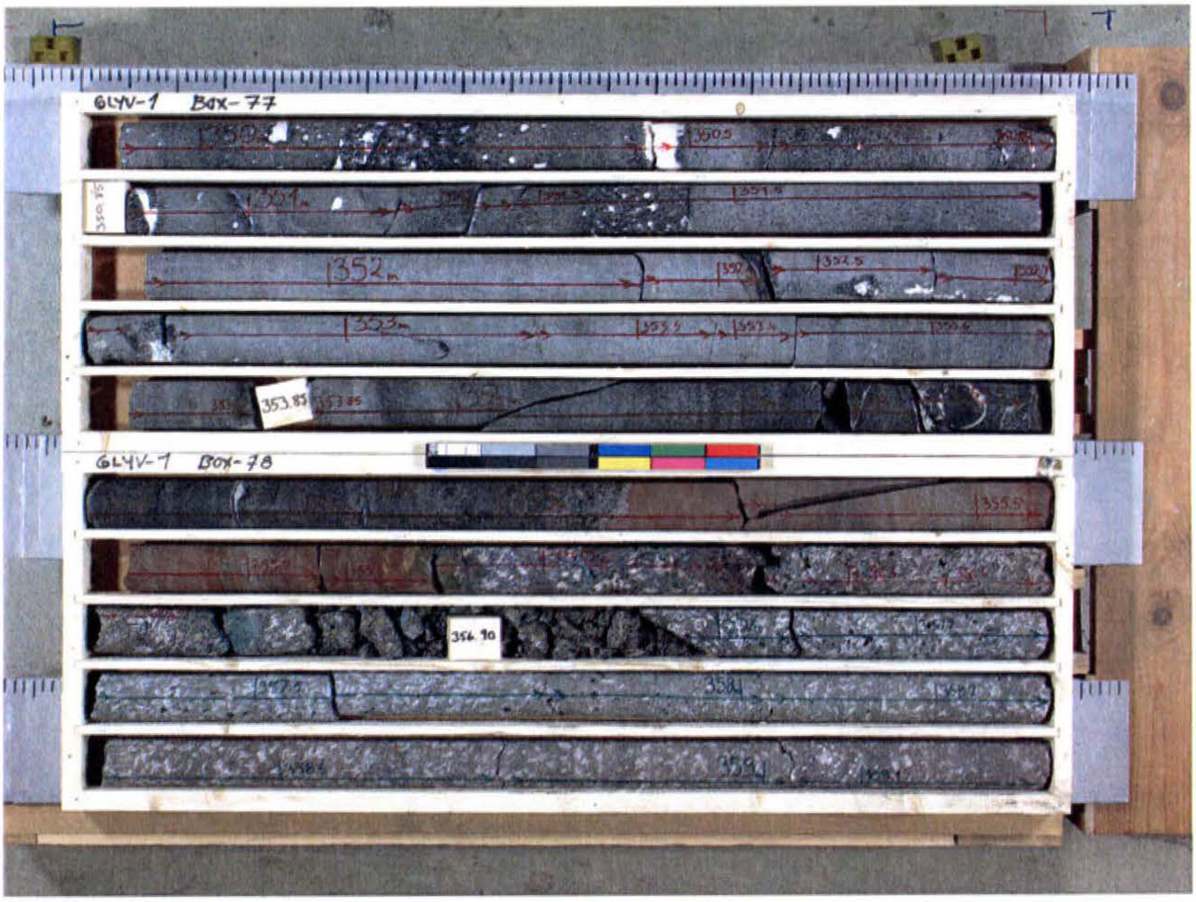


Figure 9. *Drill core from the Middle-Upper Basalt boundary in Glyvursnes-1.*

349.92-355.12 m. Lower part of aphyric, low-potassium basalt flow F15 (C-horizon flow).

349.92-350.07 m. Aphyric, sparsely vesicular lava core.

350.07-350.36 m. Aphyric, moderately vesicular intermediate zone.

350.36-354.93 m. Aphyric, sparsely vesicular to massive lava core.

354.93-355.13 m. Aphyric, moderately vesicular basal zone.

355.13-355.91 m. Greyish red, fine-grained, laminated sediment (top of Middle Basalt FM).

355.91-359.39 m. Uppermost part of coarse plagioclase-phyric compound flow F16.

355.91-356.80 m. Highly plagioclase-phyric, auto-brecciated lava crust.

356.80-356.92 m. Highly plagioclase-phyric, moderately vesicular continuous lava crust (core fractured).

356.92-357.81 m. Highly plagioclase-phyric, sparsely vesicular lava core.

357.81-357.82 m. Indistinct, 0.5 cm thick chilled top of flow-unit (lope).

357.82-357.96 m. Sparsely plagioclase-phyric, moderately vesicular lava crust.

357.96-359.39 m. Highly plagioclase-phyric, very sparsely vesicular to massive lava core.

A sparsely plagioclase-phyric, vesicular segregation vein occurs at 359.03-359.11 m.
The vesicles and veins in the upper, aphyric flow are competely filled with zeolites. The vesicles in the lower, plagioclase-phyric flow mainly contain greenish or black clay. The smaller vesicles are completely filled with clay, while the larger ones are partly empty with a lining of clay.

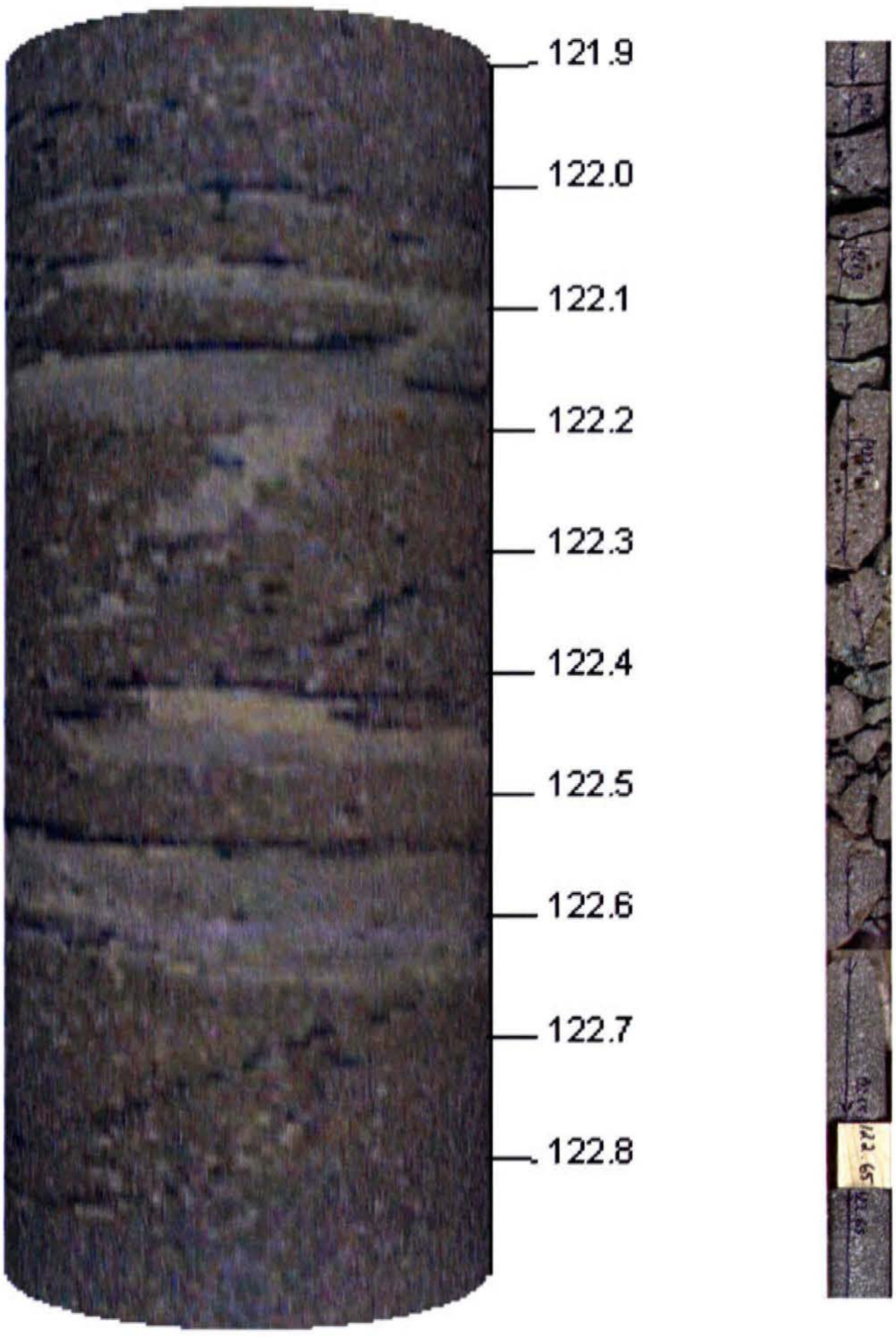


Figure 10. *Three dimensional view of the borehole wall in Glyvursnes-1 at 121.9 to 122.9 m depth from optical televiewer log (left) and photo of the core from same depth interval (right) showing the cemented zone in Glyvursnes-1. The core was drilled before cementing and shows a distinct greenish alteration along open fractures. In the OPTV image, light coloured cement is seen filling low and high angle fractures in the borehole wall. The fractures are up to 10 wide and required three cementing jobs to fill before the hole again became tight and drilling could be resumed.*

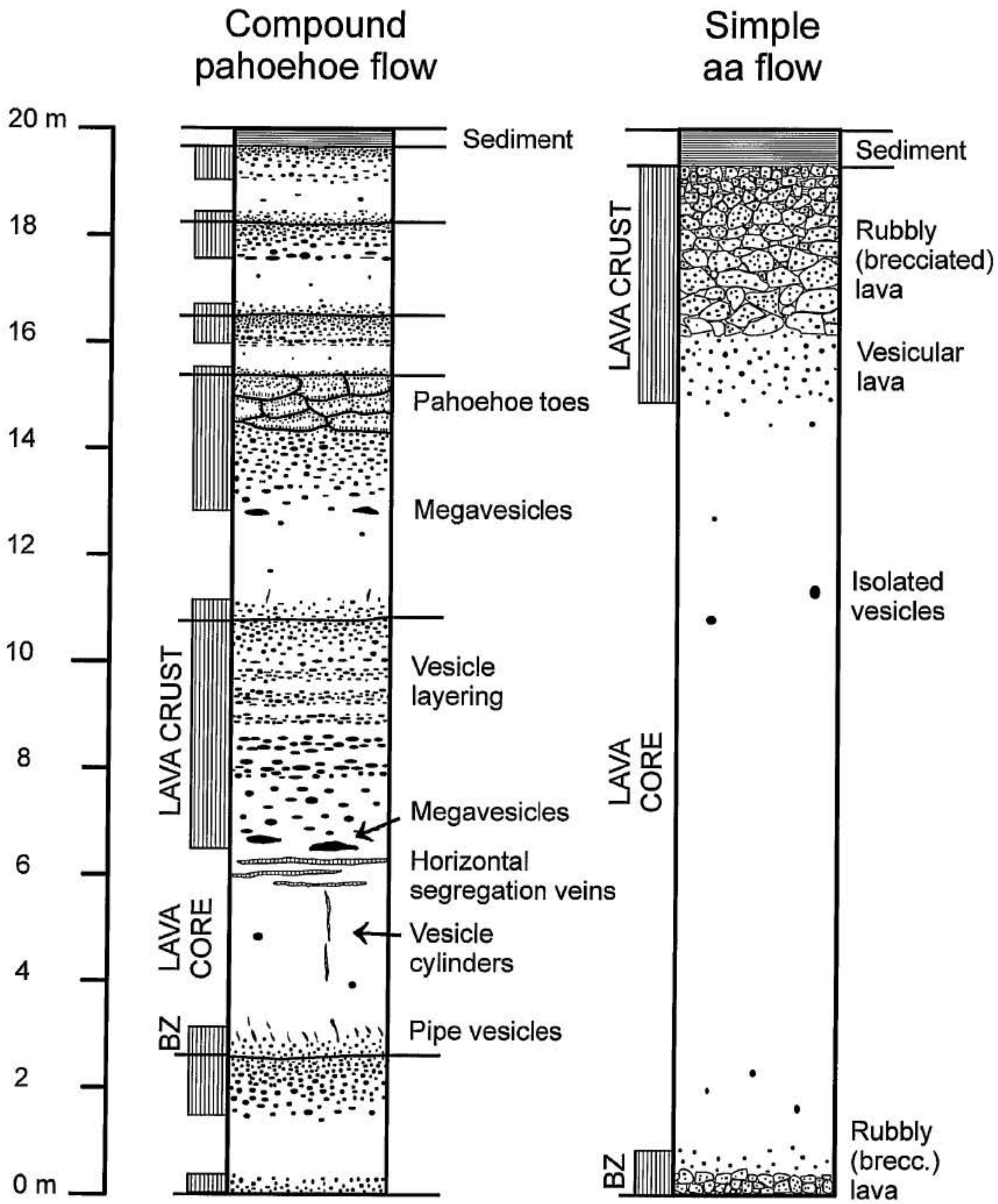


Figure 11. *Idealized vertical sections showing characteristic differences between compound pahoehoe and simple aa lava flows. Vesicular intervals are indicated by vertical ruling, BZ = basal zone. Small features like vesicles, rubble and veins not drawn to scale. (Modified from Waagstein 1998).*

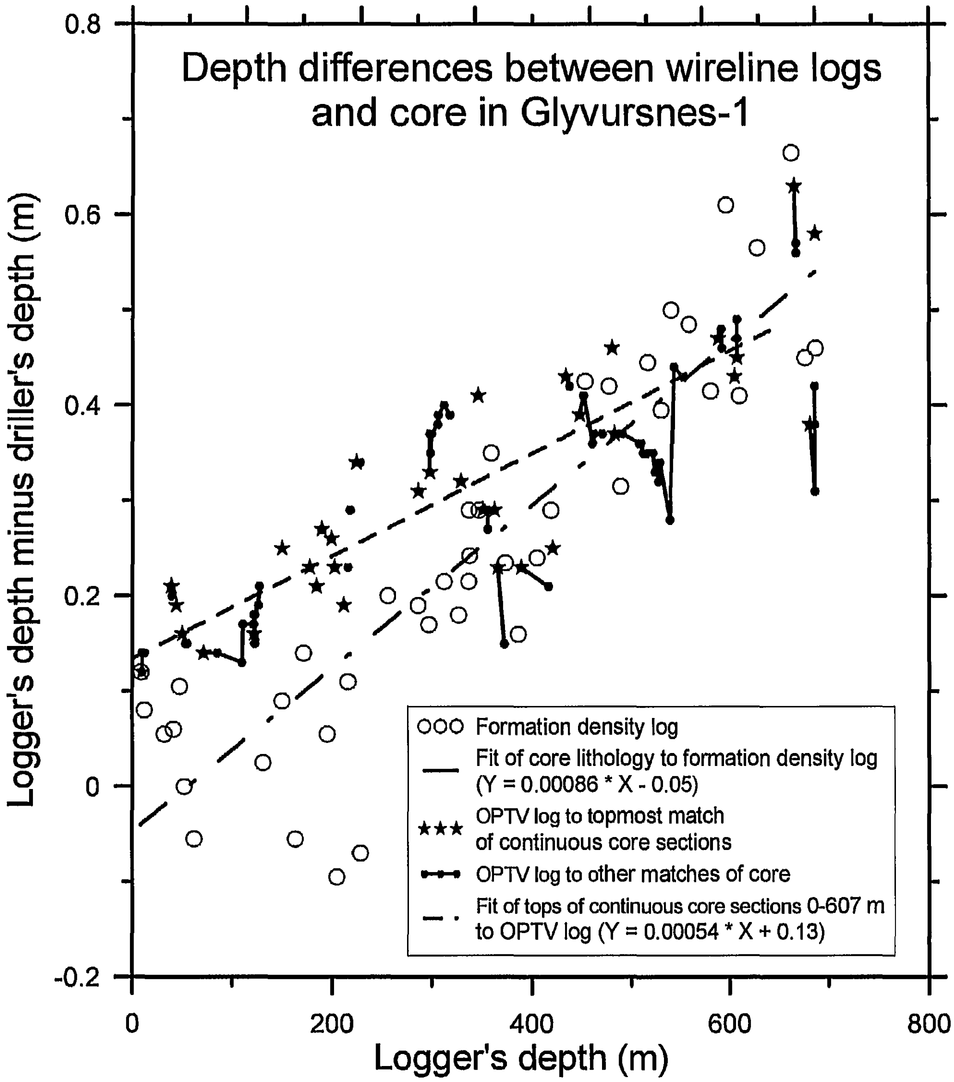


Figure 12. *The diagram shows depth matches of the formation density and OPTV wire-line logs with the full core from Glyvursnes-1. The formation density log was ghost matched with a synthetic step curve depicting the shifting lithologies of the drill core. The match process was performed at as many depth intervals as possible (Table 8.F). Similarly, all features on the optical televiewer (OPTV) log with a well-defined depth were matched with photographs of the drill core (Table 8.G). The diagram shows the result of the depth match of the density and OPTV logs with the core. During the marking of the core intervals of fitting core pieces had been fitted to the topmost driller's depth encountered (top of 3-m core). In the diagram lines connect the OPTV data points of such continuous core intervals and the uppermost features measured are marked with a star. These "first" depths are considered closely reflecting driller's depths unaffected by possible marking errors of the core. The recognition of features on the OPTV log is uncertain below 607 m and the linear regression line shown does not include features below that depth. Note that driller's depths were measured from the ground, while all wire-line logs were measured relative to the top of the casing about 8 cm above the ground. The diagram shows that both wire-line logs are roughly 0.5 m too long compared to the core. The density log shows a steeper increase than the OPTV log, but also a very large scatter of data points. Both the density master log and the OPTV log have therefore been used for conversion of log depths to core depths by using a simple linear equation: core depth = log depth * 0.9997 - 0.08 (metres) approximately corresponding to a line centred between the two regression lines on the diagram. The conversion was applied to all log curves of the composite log of the Glyvursnes well (attachment) after they were block shifted relative to the master run (Table 8.A).*

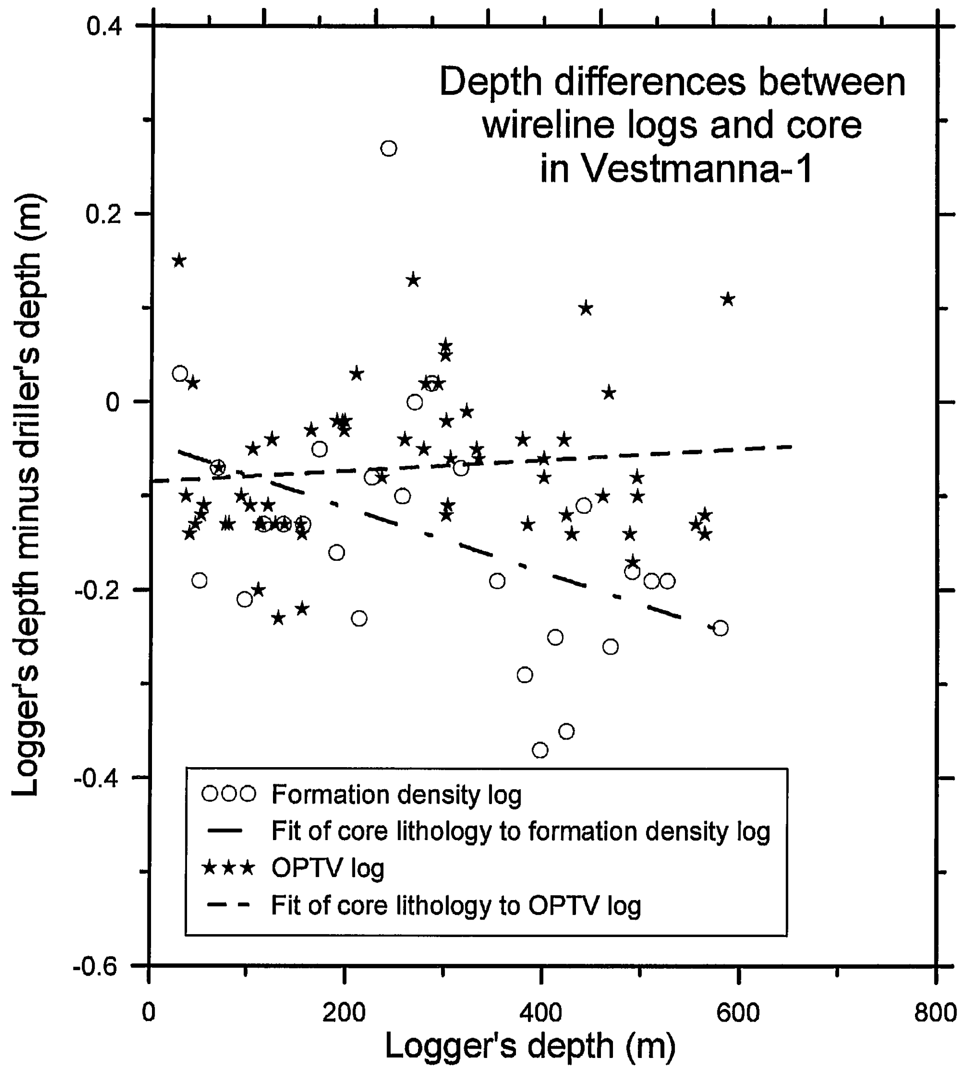


Figure 13. *The diagram shows depth matches of the formation density and OPTV wireline logs with the full core from the old Vestmanna-1 well (zero depth = top of the casing). A +0.19 m marking error of core pieces between 372.20 to 447.64 m was corrected for before matching. The formation density log was ghost matched with a synthetic step curve depicting the shifting lithologies of the drill core. The match process was performed at as many depth intervals as possible (Table 9.E). Similarly, features on the optical televiewer (OPTV) log with a well-defined depth were matched with the lithological description or photographs of the drill core (Table 9.F). The well had been reamed before logging in order to remove old deposits of tufa blocking the well. However, a thin coating of tufa was left in many places, especially in the upper 300 m, and hampered the recognition of lithological features on the OPTV log. The diagram shows a large scatter, but suggests a good match between OPTV and core depths. The density depths, on the other hand, seem on average to be about 0.1 m too low. In the composite log of the Vestmanna well (attachment) the density and gamma-ray curves of the master run have therefore been block shifted by –0.1 m and all other log curves displayed have been block shifted accordingly (Table 9.A).*

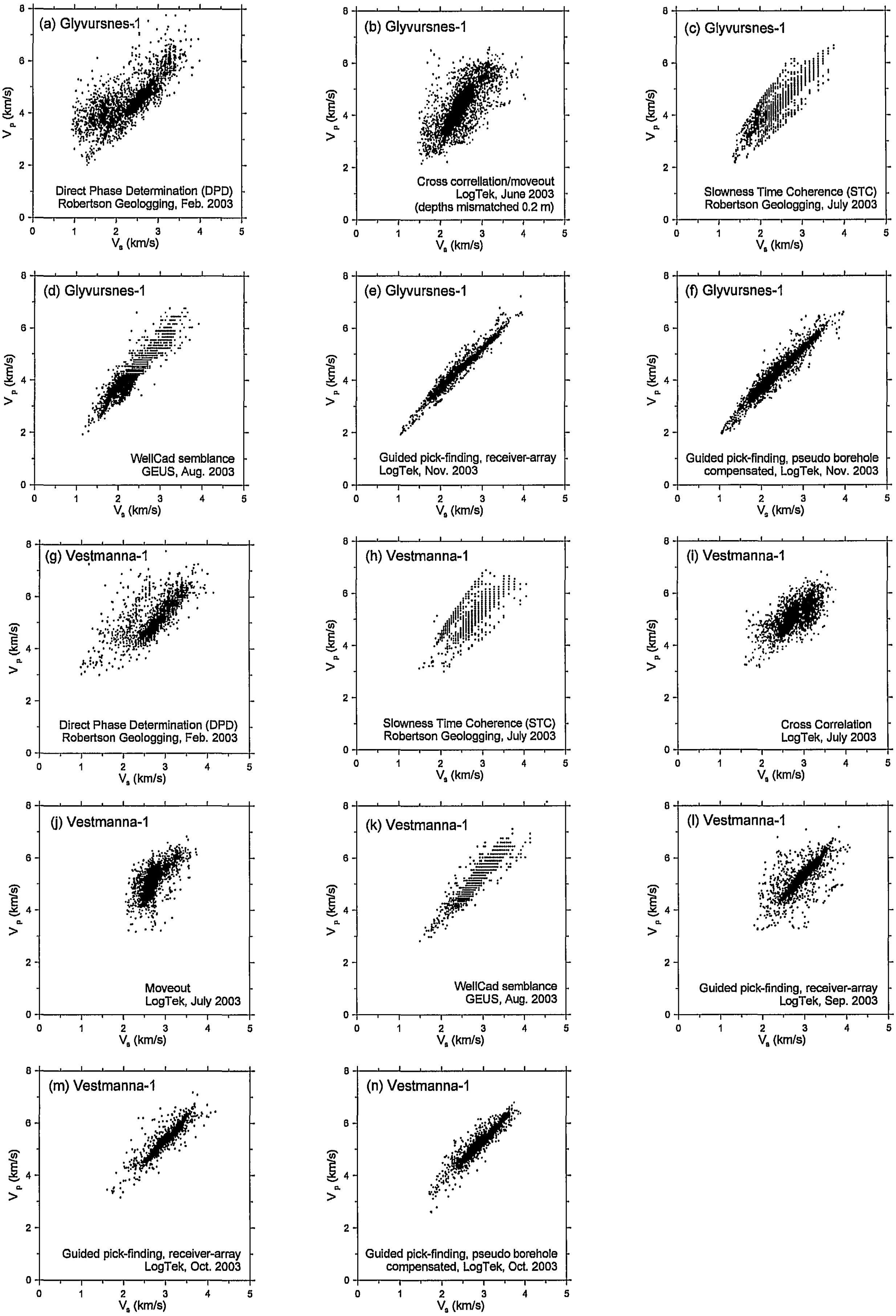


Figure 14. *Results of different processings of sonic waveforms between 7 and 698 m in Gluvursnes-1 and between 21 and 586 m in Vestmanna-1.*

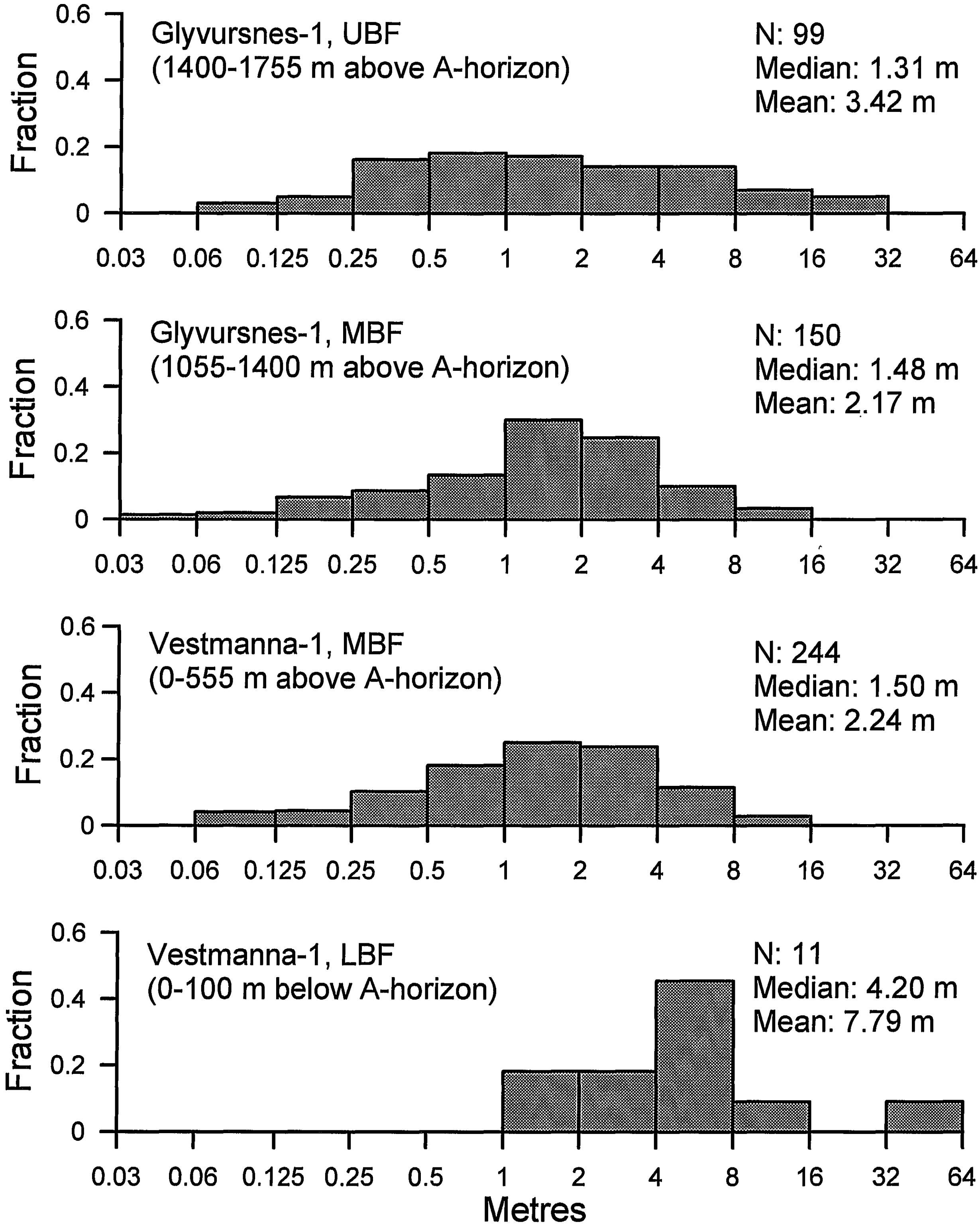


Figure 15. *Logarithmic distribution of flow-unit thicknesses in the Glyvursnes-1 and Vestmanna-1 wells. LBF, MBF and UBF are the Lower, Middle and Upper Basalt Formations, respectively. The stratigraphic intervals are shown in metres relative to the A-horizon (the coal-bearing sequence on the top of the Lower basalt Formation). The thicknesses in the old Vestmanna-1 are rounded to multiples of 0.1 m.*

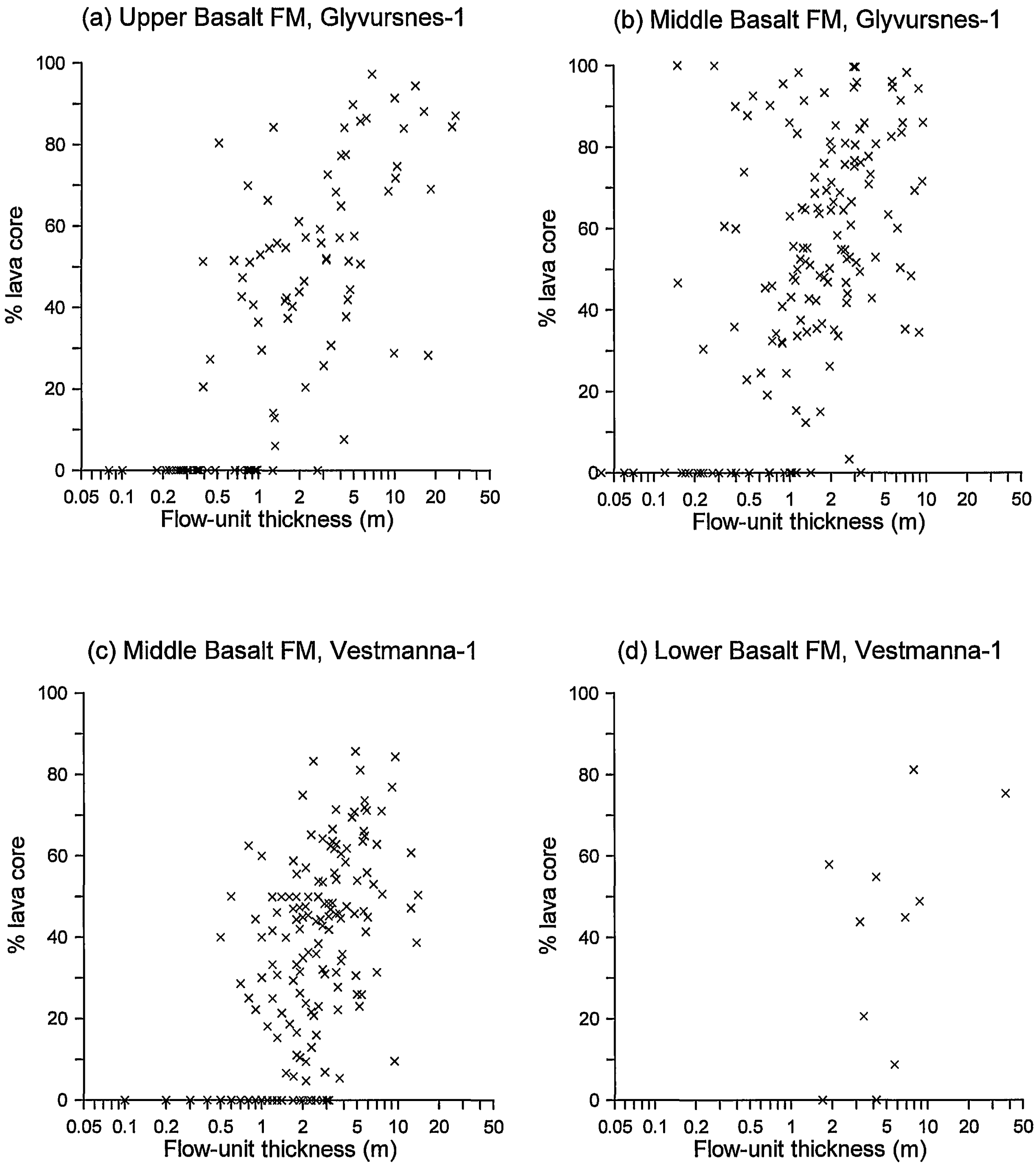


Figure 16. *Percentage of massive lava core in flow-units versus total flow-unit thickness at different stratigraphic levels in the Glyvursnes-1 and Vestmanna-1 wells.*

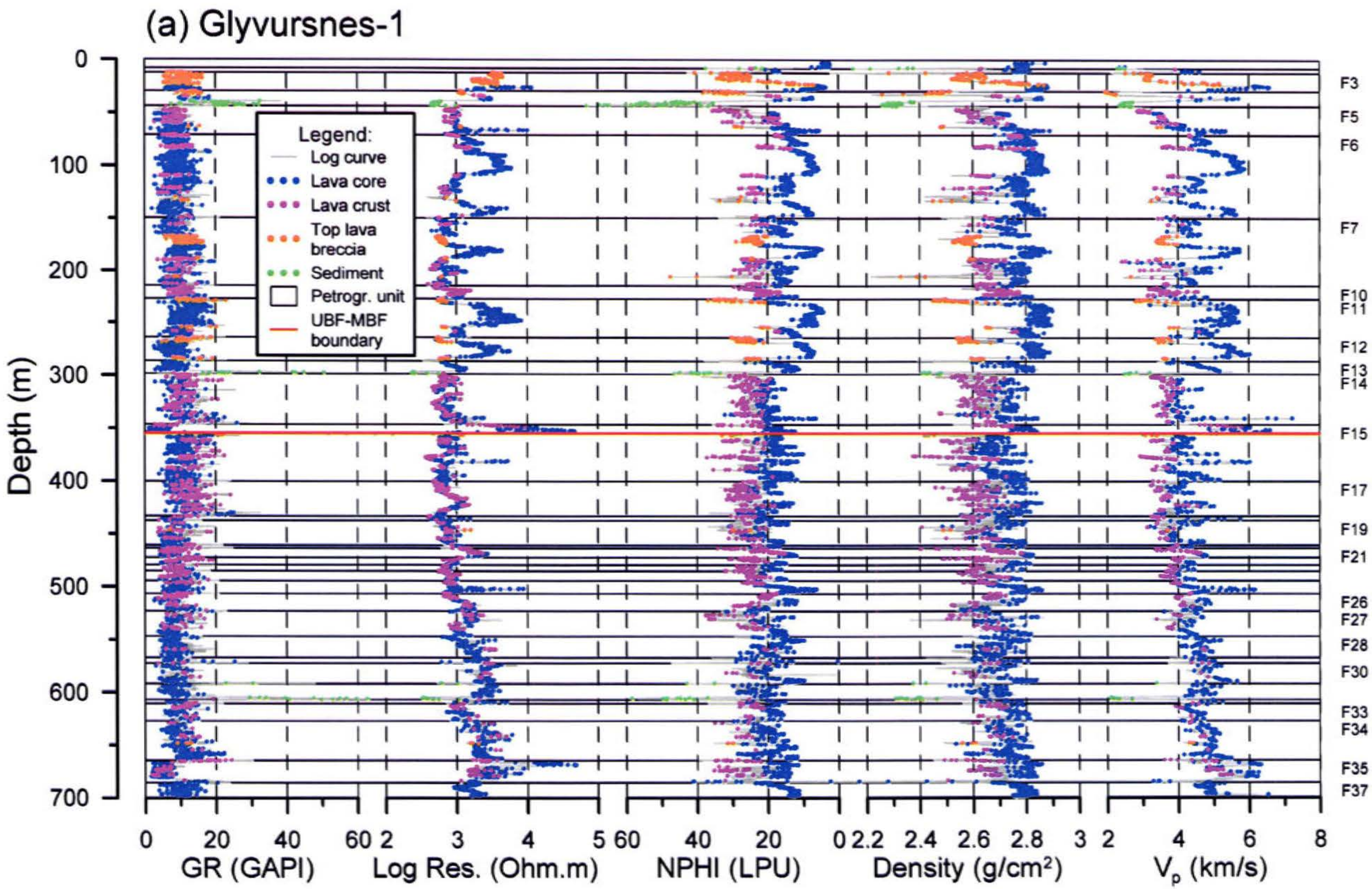


Figure 17.a. *Distribution of physical properties with lithology and depth in Glyvursnes-1.*

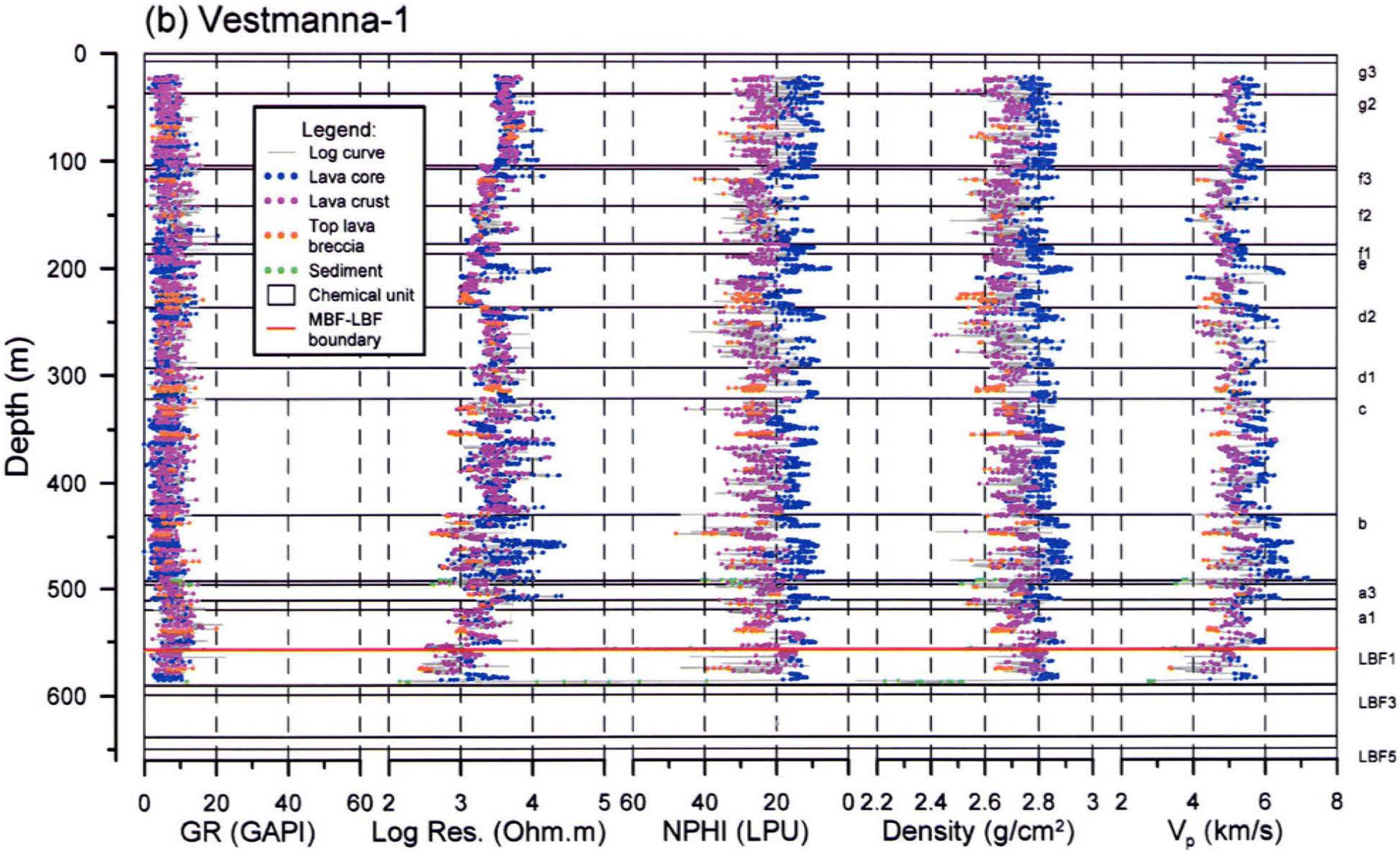


Figure 17.b. *Distribution of physical properties with lithology and depth in Vestmanna-1.*

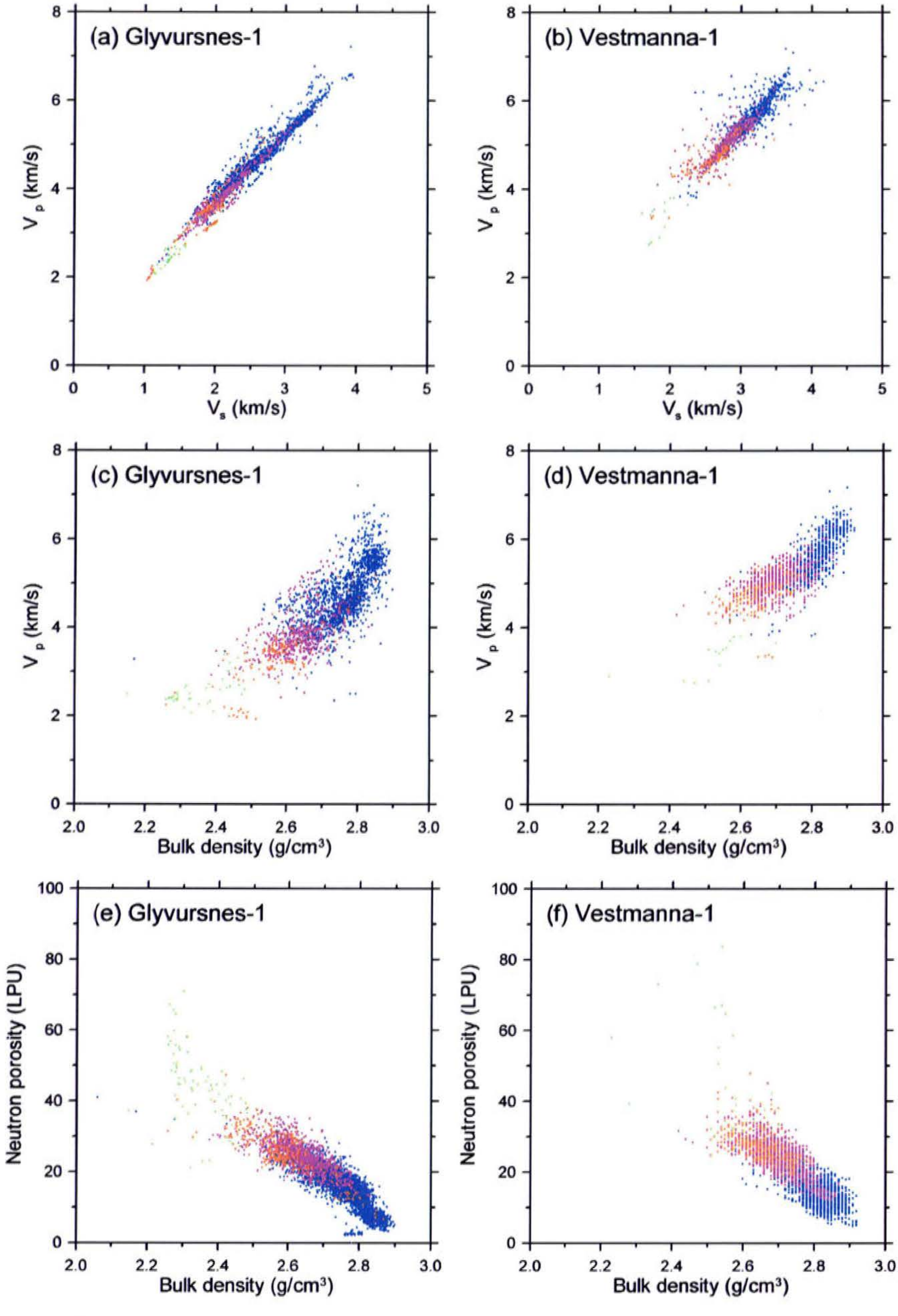


Figure 18. *Vp versus Vs, Vp versus bulk density and neutron porosity versus bulk density in Glyvursnes-1 and Vestmanna-1 groupped after lithology (see Fig. 17 for colour coding). Note that Glyvursnes logs have been resampled, i.e. interpolated (see*