DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2005/3

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Contribution to the SeiFaBa Project
Funded by the Sindri group

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2 Abstract

Wireline logs through basaltic successions in seven exploration wells and two research wells from the Faroe Shetland area have been investigated. The two research wells, the Vestmanna-01 and Glyvursnes-01, were fully cored and the wireline logs are in these wells correlated to core descriptions. Basaltic rocks are characterised by low concentrations of the most common radioactive isotopes, and basaltic successions are thus characterised by low natural gamma radiation compared to most other rock types. In the Faroe Shetland area natural gamma radiation may generally be used to distinguish between siliciclastic sediments and basaltic rock types.The basaltic successions can be divided into units of five different classes based on the overall response of neutron porosity (NPHI), bulk density (RHOB), seismic velocity (VP) and resistivity (e.g. MSFL). These classes are:

1. *Low frequency lava beds*, which are characterised by high amplitude asymmetric log response with a period exceeding 5 meters on all porosity related logs (NPHI, RHOB, VP and resistivity logs). Typical velocity range is ca. 2000-6000 m/s. Low frequency lava beds are frequently representing a single large lava flow of more than 5 meters thickness. The log responses are in these cases reflecting a vertical subdivision of the lava flow in an upper porous crust, a massive core and a thin lower porous crust. In the two cored wells a similar subdivision can be defined by visual inspections. However, significant discrepancies are seen between the subdivisions based on wireline logs and the subdivisions based on visual core inspection. Examples where a fairly complex succession defined by visual core inspection has a log response of a low frequency lava bed are present in Vestmanna-01 and Glyvursnes-01. Typical velocity range in a low frequency lava bed unit is ca. 2000-6000 m/s at ca. 1500 m depth.
2. *High frequency lava beds* are characterised by log response with a period which generally are less than 5 meters on all porosity related logs. The amplitude of deflections on log traces are generally less than in low frequency lava beds. In the two cored wells it is seen that the low porosity intervals of high frequency lava bed units may correlate to individual thin flow units. However, the correlation is not perfect. Typical velocity range in a low frequency lava bed unit is ca. 2500-5500 m/s at ca. 1500 m depth.
3. *Volcaniclastic sediments*, which are generally characterised by higher porosity than found in both classes of lava beds. In addition slightly higher natural gamma radiation is frequently observed in volcaniclastic sediment units. Typical velocity range in a low frequency lava bed unit is ca. 2000-3000 m/s at ca. 1500 m depth.
4. *Foreset breccias* (lava deltas) are characterised by porosities that generally are higher than in volcaniclastic sediments and an amplitude of deflections that are less than in lava beds. Typical velocity range in a low frequency lava bed unit is ca. 3000-4500 m/s.
5. *Basaltic intrusives*, which are characterised by a symmetric high amplitude log response on the porosity related logs and low porosity. In shaley sediments the response of natural gamma radiation is also symmetric and the intrusives are characterised by low natural gamma radiation. Typical velocities of basaltic intrusives are ca. 6000 m/s at ca. 3000 m depth.

The ranges of intrinsic values of parameters measured by the logging tools vary from well to well. This may to some extent reflect imperfect calibration of the logging tools as indicated by the large variation of the level of natural gamma radiation measured in the basaltic succession in the different wells (e.g. 3-10 GAPI in UK 154/03-01 and 22-56 GAPI in UK 205/09-01).

However, the different ranges of intrinsic values of porosity related parameters measured in the different wells appear mainly to be related to burial/depth. Preliminary linear relation between seismic velocity and burial depth and between bulk density and burial depth for basaltic successions has been estimated using data from the seven exploration wells:

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

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

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

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

Statistical values for the properties of basaltic units and a data base containing a synopsis of data related to all picked units are compiled.

3 Introduction

This report is presenting the results of log interpretations (task 3) of a research project "Petrophysical Properties of Faroes Basalts (SeiFaBa)" funded by the Sindri Program established by oil companies involved in exploration licences on the Faroese Continental Shelf and the Faroese petroleum authorities, represented by Jardfrøðisavnið. The Sindri Group is comprised by the following companies: Amerada Hess, Anadarko Faroes Company, Atlantic Petroleum, BG-group, bp-Amoco, Dong, ENI, Enterprise Oil, Føroya Kolvetni, Phillips, Petro-Canada, Statoil and Shell.

The project is contributing to the theme "Relevant technologies for imaging within basalt-covered areas" by investigating at different scales the physical properties of basaltic successions and investigating propagation of seismic waves through basaltic successions. In this report basaltic successions are investigated using wireline logs from nine wells: UK154/03-01, UK164/07-01, UK164/25-01, UK205/09-01, UK209/03-01, UK209/04-01, UK209/09-01, Glyvursnes-01 and Vestmanna-01 (one of which is deviated; UK164/25-01z) in the Faroe-Shetland Area. The wells represent different settings of basaltic volcanic and intrusive rocks and are the most comprehensive database of vertical sections through basalts off NW Europe studied until now.

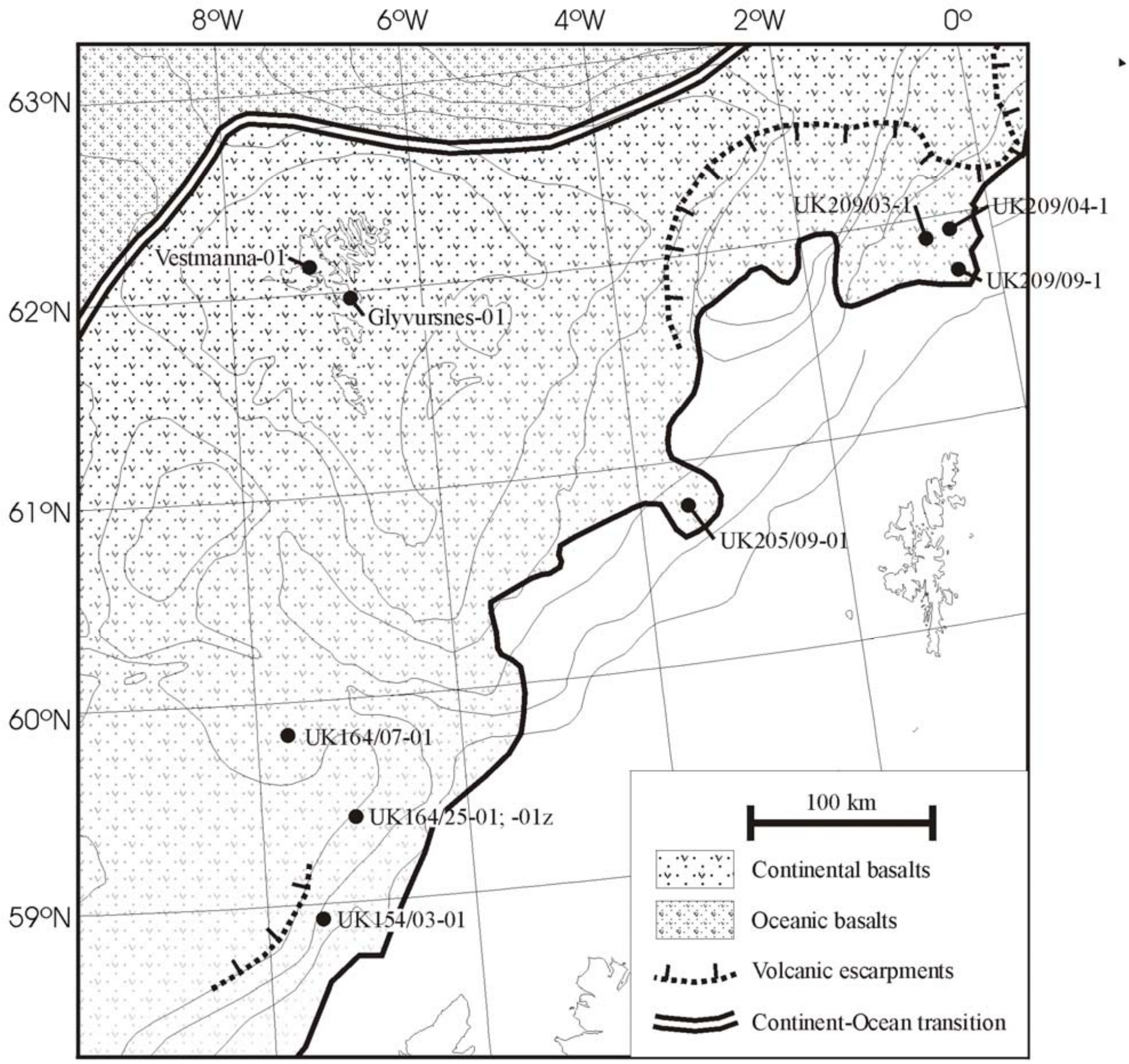

Figure 3.1. Simplified map showing the location of the nine wells presented in this report.

The wells are situated at different distances from the axis of the Early Paleocene volcanic province that was formed before and during break-up between NW-Europe (including the Faroe-Rockall Plateau) and Greenland. This is reflected in the basaltic successions found in each well (chapters 5-13). The petrophysical variation between different wells and the general characters of different classes of log units are analysed in chapter 14. The possible influence on a seismic signal of the basaltic successions found in each well is represented by estimates of stratigraphic filters (chapter15). The interpretation presented in this report relies on previous published work concerning the morphology of basalts and interpretation of wireline logs through basaltic successions. A short review of this work is presented in chapter 4.

4 Basaltic rocks, background

Basaltic lava flows have traditionally been investigated from their morphology, the way of emplacement and by geochemical studies based on surface fieldwork. However, distinguishing characteristics, which are observed during surface mapping, are difficult to observe in drill cores, because only small volumes of the rock are available for description (Keszthelyi 2002). It becomes even more difficult to recognize these characteristics on wireline logs. Resolution of the logging tools so far used in studied wells penetrating basaltic successions is typically in the range 10-150 cm, and fine details used in the description of surface rocks and cores are therefore not observed. In addition most wireline logs measure properties that not are used in description of surface rocks and cores. This means that apparent discrepancies due to the various methods can arise. Despite the discrepancies between observations of wireline logs and descriptions of surface exposures and cores of basaltic rocks analysis of wireline logs build on the vast database of morphological and geochemical descriptions based on surface field work. One important aim of the analysis of wireline logs through basaltic successions is to describe the successions in terms relevant to understand the morphologic and compositional variation of the successions.

4.1 Morphology of sub-aerially extruded basaltic lava flows

It is known from various workers that sub-aerially extruded lava flows have some characteristics in common and the following discussion focuses on those characteristics which may be expected to be confirmed by wireline logs (the following is mainly based on a review made by Boldreel 2002 based on Walker 1993; Cashman & Kauahikaua 1997; Self et al. 1997; Self et al. 1998; Thordarson & Self 1998; Waagstein 1999; Keszthelyi 2002). A basaltic lava unit formed in a single volcanic eruption is called a flow field which consists of one or several lava lobes erupted more or less continuously from the same vent area or fissure. The most diagnostic property of a flow field is likely to be the chemical composition of the basalt magma that is assumed to be fairly constant during an eruption.

A basaltic lava flow may consist of several lobes, and are then called a compound flow. The lobes are termed flow-units. Each of the flow-units is partly or completely surrounded by chilled crust. A flow-unit consists of an upper lava crust, a lava core and a basal zone. The core typical consists of massive basalt with few or no vesicles and sometimes displays flow banding. Based on the appearance of the upper crust, two morphological types, aa and pahoehoe, are distinguished. Simplified cross sections of a typical compound pahoehoe flow and a typical simple aa flow are shown in Figure 4.1.

The upper crust of pahoehoe lava flows are coherent and highly vesicular (compared to the flow core) and the surface is generally unbroken, frequently with rope-like flow folds. Pahoehoe flows are therefore also known as ropy lava. The crust typically makes up roughly half of the total thickness of a pahoehoe flow. The crust is highly vesicular near the top surface with abundant small vesicles often exceeding 50 % of the bulk rock volume. The vesicles show an overall decrease in abundance and increase in size downwards reflecting the increase in gas pressure exerted by the thickening lava crust. The vesicles are often arranged in horizontal layers with a vertical spacing of about 10 centimetres especially in the upper part of the crust. The crust of pahoehoe lavas are normally distinguished from the core by its vesicularity. In the core section horizontal vesicular veins or sheets of basalt up to about 10 centimetres in thickness may occur near the top of the core section but otherwise the core of the flow is usually massive with no or only a few relatively large vesicles. The basal vesicular zone is usually a few tens of centimetres thick at most and sometimes sub-vertical pipes are found within the basal zone.

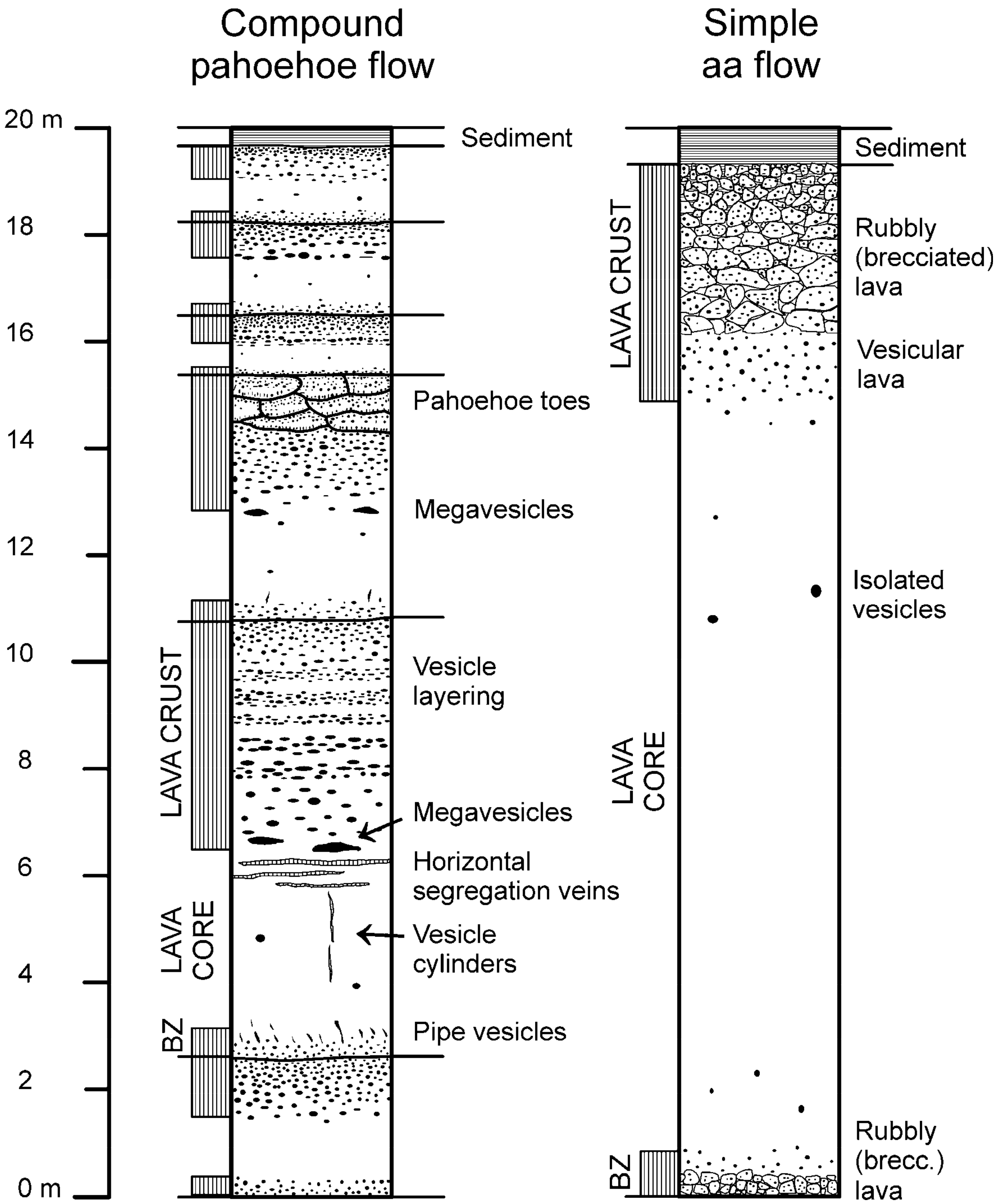

Figure 4.1. Idealized vertical sections showing characteristic differences between compound pahoehoe and simple aa lava flows. Vesicular intervals are indicated by vertical ruling, BZ = basal zone. Small features like vesicles, rubble and veins not drawn to scale. (From Waagstein & Andersen 2004)

Aa lava flows are characterised by a rubbly or brecciated surface, and the crust is composed lava fragments. In aa type lava near the surface of a flow-unit the rubble may be unconsolidated with fractures and voids filled by tuff and sometimes the rubble fragments are welded. The fragmentation decreases downward and often a complete gradation into un-brecciated basalt in the core of the flow-unit are seen. Both in pahoehoe and aa lava flows the basal zone is vesicular and usually much thinner than the upper crust. In the lower formation of the Faroes flow-units are typically from several metres to several tens of metres thick, as seen on Suðuroy (Waagstein 1999). Thick flow-units usually have a several metres thick upper rubbly crust whereas the lower crust or basal zone generally is thin (0-1 metre). The vesicles and fractures are filled with secondary minerals. On Hawaii it is found that aa lavas consist of innumerable thin flow-units (0.2-2.0 m).

Pahoehoe lavas are formed by relatively low viscosity magmas and are generally the product of hot gassy eruptions, while aa lavas are formed by more viscous magma during cooler or as the distal, cooled, part of an eruption, where the proximal part are emplaced as pahoehoe lava.

Thick cores often show a more or less columnar jointing in the lower part which propagated upwards perpendicular to the base of the flow during cooling. Thinner and less regular columns in the upper part may propagate downwards from the top of the flow. Zones of abundant vesicles zones are frequent. In a study of vesicle distribution in basalt from the Colombia River basalt plateau McMillan et al. (1987) concluded that two-stage vesiculation may produce zones rich in vesicles within the lava core. Another study was made by Walker (1989) who studied vesicle distribution based on profiles across flow-units in Hawaii primarily of pahoehoe type but also of aa type. According to the studies of Walker (1989) the vesicles distribution pattern in the core does not need be symmetrical relative to a horizontal median plane.

4.2 Chemistry and mineralogy of basaltic lava flows

The lava from a single basaltic eruption is generally homogenous on a macroscopic scale. Individual flow units of a lava field are thus expected to have the same chemical and mineralogic composition. When cores or cuttings are available from a borehole, lava fields may thus be identified by chemical analysis (e.g. Waagstein & Hald 1984).

When a magma chamber cools the size and abundance of phenocrysts will increase due to crystallisation as the magma slowly cools. At the same time the composition of the melt changes. Due to this process a basaltic magma will generally become more enriched in light elements - primarily silicium. If a magma chamber is emptied during several consecutive eruptions it is likely that the size and abundance of phenocrysts will increase from one eruption to the next. At the same time the composition of the melt will also change. If some phenocryst settles in the magma chamber, the overall composition of the magma will change.

Immediately after emplacement the composition of a lava flow is generally constant along a vertical profile. It is composed of a glass with a variable amount of phenocrysts. The phenocrysts equilibrated with the magma at the melting temperature of the magma and the pressure in the magma chamber. Especially the glass - but generally also the phenocrysts - are not stable at surface conditions and will therefore tend to (re-)crystallise. Depending on the available time and climatic conditions the chemical profile may changed due to re-crystallisation (alteration) and soil formation before the lava flow are buried. In A study from Picture Gorge Subgroup showed that the Potassium and Rubidium content increases in the upper part of the soil profile (Sheldon 2003).

4.3 Sediments intercalated with sub-aerially extruded basaltic lava flows

Frequently thin sedimentary horizons are seen between individual basaltic lava flows. Sediments may be of local origin and consist exclusively of basaltic material of the same composition as the underlying basalt flows, volcaniclastic sediments. However, frequently interflow sediments contain material of non-basaltic composition originating from an external source. In addition soil formation may alter the composition of interflow sediments. It is therefore common that interflow sediments have a composition deviation slightly from the underlying and overlying lava flows.

4.4 Products of sub-aqueous basaltic extrusions

When basaltic lava is extruded in water, the volcanic products are different from those formed during sub-aerial extrusions.

At sufficiently great water depth the confining pressure will be so high that gas stay in solution in the magma. The threshold depth for vesicle formation is typically a few hundred meters. Water has a large heat capacity compared to air, and the crust of sub-aquatic lava flows are therefore cooling fast becoming stiff and inflexible, and lava escapes through tears in the crust forming characteristic sausage or pillow like bodies with a diameter from a few tens of centimetres to about one meter. Pillows are characterised by a rim of a few centimetre wide, rapidly cooled glass rim and a fine grained crystallised core with non or few vesicles. Radial fractures are common, and the pillows brakes easily forming pillow breccias. Pillow basalts and pillow breccias are characteristic of deep water sub-aquatic basaltic eruptions.

Water boil/vaporise when in contact with a hot magma and thus bind large amount of heat. The boiling temperature of water and specific density of water vapour increases considerably with pressure (depth). At sufficiently low pressures basaltic magma cools sufficiently fast that thermal stresses in the basalt causes it brecciate completely, and the expanding water vapour causes the smallest pieces to be carried into the atmosphere and transported far with the wind. Wide spread tuffaceous deposits (e.g. the tuff of the Balder Formation; Andersen et al. 2000) are formed in this way. Although tuffs are petrographically different from volcaniclastic sediments formed by breaking down sub-aerial basaltic rocks, the two rock types have many properties in common, and they can only be distinguished by detailed petrographic analysis.

4.5 Basaltic foreset breccias

The formation of a foreset bedded hyaloclastite breccia by basaltic lava flowing into the sea was observed during the 1969-71 Mauna Ulu eruption of the Kilauea volcano, Hawaii (Moore et al., 1973). Underwater observations of lava streams revealed the presence of a submarine “delta” comprising foresets layers dipping at approximately 35º. The dipping layers of the volcanic “delta” are mostly made up by hyaloclastic volcanic fragments and volcaniclastic sand. Above the shoreline the topsets of the volcanic “delta” are sub-aerial pahoehoe lava beds. Well-exposed equivalents of the Mauna Ulu hyaloclastite has been described from volcanic provinces in Antarctica (Nelson, 1966), Iceland (Jones, 1966) and West Greenland (Pedersen 1985; Pedersen & Dueholm, 1992; Pedersen et al., 1996). The exposed basaltic foreset breccias in Antarctica, Greenland and Iceland are all characterised by a mixed lithology dominated by basaltic breccias with irregular bodies of pillow lava, lava beds, finer hyaloclastic material and discontinuous layers of shaley sediments (Jones & Nelson 1970; Pedersen 1985). Regional reflection seismic mapping in the Faroe-Shetland Area and west of the Hebrides has revealed a number of buried bodies believed to be basaltic foreset breccias (e.g. Smythe et al. 1983; Gatliff et al. 1984; Andersen 1986; Boldreel & Andersen 1994; Musgrove & Mitchener 1996; Egerton 1998).

4.6 Wireline logging through basaltic successions

The geophysical response of interbedded sediment/tuff and basalt may be examined from wireline logging data and drilling penetration rate. Most published studies are based only of wireline logs. In some studies the logs are supplemented by visual descriptions of sidewall cores and cuttings.

Seldom the wells have been both logged and cored through the basaltic succession. Recently micro formation scanning data (and other imaging tools) showing very detailed images of the formation in the well has become available as part of the logging suite. Image logs may to some extent replace/supplement visual description of the core in basaltic successions. The combination of logging and coring of thick successions of basalts is only available in a few international scientific programs like i.e. Deep Sea Drilling Program (DSDP), its successor the Ocean Drilling Program (ODP) and the International Continental Drilling Program (ICDP). An early example of a cored and logged research well through basaltic successions is the Vestmanna-01 well on the Faroe Islands (cored with a recovery rate exceeding 99.9 %; Waagstein & Hald 1984; Nielsen et al. 1984). A complete new log suite was acquired in this borehole in 2002 (Waagstein & Andersen 2004) and constitutes part of the data used for this study.

Wireline based studies of sub-aerially extruded basalt and interbedded sediment/tuff layers from various places – both onshore and offshore – around the world have been published by a number of authors as exemplified by the following list.

- In the Faroe-Shetland and Atlantic Area (Boldreel 2002, Lopra-1 well; Planke et al. 1999, ODP Hole 990 southeast Greenland margin; Ritchie et al. 1999, UK 209/5-1; Cambray 1998, ODP Hole 917A southeast Greenland margin; Planke & Flóvenz 1996, ODP Hole 642 at the Vøring Planke 1994, ODP Hole 642E at the Vøring Plateau; Nielsen et al. 1984, Lopra-1 and Vestmanna-1 well)
- North Sea basalt flows from the Middle Jurassic (Rider 1996)
- Pacific region (Delieus et al., 2003, ODP Hole 1137 & 1140 at Kerguelen Plateau; Buysch et al.2003, Hawaii
- USA : Western part of USA Helm-Clark et al. 2004; Goldberg et al. 1994 Newark Basin; Broglia & Moos 1988 Bermuda Rise
- Deccan Trap; Singh 1996; Buckley & Oliver 1990
- Botswana Cheney 1981 the Jurassic Stormberg basalt;
- Japan and Chile Berliez et al. 1988;
- China: Jinglan et al. 1999
- A geothermal well with no cited geographical location (Sanyal et al. 1980).

Wireline logs through products of deep water sub-aqueous basaltic eruptions are studied in a few holes.

- Bartetzko et al. 2001, DSDP/ODP Hole 395A mid-Atlantic Ridge
- Bartetzko et al. 2002, DSDP/ODP Holes 504B and 896 at the Costa Rica Rift);

Studies of wireline logs through products of shallow water sub-aqueous basaltic eruptions and basaltic foreset breccias are not published. However, the Lópra-1A well on Suðuroy, Faroe Islands, penetrated a succession of dominantly volcaniclastic/hyaloclastic rocks in the depth interval (ca. 2490 -3520 m).

Based on the above mentioned studies the following is considered of special interest in relation to the present study.

According to all studies, which include a siliciclastic succession, basaltic lava flows and intrusions are generally characterised by rather low natural gamma radiation compared to the radiation level from typical siliciclastic sediment successions.

Analysing natural gamma radiation through thick vertical sections of basalt flows it was pointed out by Nielsen et al. (1984) that different formations could be distinguished based primarily on the general level of the natural gamma ray log. Using spectral gamma data it has been demonstrated that “high-gamma” basalts exist in wells from the Deccan Basalts, India, and may be used as stratigraphic markers (Buckley & Oliver 1990). Frequently sediment interbedding the basaltic flow-units shows are characterised by very high gamma counts (up to 10 times higher than the basaltic flow-units) and very low resistivity (e.g. Nielsen et al. 1984; Singh 1996).

The log response of a sub-aerially erupted lava flow is apparently reflecting the flow morphology. Based on the variation of all porosity related log traces (neutron porosity, bulk density, sonic velocities, and resistivity; Figure 4.2), it is composed of a rather porous crust, a massive core and a rather thin porous basal zone (e.g. Planke 1994; Boldreel 2002). Planke (1994) proposed that within each lava flow the upper crust is characterised by gradual downward decrease of apparent porosity. According to this model the overall porosity gradient in the upper crust is constant, and minimum porosity is only attained at a depth of ca. 6 m below the top of the flow. A division into four zones (Figure 4.2), where the upper crust is divided into a brecciated zone and an zone transitional to the core have been proposed based on a combined study consisting of geophysical, petrological and geochemical analysis has been proposed (Delius et al. 1995; Planke et al. 1999). The basal zone is characterised by gradients in values from the wireline logs representing porosity. Here P-wave velocity, density and resistivity decrease rapidly whereas porosity increases near the base of the unit (Planke & Flóvenz, 1996; Planke 1994; Goldberg et al. 1994).

Neutron porosities in massive basalts are as much as much as 10 LPU’s higher than the true porosity, suggesting that mafic igneous rocks are stronger neutron absorbers/scatteres than carbonates and siliciclastic sedimentary rocks (Broglia & Moos 1988). This is partly due to a high content of hydrous alteration minerals. Algorithms have been developed to estimate true porosity of basaltic rocks from scattering of neutrons (Broglia & Ellis 1990).

Although, subdivisions equivalent to those mentioned above have been observed in the log response from basaltic lava flows in the wells investigated during this project this study, comparisons between core descriptions from Vestmanna-01 and Glyvursnes-01 wells (Waagstein & Hald 1984; Waagstein & Andersen 2004) and log responses from the same wells suggest that subdivisions of lava flows based on log analysis may not be equivalent to the sub-divisions used in morphological descriptions of basaltic lava flows (e.g. Self et al. 1998).

4.6.1 Interpretation strategy.

It is assumed that the principles and observations regarding the interpretation of wireline logs through volcanic basalt successions and basaltic intrusives mentioned in the previous section can be applied to the interpretation of the wireline logs in this study.

The physical properties of a basalt flow measured during logging are thus primarily related to processes active during the eruption (i.e. whether a lava is of pahoehoe or aa flow type; whether it was growing through inflation or retained a constant thickness; cooling and fracturing story and secondarily to alteration processes. To the extent lava flows are thick enough they are expected to be recognised on a generalised asymmetrical cyclic log response (Figure 4.2). However, frequently lava flows are so thin that individual lava flows not are recognised based on the log response.

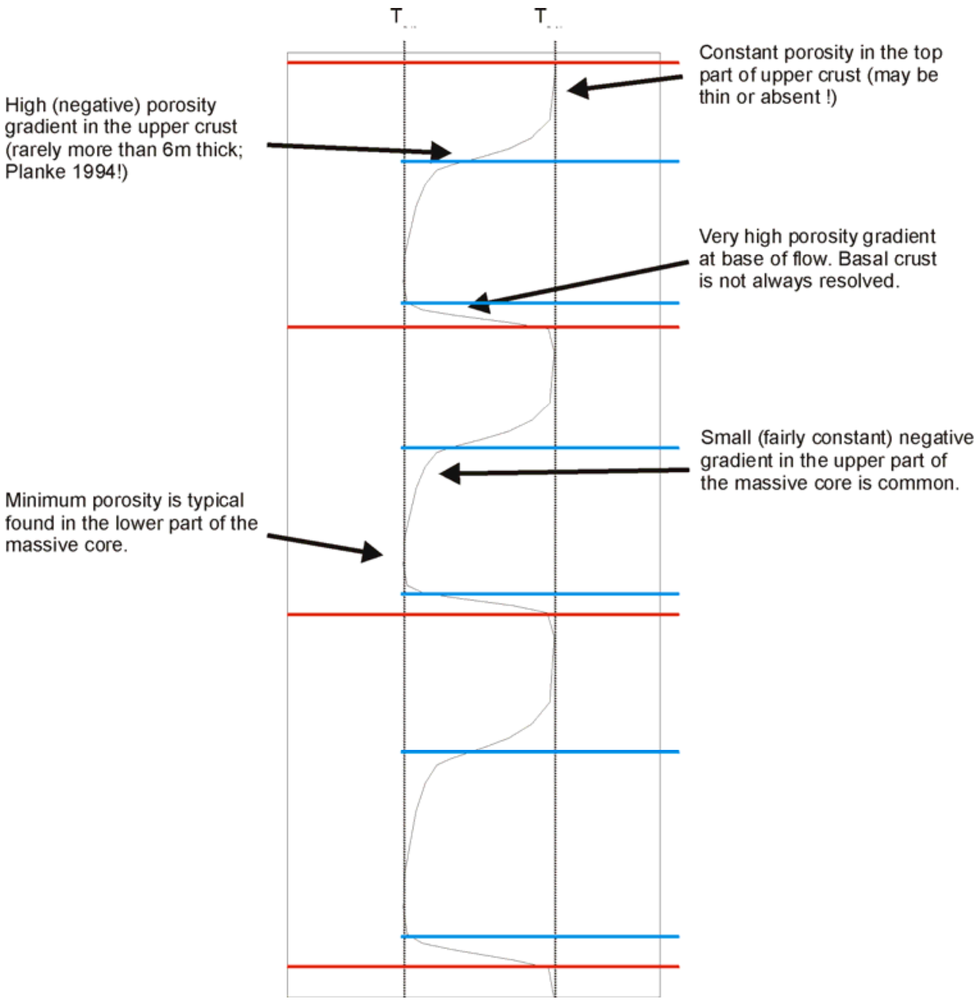

Figure 4.2. Schematic log trace (porosity) through three basaltic lava flows. Note the asymetric log response. Other porosity related log traces show the same asymmetry but may have opposite polarity.

The natural gamma radiation from basaltic rocks is low compared to most siliciclastic sediments. In a general way this reflects a low content of incompatible elements in basaltic rocks. Measurements of gamma radiation are thus suited to recognise possible basaltic successions in wells. In addition the magnitude of natural gamma radiation may indicate the relative content of incompatible elements in basaltic rocks and may thus in some instances as a stratigraphic tool (Buckley & Oliver 1990; Waagstein & Andersen 2004). Natural gamma radiation logs may also reflect alteration processes in which potassium (or possibly thorium uranium) is mobilised. During soil formation in basalts potassium will be concentrated close to the surface. A characteristic decrease of the natural gamma radiation from the top of a lava flow and downwards is thus considered the likely result of alteration in the time before eruption of the following flow.

In order to enhance the stratigraphic interpretation of lava flows it was found by Boldreel 2002, that scale shifting of the two tracks; RHOB combined with NPHI and V_P combined with Vs is very useful (see enclosures). The principle behind this approach is that first a massive core is identified. Assuming that this is the most massive part of the lava flow the curves are shifted so that they have a pseudo origin at the core. The scale of the V_P and V_S logs are just shifted some that units are maintained. The RHOB and NPHI logs are measured on a Limestone basis and thus measures LPU (Limestone Porosity Units). In the track where the RHOB and NPHI are plotted together the scale division is maintained. Using this scale shift also reveal that the RHOB/NPHI ratio varies for individual flows and also from different wells which could indicate that differences exits between the units found in different wells.

Sills intrude into the geological column and are not exposed to cooling in the same manner as lava flows as it cools in contact with the surroundings. A sill consists of a contact zone towards the surroundings and a massive core. The physical proportion of a sill is that the contact zone is usually much thinner than the massive core. Thus it is anticipated and shown by previous work that the shape of the wireline logs representing the physical properties of a sill is symmetric seen in cross-section. The physical properties should be expected to be similar to a massive core of a basalt flow or even more "massive". However as discussed later in the report, the transition towards the sidewalls of the intrusion sometimes makes it difficult to place a sharp limit between the intrusion and the surroundings. This becomes a problem when intrusions are plotted in cross plot relation.

4.6.2 Unit classes

Based on the log response basaltic rocks may be divided into six classes described below. During this study we have picked more than 500 units in 9 wells - one being side tracked (Figure 4.3). Sub-division of many units are possible. During the original picking most low frequency lava beds (see below) were divided into an upper crust and a core. A lower crust was also picked in many low frequency lava beds. However, based on comparison between core descriptions from Vestmanna-01 and Glyvursnes-01 (Waagstein & Hald 1984; Waagstein & Andersen 2004) and interpretation of wireline logs from the same wells, it is considered likely that sub-divisions of lava beds based on the log pattern not always reflect the actual flow morphology.

4.6.2.1 Low frequency lava beds

Units of this class are on all porosity related log traces characterised by a distinct asymmetrical cyclic log response typical for thick lava flows (e.g. Planke 1994; Delius et. al. 1995). Low frequency lava beds are characterised by long periodic oscilations (typically 5-20 m) of all porosity related log traces. It should be noted that the range of measured parameters varies considerably from well to well. For seismic velocity this is demonstrated by Table 4.1. Examples of low frequency lava bed units is described in chapters 0-13. Low frequency lava beds may generally represent thick simple lava flows. However, this is not always the case (see chapter 13).

Table 4.1. Seismic velocity in low frequency lava beds from 9 wells in the Faroe-Shetland Area. Column headings: N is total number of samples; N* is samples not rejected due to excessive caving; Mean, Median and Std. are aritmetric average, median and standard deviation around average (in m/s).

Well	N	N*	Mean	Median	Std.	Minimum	Maximum
UK154/03-01	550	550	4642.3	4896.4	824.9	2921.8	5690.2
UK164/25-01z	165	165	5069.6	5255.0	652.5	2999.8	5734.1
UK205/09-01	435	416	5092.4	5253.0	610.0	3636.9	5979.9
UK209/03-01	310	252	4723.4	4848.2	755.8	2880.3	5782.7
UK209/04-01	756	694	4915.8	5035.4	843.6	3260.6	6213.1
UK209/09-01	770	729	4240.4	4417.3	879.9	2493.6	5548.4
UK164/07-01	2854	1415	5078.1	5203.8	529.2	3771.9	5728.2
Glyvursnes-01	2483	2420	4470.7	4511.3	638.2	3287.7	5468.8
Vestmanna-01	1649	1649	5383.8	5429.9	425.9	4579.9	6057.6

4.6.2.2 High frequency lava bed units

On all porosity related log traces units of this class are seen as two or more cycles of shorter period (below 5 m). See chapters 0-13 descriptions of low frequency lava bed units. The asymmetrical response typical for low frequency lava beds may be recognised for some of the thicker cycles in a high frequency lava bed unit. High frequency lava bed units are supposed to represent succession of lava flows thinner than 5 m. However, it should not be assumed that high frequency lava bed unit generally represent a compound lava flow. Overall high frequency lava bed units are characterised by lower seismic velocities and a narrower velocity range than low frequency lava bed units (compare Table 4.1 and Table 4.2). Other porosity related parameters vary accordingly.

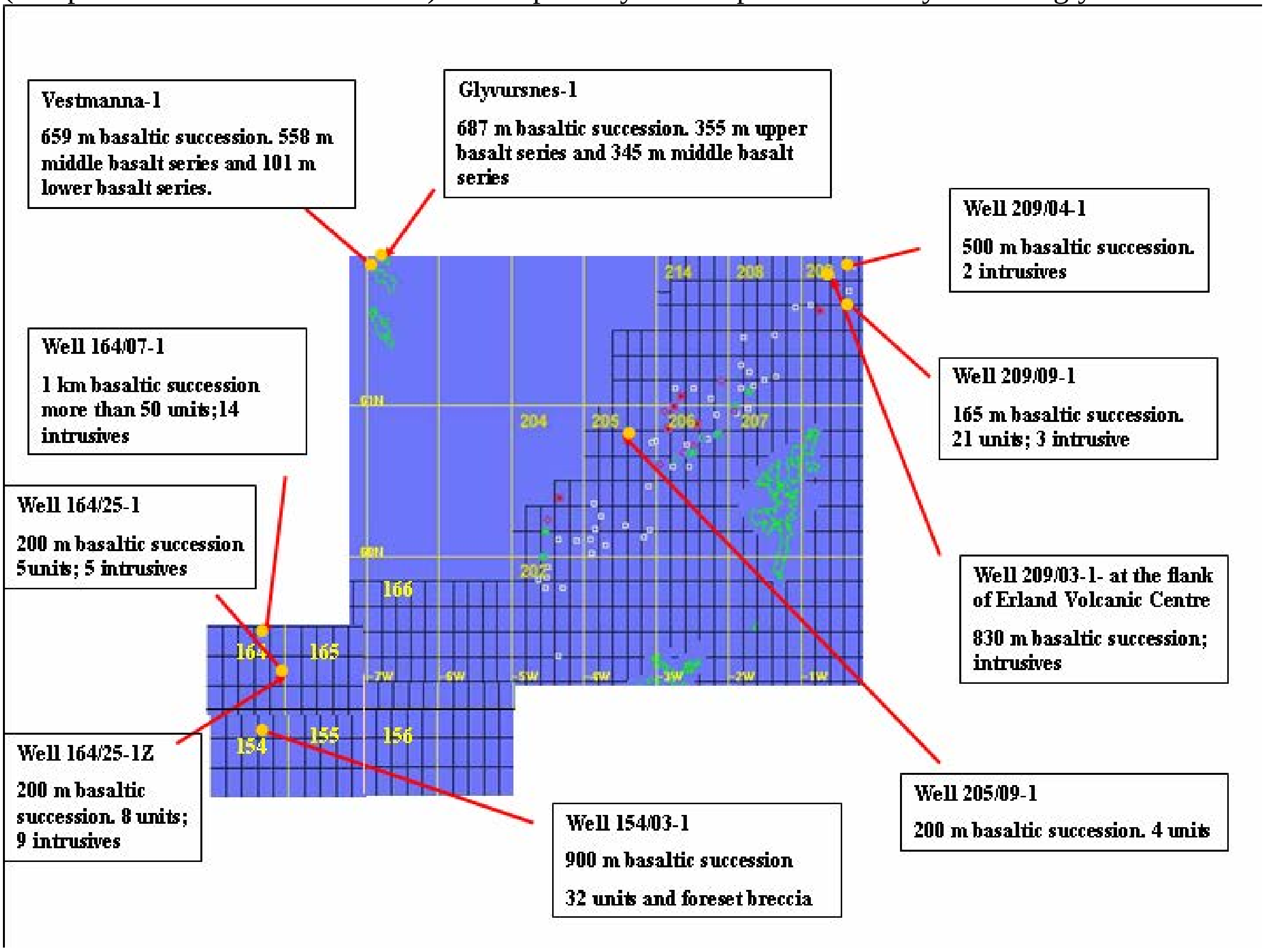

Figure 4.3. Simplified map showing the locations of the nine wells presented in the report.

Table 4.2. Seismic velocity in high frequency lava beds from 8 wells in the Faroe-Shetland Area. See Table 4.1 for column headings.

Well	N	N*	Mean	Median	Std.	Minimum	Maximum
UK154/03-01	1368	1368	3875.2	3878.3	799.4	2265.3	5442.4
UK164/25-01z	252	252	3345.8	3269.6	696.8	2306.9	4785.8
UK209/03-01	4745	4436	3727.3	3675.8	558.7	2600.6	5429.4
UK209/04-01	257	199	4456.8	4421.4	694.4	3080.3	6144.7
UK209/09-01	274	258	3092.8	3065.2	373.3	2468.8	3902.7
UK164/07-01	1336	606	4573.0	4553.7	492.9	3665.5	5428.4
Glyvursnes-01	4369	4369	4160.9	4140.4	432.2	3228.1	5218.6
Vestmanna-01	4060	4060	5156.0	5142.4	370.8	4362.2	5909.9

4.6.2.3 Intrusives

Basaltic intrusives are generally characterised by a fairly symmetric log response on all log traces. The porosity is low and this is reflected in all porosity related logs (e.g. Table 4.3). Both the “top” and the “base” of intrusives are sharp. When intruded into sediments they are seen as sharp deflections. Overall, the seismic velocities of intrusives are as high or (usually) sligthly higher (Table 4.3). Examples of log response of intrusives may be found in chapters 0-13.

Table 4.3. Seismic velocity in basaltic intrusives from 5 wells in the Faroe-Shetland Area. See Table 4.1 for column headings.

Well	N	N*	Mean	Median	Std.	Minimum	Maximum
UK164/25-01z	2963	2680	5572.8	5671.5	427.6	4111.7	6158.8
UK209/03-01	230	227	4408.9	4456.8	555.1	3476.3	5188.5
UK209/04-01	151	129	6229.3	6288.8	758.0	4673.5	7470.9
UK209/09-01	174	101	5503.3	5562.6	529.6	4185.7	6489.3
UK164/07-01	3177	3115	5604.0	5640.5	231.8	5042.3	5914.2

4.6.2.4 Volcaniclastic sediments

Volcaniclastic sediments are characterised by porosity, density, and seismic velocities comparable to siliciclastic sediments. Natural gamma radiation from basaltic volcaniclastic sediments are usually of the same magnitude as that from basaltic lava beds, and may thus be recognised based on the gamma radiation combined with the setting in an volcanic environment. A single basaltic volcaniclastic bed will easily be un-noticed by the analyst unless descriptions of cuttings indicate the bed is of basaltic origin. Descriptions of units of basaltic volcaniclastic sediments is found in chapters 5-13.

Lava breccias

In UK164/25-01 and UK164/25-01z a few beds with a natural gamma radiation slightly higher than basaltic volcaniclastic sediments lava beds and in these wells and a log response, which otherwise in between that of typical basaltic volcaniclastic sediments and high frequency lava bed units (chapter 7). It is suggested that these units represents dense volcaniclastic sediments or basaltic lava breccias.

4.6.2.5 Foreset breccias

In UK154/03-01 penetrates a basaltic foreset breccia (Mushgrove & Michener 1996). The foreset breccia is approximately 500 m thick (including a few intercalations which is assumed to represent shaley siliciclstic sedimets). The porosity related measurements are comparable to those of high frequency lava beds. However, fluctuations are considerably smaller (compare table Table 4.2 and Table 4.4). Examples of foreset breccias are described in chapter 0).

Table 4.4. Seismic velocity in high basaltic foreset brecias from UK154/03-01. See Table 4.1 for column headings.

Well	N	N*	Mean	Median	Std.dev.	Minimum	Maximum
UK154/03-01	2914	2708	3719.1	3710.7	301.8	3010.2	5092.5

4.7 Description of basaltic units

Each of the nine wells interpreted as part of this study is presented in the chapters 0-13, and representative units are described. These chapters can be read independently of each other. However, relevant discussions of any specific phenomenon are generally only treated in the chapter about the well that best illustrates this phenomenon. In addition, phenomenons of general importance are treated in the discussion (chapter 16). Log panels illustrating interpretations of the nine wells are found as enclosures 1-5 to this report. In addition documentation concerning all picked units has been extracted and is found in a hierarchic data base Synopsis\SeiFaBa-Task3-data-documentation.html, containing a synopsis of data related to all picked units. The database provides easy access to plots and statistical information concerning all units.

5 Well UK154/03-01

The well UK154/03-01 (58º55’54.12”N 07º33’53.65”W) was drilled in 1991. Total depth of the well was 2459 m with Lewisian Gneiss in the bottom of the well. The well penetrated a 900 m thick succession dominated by volcanic basaltic rocks (1184-2096 m). The main target was top bed sets in prograding sequences, which constitute the lower part of the volcanic succession in the well. The upper part of the volcanic succession (1184-1640 m) was penetrated by the 17.5” hole, the lower part by the 12.25” hole. The calliper was only run below 1620 m, and caving is generally a minor problem in this part of the well. Borehole conditions (caving) in the 17.5” hole is not known.

The suite of log measurements in 17.5” hole of UK154/03-01 (down to ca. 1575 m) comprises

- natural gamma radiation, GR,
- sonic transit time (P-wave), DT,
- resistivity measured with a dual laterolog tool, RD and RS

The log suite between 1575-1622 m comprises the natural gamma radiation, GR.

The log suite below 1620.2 m in the 12.25” hole including a short section of the 17.5” hole below the 13.375” casing comprises

- calliper, CAL,
- natural gamma radiation, GR,
- sonic transit time (P-wave), DT,
- density, RHOB,
- neutron porosity, NPHI,
- resistivity measured with a dual laterolog tool, RD and RS
- photo electric effect, PEF.

Sonic transit time is recalculated to sonic velocities and presented as the trace, VP. The relevant log traces from the depth interval of interest are presented as enclosure 1.

Geological descriptions in the completion report and side wall cores from the basaltic volcanic succession help constraining the log-interpretation.

5.1 Unit descriptions

Within this study 32 individual basaltic units have been interpreted in UK154/03-01. This excludes a few units presumably dominated by volcaniclastic material (altered volcanic tuff according to the completion report). The 32 units can be classified into three types according to the log response. All three types are characterised by low gamma radiation (GR≈10 GAPI), however, with some fluctuations, which will be discussed later in this chapter. The general characteristics and geological interpretation of the three types of units are:

1. Units composed by one thick high velocity and high resistivity layer generally with a distinct lower boundary zone characterised by a very high negative velocity gradient. The lower boundary is less distinct on the resistivity logs. A small positive velocity gradient is observed in the upper part of these units. In some units the top is defined as the top of the zone of large positive gradient. However, in most units, a top zone of lower velocity is seen above the zone of high gradient. The core of these units are characterised by a gradually decreasing gradient possibly with a few thin excursions to lower velocities. The maximum velocity is found in the lower part of the flow, frequently just above the lower boundary zone. Each of these units is interpreted as representing one eruptive event, building a

possibly inflated lava bed. Inflation is indicated by the thin low velocity zones within the core, which best can be understood, if they are assumed to represent porous zones, which would occur in case of intermittent inflation. The terms “thick lava bed” and “low frequency lava bed” are used to reference to this type of units. In figures and tables they are referenced by a type-identification, “basalt.lavabed.LF”.

2. Units composed by several thin (1-4m) high velocity and high resistivity layers separated by low velocity and low resistivity layers. These units are interpreted as a succession of thin lava beds, which either lies directly on top of each other or are separated by thin layers of volcaniclastic material. In general the thin layers of volcaniclastic material within these units can not be identified on the logs. However, descriptions of cuttings and sidewall cores indicate they are present. The terms “high frequency lava bed composite” or just “high frequency lava beds” are used to reference to this type of units. In figures and tables they are referenced by a type-identification, “basalt.lavabed.HF”.
3. One nearly 500 m thick unit characterised by moderately high velocities. Measured resistivities in this unit are generally lower than in the two upper units. A few distinct lava beds are intercalated in this unit. Based on the gamma radiation, which is comparable to that of the lava beds with a few oscillations to higher values and the description of cuttings and sidewall cores, this unit is considered to be volcaniclastic in origin. However, the density is unusually high compared to volcaniclastic rocks in other wells. Based on a description of seismic data through the well found in the completion log, it is considered that this unit represents a basaltic foreset breccia (a lava delta). The terms “lava breccia”, “hyaloclastite” and “foreset breccia” are used to reference to this unit. In figures and tables it is referenced by a type-identification, “basalt.lavabed.LB”.

Below a few examples are presented of each of the three type mentioned above.

5.1.1 Low frequency lava beds

15431-F4 (Figure 5.1): In this unit only calliper, CAL, seismic velocity, VP, and resistivities, RS and RD, are available for interpretation. The gamma radiation is low (<10 GAPI) throughout the unit. The uppermost 3-4 m are characterised by increasing velocity, and the core of the lava bed is only about 3 m thick. A small velocity decrease within the core between 1207 and 1208 m are associated with a resistivity (RD) decrease, and may thus represent a more porous zone within an otherwise massive core. The resistivity spike just below the top is a typical feature seen in this well. It is not a typical bed distortion effect of the resistivity measurements, as we would have expected maximum distortion in the lower part of the bed just above the boundary. However, compared to the velocity log, it is unlikely that the high resistivity spike is directly related to the porosity, which we assume to be well correlated with the seismic velocity. It is thus possible that the high resistivity spike is the effect of a partly unsuccessful attempt to eliminate bed effects during recording. However, we have not found details concerning the processing in the log and completion reports.

15431-F24 (Figure 5.2): This10 m thick unit is a fairly ideal example of the low frequency lava beds comparable to basaltic lava beds described from ODP wells in the Northeast Atlantic (Planke 1994; Delius et al. 1995). In a ca. 3 m thick upper zone, the seismic velocity increases almost monotonously from about 2000 ms^{-1} to ca. 6000 ms^{-1}. A slight velocity decrease around 1502 m indicates that the porosity decrease not is perfectly monotonous. The velocity in the core is ca. 6000 ms^{-1}, close to the maximum velocity observed in the basalts in this well. The zone of negative velocity gradient at the bottom is ca. 1 m thick, which is fairly typical.

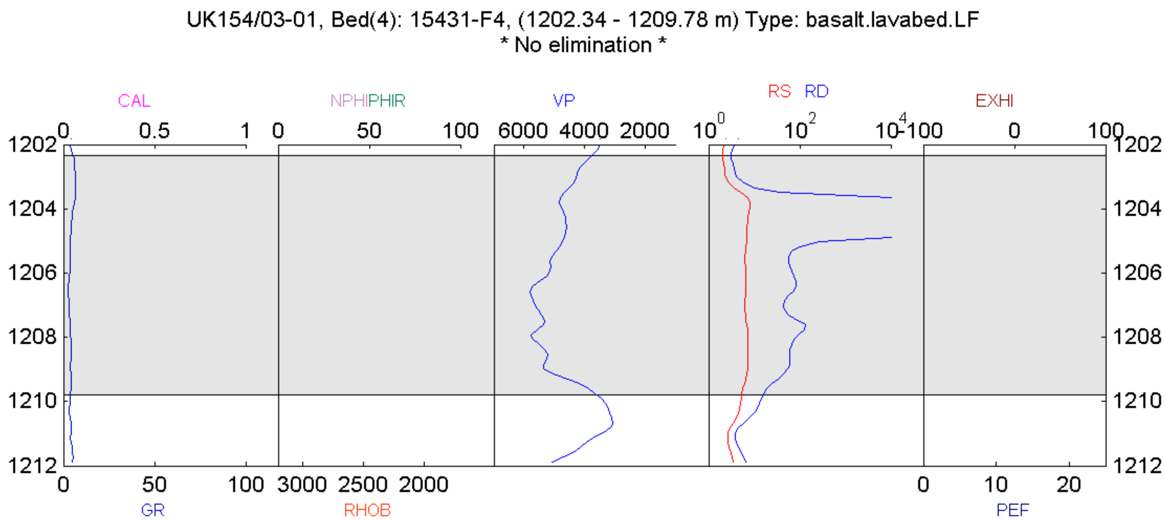

Figure 5.1. Log traces from depth interval 1202-1212 m in well UK154/03-01. Headers and footers of each panel indicate all traces available at any depth in the well. However, CAL, RHOB, NPHI and PEF is not recorded at this depth. PHIR and EXHI traces are derived from RHOB and NPHI.

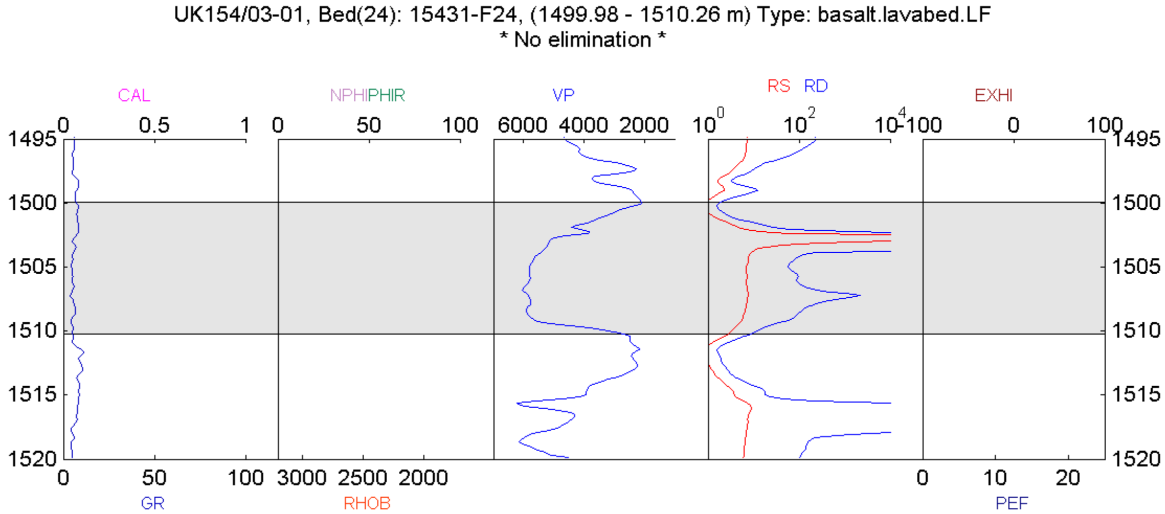

Figure 5.2. Log traces from depth interval 1495-1520 m in well UK154/03-01 showing unit 15431-F24.

15431-F26 (Figure 5.3): The upper crust of this 12 m thick unit is distinctly different from the 15431-F24 and lava beds described by Planke (1994) and Delius et al. (1995). The ca. 3 m thick top zone is characterised by a fairly constant velocity around 4000 ms^{-1}, which both at the top and the bottom are characterised by abrupt velocity changes. Low frequency lava beds with upper crusts of this character are common in the nine wells investigated during this study, but occur less frequently than units with fairly gradational velocity increase in the upper crust. Otherwise the unit is typical with a fairly constant velocity (ca. 6000 ms^{-1}) in the core with a few excursions to lower velocities (presumably porous zones). It is quite common, but not a general rule, that the highest velocity is found just above the basal zone of negative velocity gradient. This could possibly indicate mineral fractionation within the lava bed while still liquid.

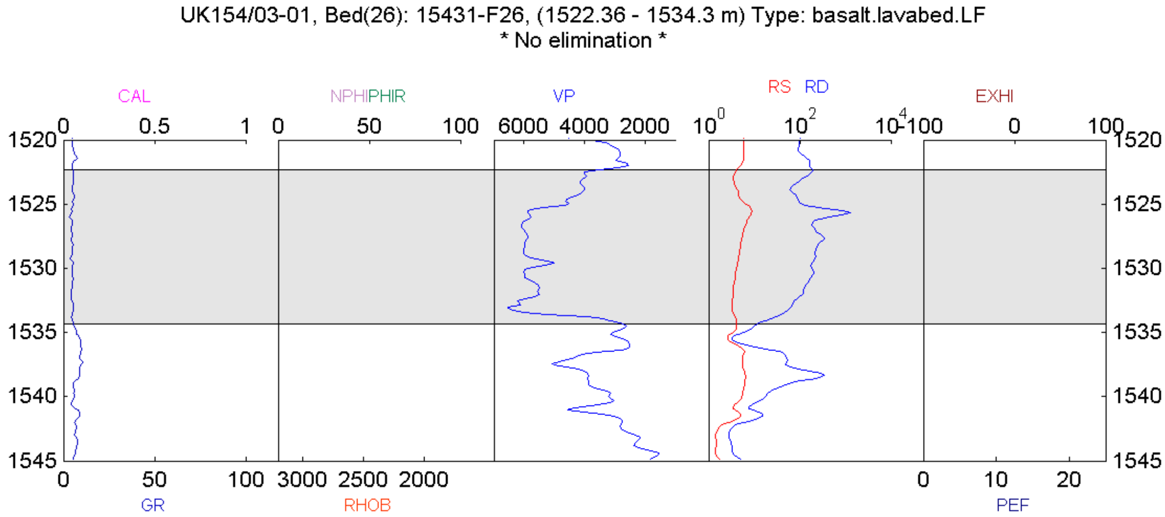

Figure 5.3. Log traces from depth interval 1520-1545 m in well UK154/03-01 showing unit 15431-F26.

5.1.2 High frequency lava beds

15403-F8 (Figure 5.4): The serrated velocity trace through the nearly 25 m thick unit is typical for this type of basaltic units. The lowest velocities in the unit are all higher than the velocities in the ca 1.5 m thick volcaniclastic unit immediately above and in volcaniclastic sediments found between low frequency lava beds. This indicates that only minor amounts of sediments (if any) can be present between the high velocity layers in this (and similar high frequency lava bed units. The velocity of the high velocity layers (4000-5000 ms^{-1}) are considerably lower than that found in the core of low frequency basalts. It is thus concluded that thin basalt beds generally not get as massive as the core of low frequency basalts. The resistivity logs have distinct deflection for each of the layers identified on the velocity trace.

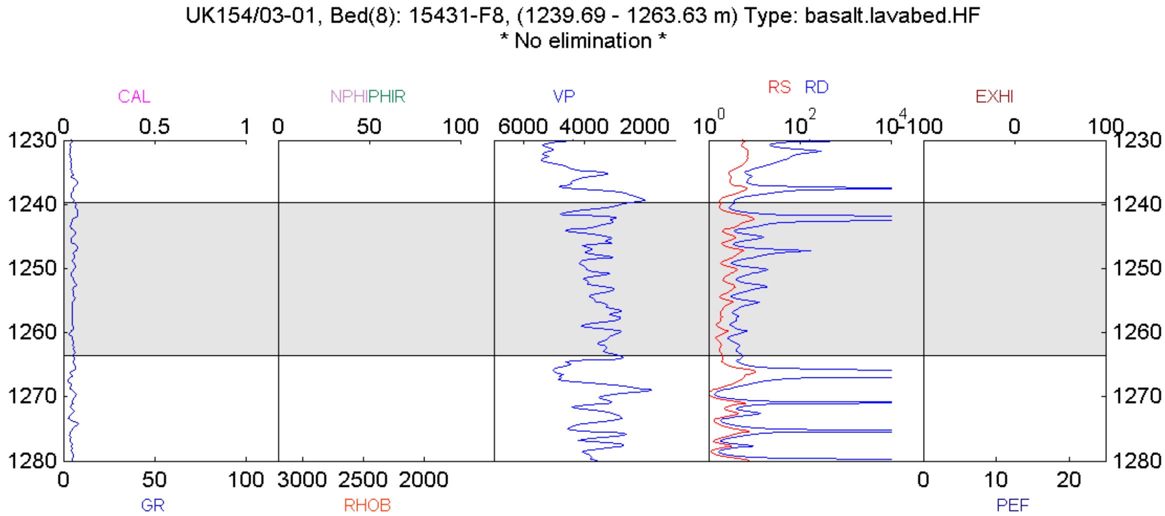

Figure 5.4. Log traces from depth interval 1230-1280 m in well UK154/03-01 showing unit 15431-F8.

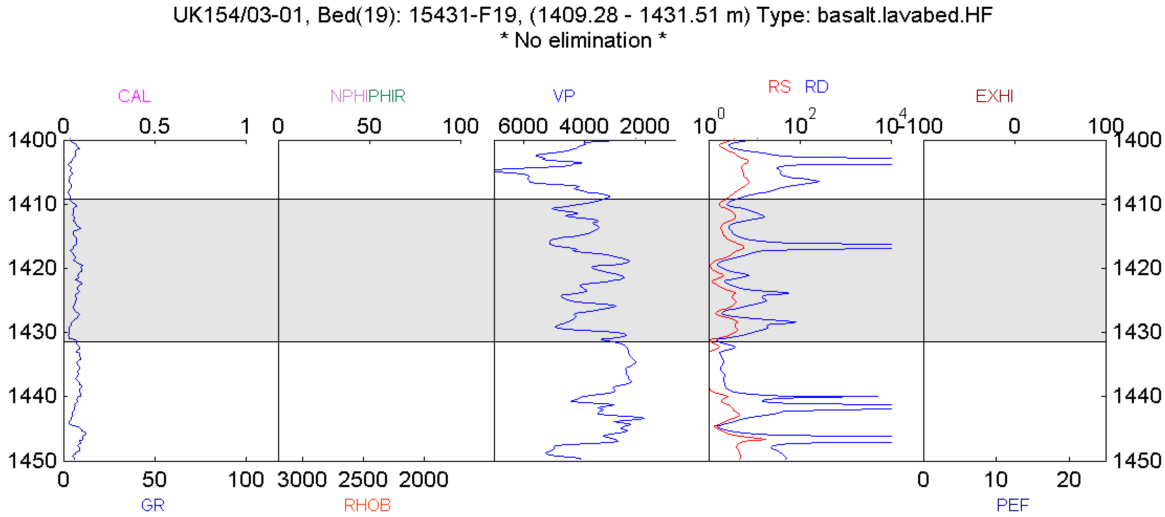

Figure 5.5. Log traces from depth interval 1400-1450 m in well UK154/03-01 showing unit 15431-F19.

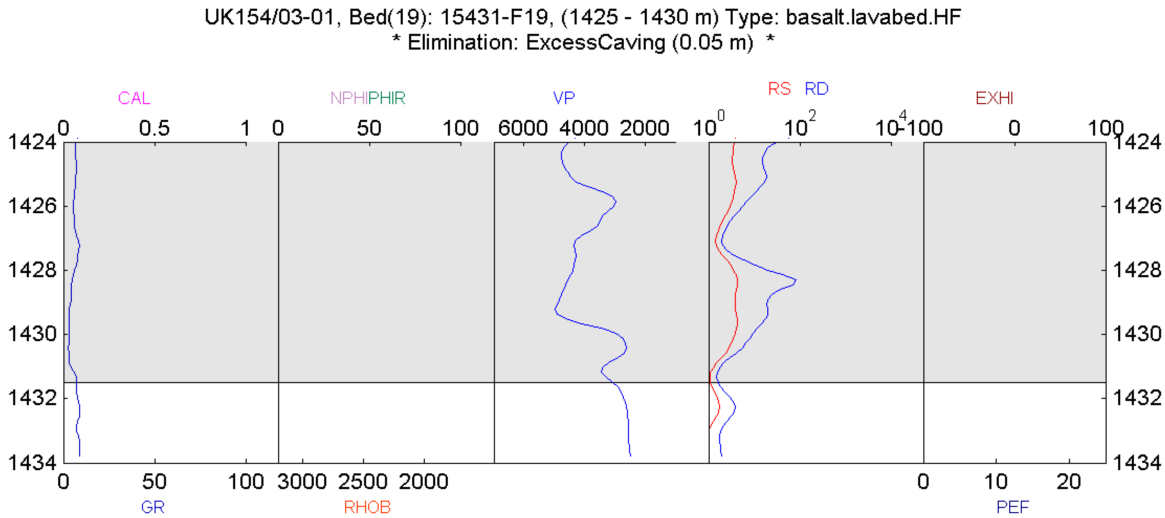

Figure 5.6. Log traces from depth interval 1424-1434 m in well UK154/03-01 showing detail of unit 15431-F19. This show the lowermost basalt layer in unit 15431-F19 of high frequency lava beds.

15403-F19 (Figure 5.5 and Figure 5.6): In this ca. 22 m thick group of high frequency basalts, the individual layers of "massive" basalt are thicker than in unit 15403-F8. When the thickness of basalt layers in high frequency lava beds exceeds ca. 3 m, indications of the porous upper crust are seen on the velocity trace (e.g. in the two lowermost basalt layers between 1420 and 1430 m; detail in Figure 5.6). The high frequency basalts are, due to observations like this, considered as thinner and more porous equivalents of the thick bedded basalts rather than a specific genetically group of basalts.

5.1.3 Foreset Breccia

The foreset breccia in this well comprises a 500 m thick unit (1622-2041m; Figure 5.7, Figure 5.8 and Figure 5.9 and Figure 5.10) characterised by a low gamma radiation as compared to that of the lava beds and a fairly constant velocity (ca. 4000 ms^{-1} in the upper 300 m and ca 3500 ms^{-1} in the lower 200 m. Six out of seven sidewall cores from this unit are described as altered basalt, and the last as basaltic sandstone. A few up to 15 m thick intervals with siliciclastic sediments (or mixtures of siliciclastic and volcaniclastic sediments) are found in this unit.

The high values of the NPHI log are quite typical for basalts (Broglia & Ellis 1990), and they reflect a high content of hydrous alteration minerals as well as pore water. An alternative estimate, represented as the PHIR trace, of the porosity have thus been calculated using the density log (RHOB) assuming a matrix density of 2950 kg m^{-3} (see chapter 14 for further details). The PHIR trace is considered to provide a better estimate of the porosity in UK154/03-01. However, even the range of PHIR values (20-30 % porosity) are considered fairly high, and it is possible that 2950 kg m^{-3} is to high an estimate of the matrix density. However, no data concerning the matrix densities of rocks from this well is available. In the bottom of the unit two distinct lava beds have been identified with estimated porosities down to 10 % (PHIR) and seismic velocities up to 5500 m s^{-1}. Occasional lava flows are common in volcanic foreset breccias (e.g. Pedersen 1985; Pedersen & Dueholm 1992), and the symmetric response of 15431-F31 may be indicative of brecciation of the flow bottom, which may be expected in basalts flows emplaced into water. The log response of unit 15431-F30 are fairly typical of a lava beds and does not in itself indicate a wet environment.

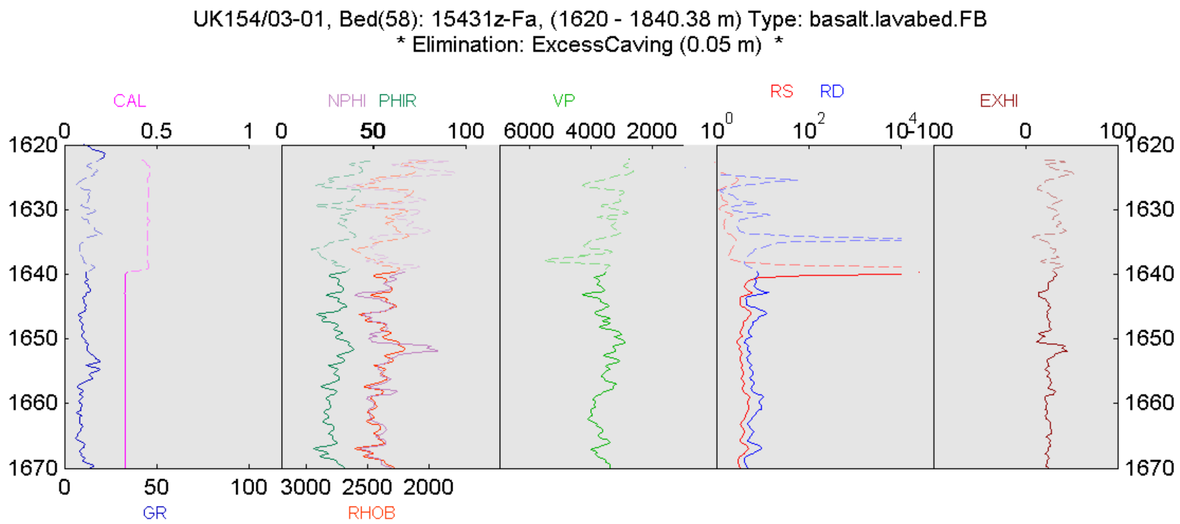

Figure 5.7. Log traces from depth interval 1620-1670 m in well UK154/03-01 showing the upper part of unit 15431z-Fa. Stippled data traces in the upper part of the plot indicate that the difference between the calliper and the diameter of the bit exceeds a threshold value (5 cm) above which the data are considered less reliable due to imperfect gap correction. This problem is quite serious in basalts as gap corrections typically are made based on assumptions about the lithology of the formation. Generally these assumptions are based on a database of sediment lithologies and is likely to be unrealistic in basalts. Therefore data points where the difference exceeds the threshold value are not considered representative of intrinsic parameters and not used in calculation of averages, trends and other statistical measures.

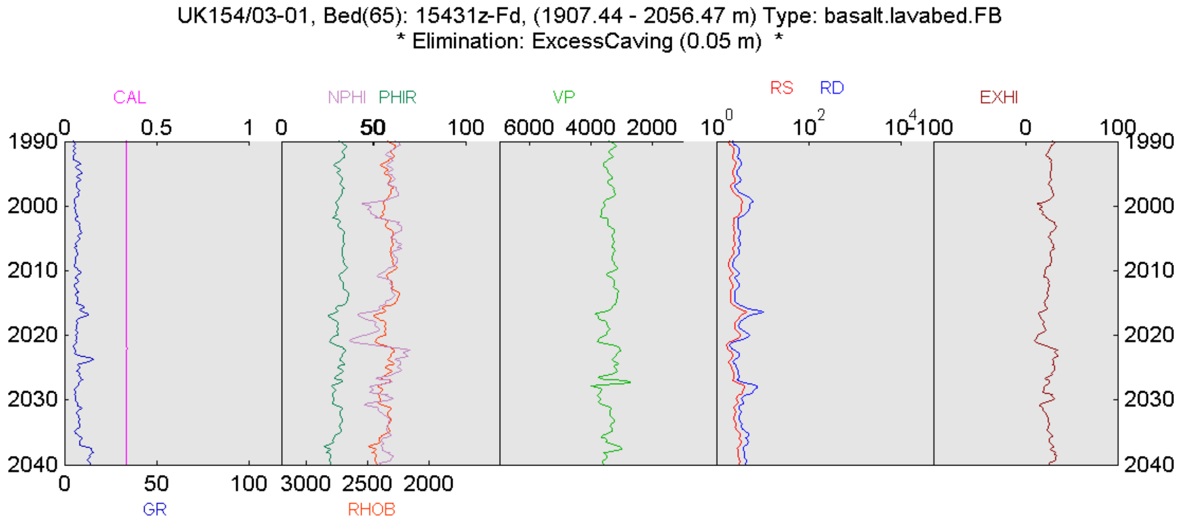

Figure 5.8. Log traces from depth interval 1990-2040 m in well UK154/03-01 showing part of unit 15431zFd.

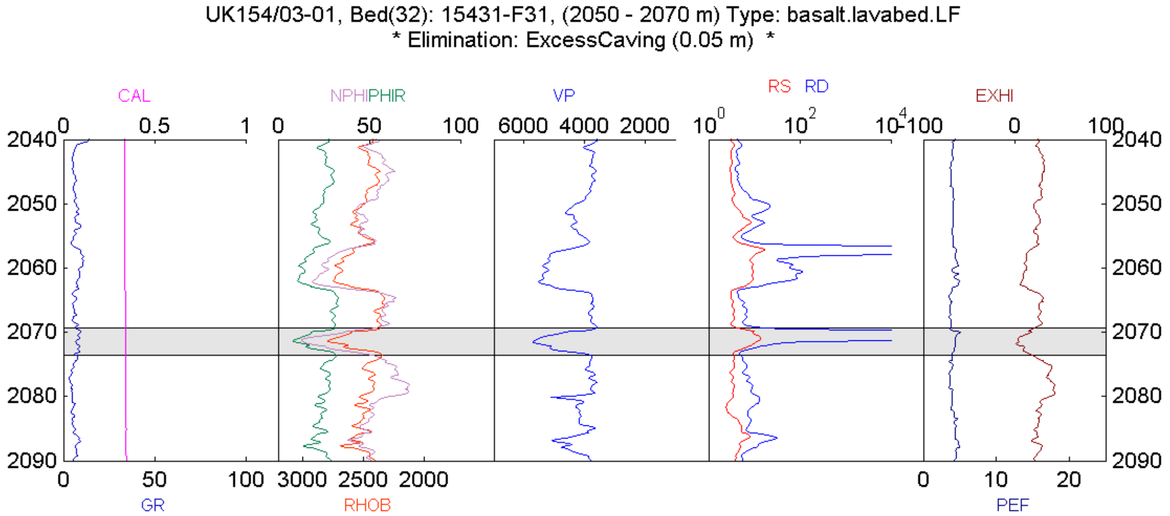

Figure 5.9. Log traces from depth interval 2040-2090 m in well UK154/03-01 showing part of unit 15431-zF. Two lava beds 15431-F30 (2056.47-2063-53 m) and 15431-F31 (highlighted) are embedded in the foreset breccia within the displayed interval.

5.2 Properties of basaltic rocks in UK154/03-01

Four cross plots (Figure 5.11, Figure 5.12, Figure 5.13 and Figure 5.14) illustrates the distribution of properties of basaltic rocks in UK154/03-01. In all but two units of the two types of lava bed units, the gamma radiation clusters within a narrow range (3-12 GAPI). The four lava bed units that contains samples with higher values of gamma radiation (15431-F17 with max GR=18.9 GAPI; 15431-F1 with max GR=14.5 GAPI; 15431-F28 with max GR=12.5 GAPI; 15431-F21 with max GR=12.2 GAPI) are all of the high frequency type This could indicate the presence of siliciclastic material in sediment layers between the individual lava beds. However, both in unit 15431-F17 and in unit 15431-F1 the high gamma radiation are seen in the top of the unit indicating either sediments with siliciclastic material in the top of the unit or alteration of the upper part of the lava bed at an early stage just after deposition (Figure 5.10; Delius et al. 1995). It could be argued that the top of the unit boundary in Figure 5.10 could be moved down with ca. 1 m. However, some part of the interval with high gamma radiation would still be within the lava bed unit. We have therefore retained the pick at the local of maximum curvature on the VP trace. High gamma radiation in the top of lava flows occur frequently in lava beds from ODP wells in the Northeast Atlantic and has been discussed in the literature (e.g. Delius 1995), and it is mostly considered an effect of early alteration/soil formation. Similar gamma radiation anomalies are also observed in basaltic lava beds in other wells analysed as part of this study (e.g. UK164/07-01, UK209/03-01 and UK209/09-03; chapters 6, 9 and 11).

The gamma radiation from the foreset breccia (unit 15431z-Fa -Fe) is generally ca. 8.5 GAPI, higher than that from the lava beds (ca. 6 GAPI; e.g. Figure 5.1 and Figure 5.2). The minimum value is ca. 3.9 GAPI, comparable to the minimum values of most lava beds; but only a small proportion of the GR values are lower than 5 GAPI. The trail of data points reaching out to nearly 50 GAPI at seismic velocities around 3000-3500 ms^{-1} in Figure 5.11 is considered a strong indication of contamination of the basaltic foreset breccia with potassium rich siliciclastic sediments. Some siliciclastic layers have been mapped out (see digital data documentation; Synopsis\W1-B61.html). The most extreme values are associated with distinct sediment beds. Contamination with potassium rich siliciclastic sediments should be expected in basaltic foreset breccias, so the distribution of GR values from this unit supports the interpretation that this unit represent a foreset breccia (or possibly two or more stacked above each other). Based on the distribution of GR values (especially at velocities above 4000 ms^{-1}) it is likely that the magma emplaced as the foreset breccia is within the same compositional range as the magmas which later were emplaced as the lava beds.

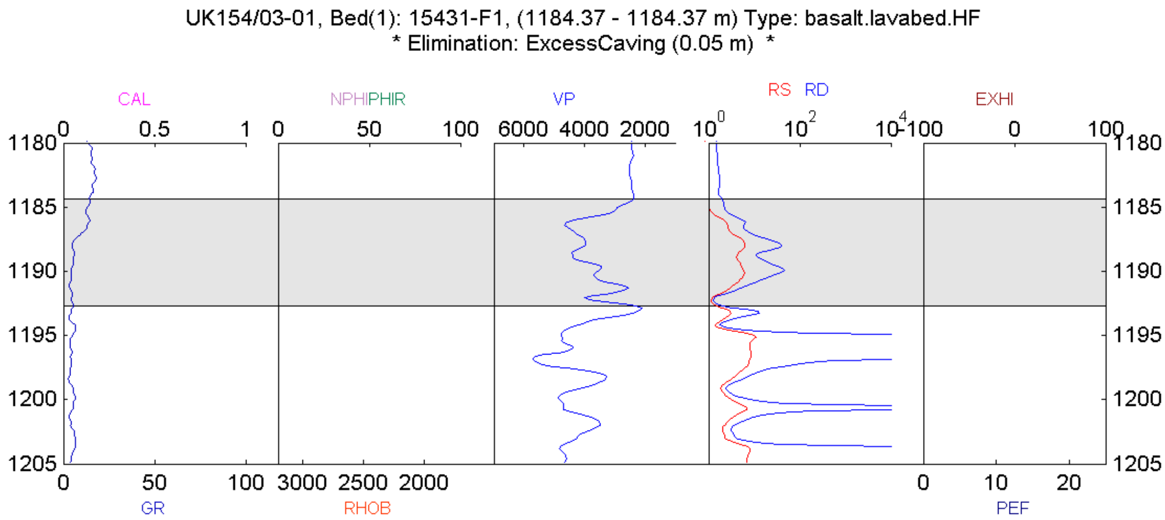

Figure 5.10. Log traces from depth interval 1180-1205 m in well UK154/03-01 showing the high GR values in top of unit 15431-F1.

A fair linear correlation among density, ZDEN, and neutron porosity, CNC, is seen in Figure 5.12. A considerable spread is seen among data points from the foreset breccia (unit 15431-FF). Velocity, VP, is also well correlated to both to neutron porosity, CNC, and density, ZDEN (Figure 5.13 and Figure 5.14). The trends reflect that basalt has high matrix density and velocity. The neutron porosity and density log was only run in the lower part of the well and therefore only two lava bed units are represented in Figure 5.12, Figure 5.13 and Figure 5.14.

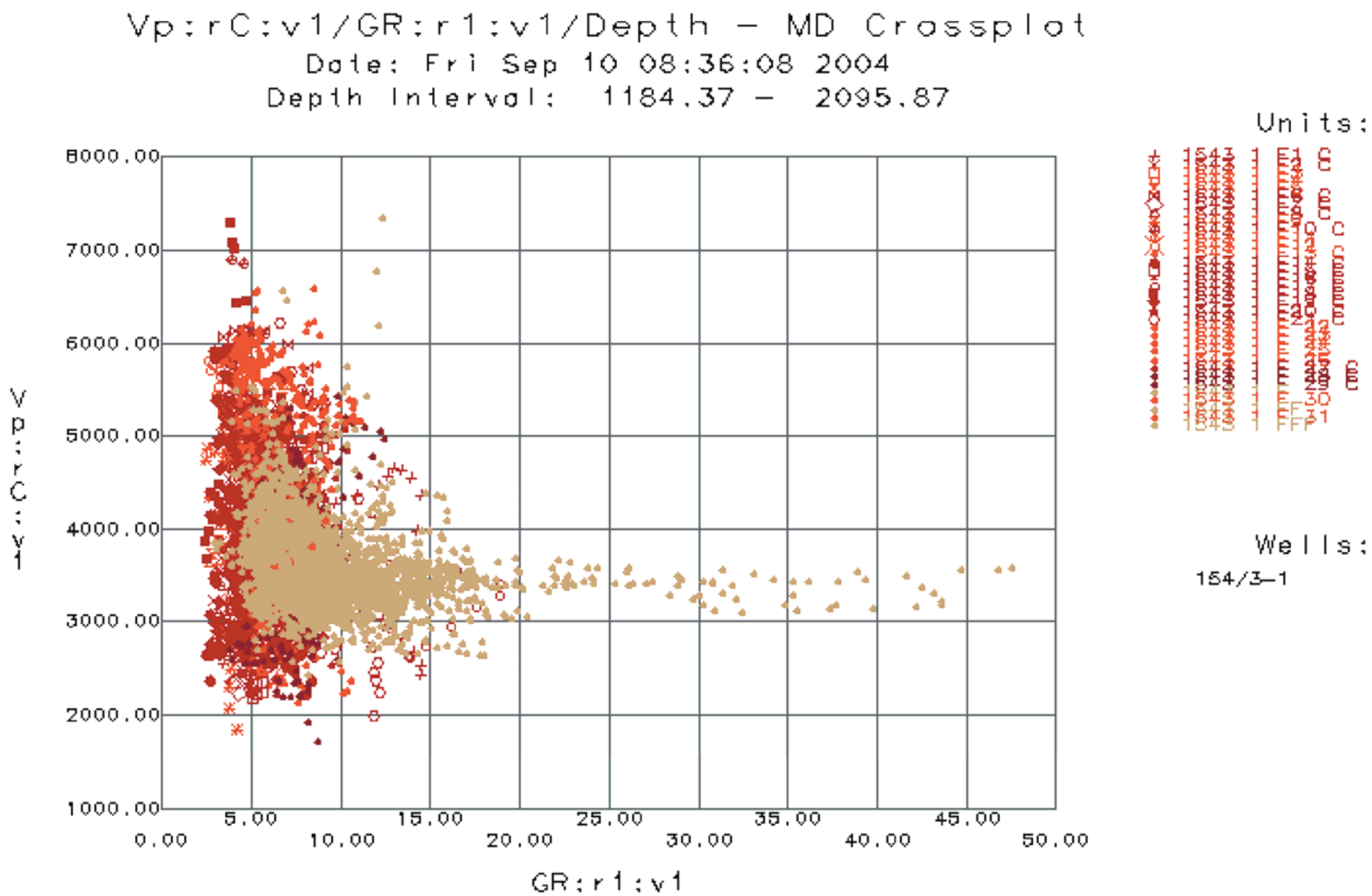

Figure 5.11. Gamma radiation (GR) versus seismic P-wave velocity (VP) for all interpreted basaltic units in UK154/03-01.

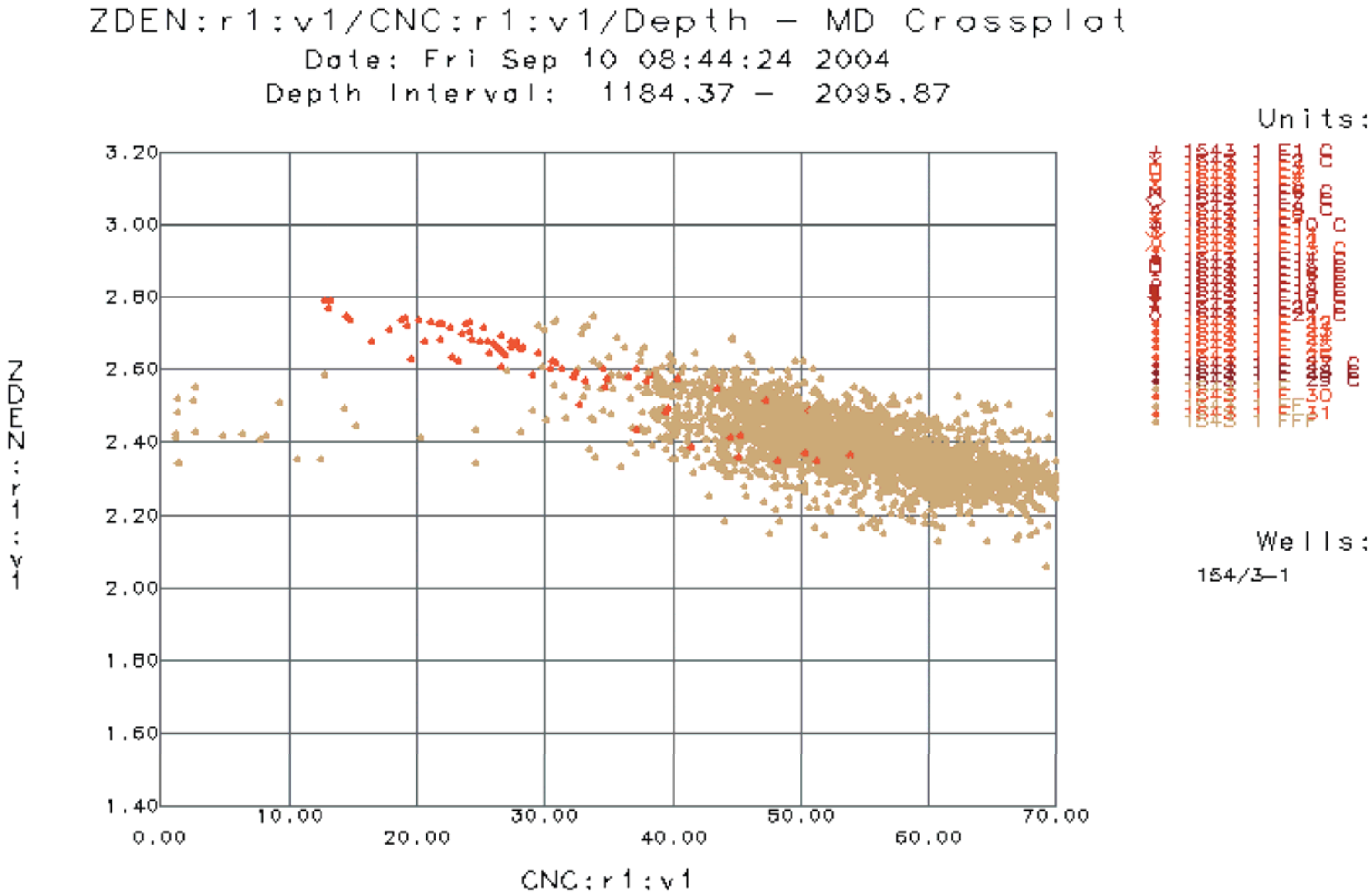

Figure 5.12. Neutron porosity (CNC) versus density (ZDEN) for all interpreted basaltic units in UK154/03-01.

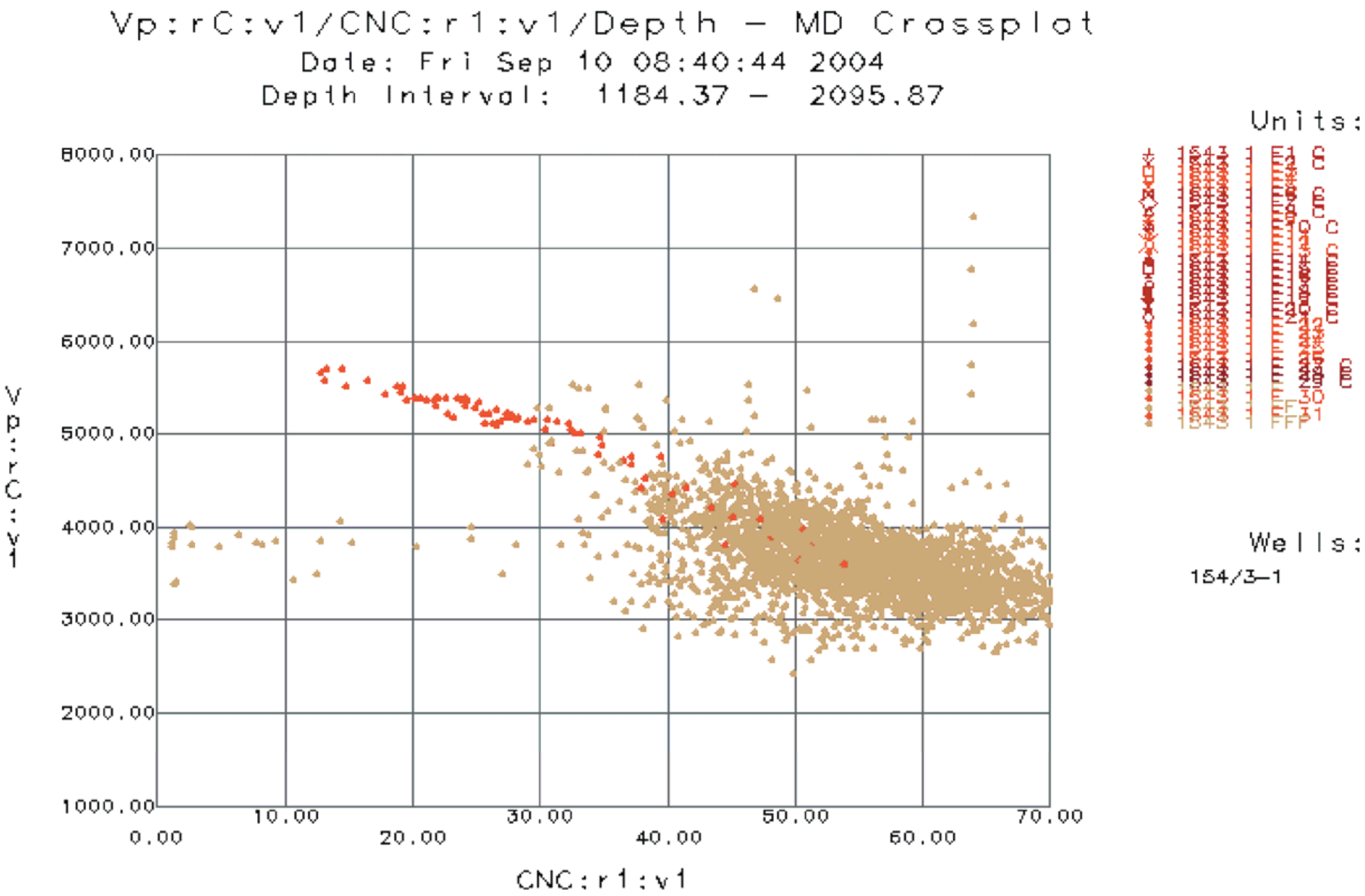

Figure 5.13. Neutron porosity (CNC) versus seismic P-wave velocity (VP) for all interpreted basaltic units in UK154/03-01.

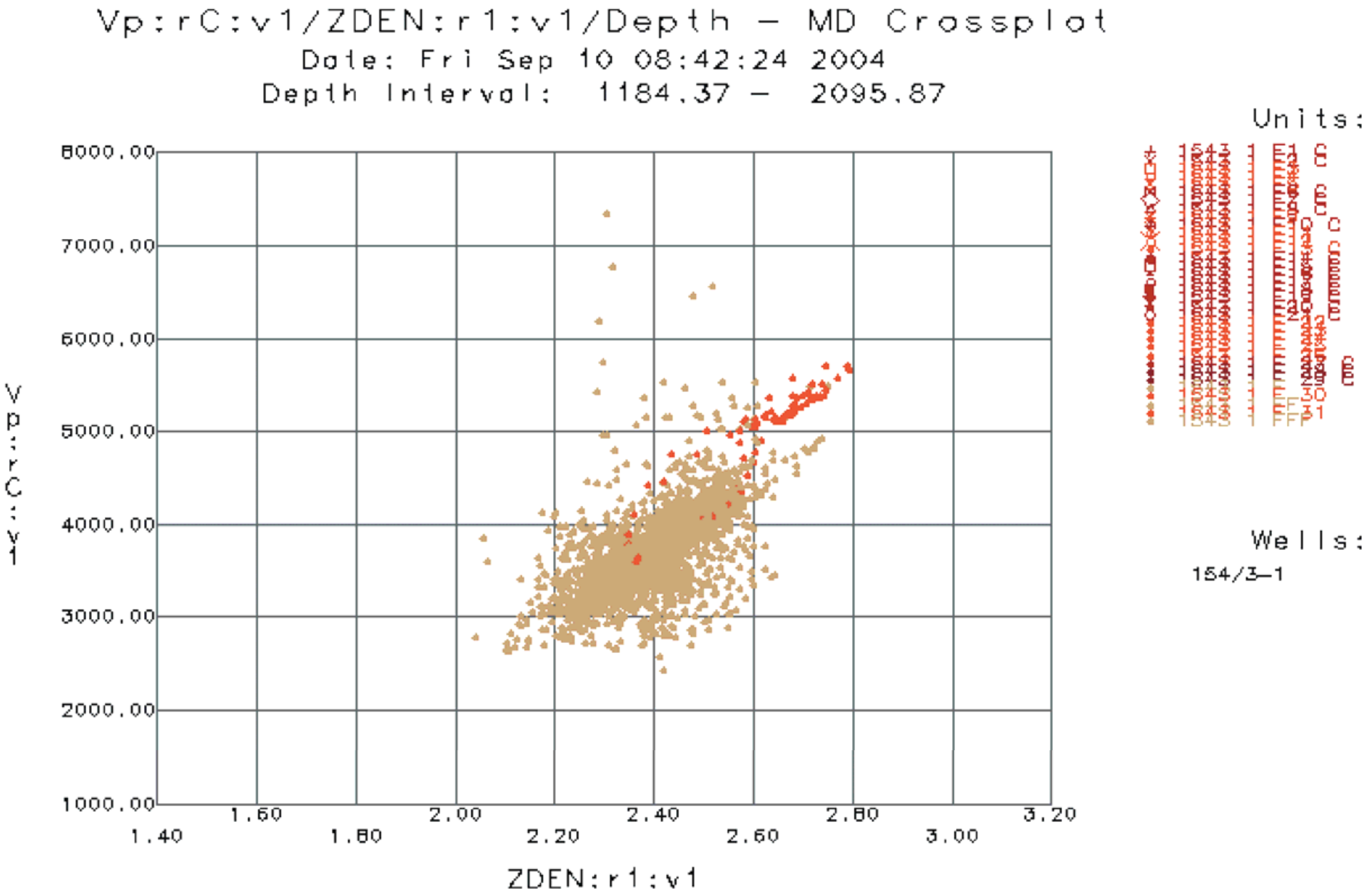

Figure 5.14. Density (ZDEN) versus seismic P-wave velocity (VP) for all interpreted basaltic units in UK154/03-01.

6 Well UK164/07-01

The well UK164/07-01 (59°42'32.184''N 07°46'06.124"W) was drilled to a depth of ca. 5100 m (TVD). The well was targeted at possible syn-rift reflectors in a large dome shaped structure below a basalt succession. The well penetrated a succession of more than 1 km of Eocene basaltic rocks (2092.9-3295.4 m MD) in the 12.25" hole. Borehole conditions during logging of this section were not ideal for logging, as considerable parts of the hole were caved. Some intrusives were found in the Paleocene and Mesozoic succession below the volcanics.

The suite of log measurements in the depth interval of interest in UK164/07-01 comprises

- calliper, CAL,
- natural gamma radiation, GRSL,
- sonic transit time (P-wave), DT,
- density, RHOB,
- neutron porosity, NPHI,
- resistivity measured with a dual laterolog tool, LLD and LLS
- spectral gamma, K, Th and U,
- photo electric effect, PEF.

Sonic transit time is recalculated to sonic velocities and presented as the trace, VP. In addition a micro laterolog was run. Results from this tool in the basalt section are not considered representative. According to the completion report the pad may have been impaired. Both the neutron log, the density log and the photo electric log is adversely affected by hole conditions. The laterologs are apparently not influenced by hole conditions, and they appear to be properly processed to remove bed effects due to the large resistivity contrasts at the top and bottom of basalt beds. The relevant log traces from the depth interval of interest are presented as enclosure 1.

- Geological descriptions in the completion report and twenty five side wall cores mostly retrieved from the sedimentary intervals in the uppermost and lowermost part of the basaltic volcanic succession help constraining the log-interpretation.

6.1 Unit descriptions

In UK164/07-01 we have interpreted more than 50 basaltic units, mostly low frequency lava beds interbedded with volcaniclastic sediments. Some high frequency lava beds are also interpreted. In addition to these three types of basaltic rocks, which also are present in UK154/03-01, possible intrusives are also present in this well.

Values of the total gamma radiation calculated from the spectral gamma logs are typically in the range 20-40 GAPI. This is considerably higher than in UK154/03-01. However, the gamma radiation from basaltic rocks in UK164/07-1 is distinctly lower than that from siliciclastic sediments, so the gamma log is also in this well suitable to help locating boundaries between basalts and siliciclastic sediments. The general character of the four types of basaltic rocks in UK164/07 is:

1. Units of *low frequency lava beds*. These units are composed by one thick layer with high velocity and resistivity (as mentioned in previous chapter). In addition the density is high, especially if compared to the neutron porosity. The neutron porosity is generally low, but rarely below 10 LPU, even in the most massive parts of the units of this type. In some units the minimum value of the neutron porosity is more than 20 LPU. The thin lower crust and thicker upper crust in units of this type is seen on the velocity trace VP, and also on the density trace, RHOB, the neutron porosity trace, NPHI, and the resistivity traces, LLS and

LLD. These boundary zones are thus clearly porosity related as has been concluded in previous studies (e.g. Planke 1994; Delius et al. 1995). In intervals with good hole conditions correlation between the seismic velocity, density, neutron porosity and resistivities is high, and narrow zones in the core with increased porosity can be identified on all five logs. As in UK154/03-01, the upper crust is either comprised of a zone with increasing velocity or by a zone of fairly constant velocity above a zone with increasing velocity.

2. Units of *high frequency lava beds*. As for the above mentioned type this type is characterised by a fair correlation between the seismic velocity, density, neutron porosity and resistivities. The thickest individual high velocity layers in some units of high frequency lava beds may have most of the characteristics of a low frequency lava bed, but with a somewhat lower seismic velocity (5000-5500 ms^{-1}).
3. Units of *volcaniclastic sediments*. All but one sidewall core in the volcanic succession of UK164/07-01 are described as tuffs, claystones or other sediments, one is described as basalt. According to the completion report, sediments are also relatively frequent in the volcanic succession. On the log traces sedimentary units are generally recognised based on low velocity and density combined with high neutron porosity and resistivity. A slight increase in gamma radiation may also occur in the sedimentary intervals of the volcanic succession. However, the gamma radiation of the sedimentary layers in the volcanic succession is generally considerably lower than that of Cretaceous siliciclastic sediments in the well.
4. Units of *intrusives*. The properties of basaltic intrusives are comparable to those of the core of the thickest lava flows. Seismic velocity and density may be slightly higher and neutron porosity slightly lower. They are recognised as intrusives based on the character of the boundaries of the units. Basically the upper and lower boundaries are symmetrical about a plane perpendicular to the wellbore. Ideally sills will have sharp boundaries (like the base of thick lava beds. Dykes which are almost parallel to the well bore will have more gradational boundaries.

Details concerning individual units are found in the digital data documentation (Synopsis\W8.html). Below a few typical units is described.

6.1.1 Low frequency lava beds

16471-F2 (Figure 6.1): This is a typical, but fairly thin, low frequency lava bed with a fairly thin (ca. 1 m) upper crust and a comparatively thick core (7 m) with constant velocity (ca. 5500 ms^{-1}), density and neutron porosity.

16471-F9 (Figure 6.2): A 13.5 m thick lava bed with an 8 m thick zone of gradually increasing velocity. In this lava bed the velocity in the upper part of the flow is poorly correlated with porosity, density and resistivities. The core is only about 5 m thick, contains several narrow zones with higher porosity/lower density and velocity, and the maximum velocity is ca. 5600 ms^{-1}.

16471-F31 (Figure 6.3): This ca. 12 m thick lava bed is as 196471-F9 also characterised by a fairly thick zone of gradually increasing velocity (ca. 5 m). The correlation between velocity and resistivities are good. However, the correlation between velocity and density (or porosity) is rather poor also in this unit. Hole conditions can, at least to some extent, explain the lack of correlation in unit 16471-F9. But in 16471-F31, the main reason appears to be that the vertical resolution of the sonic tool is less than that of the density and neutron porosity tools.

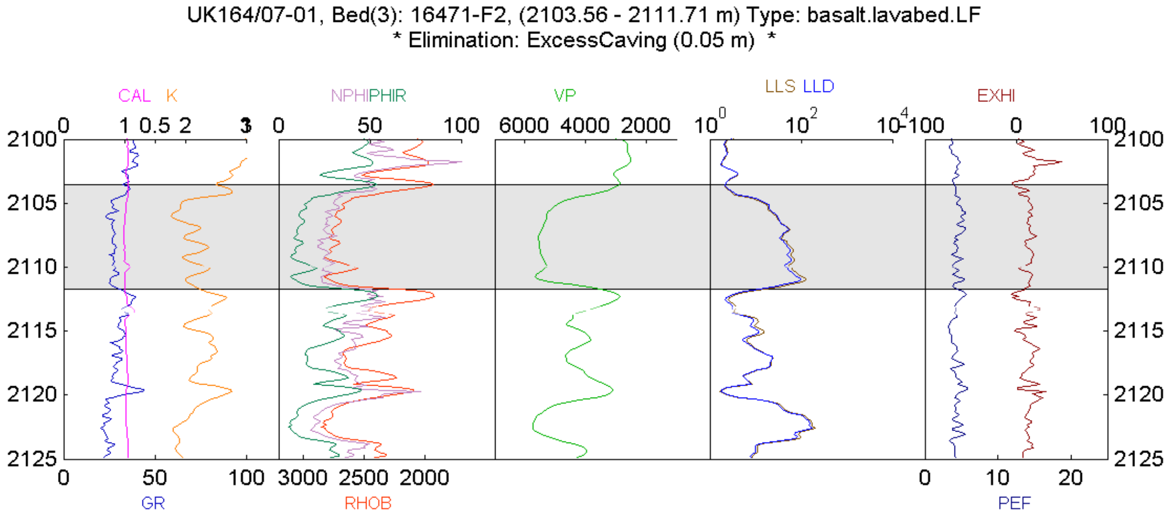

Figure 6.1. Log traces from depth interval 2100-2125 m in well UK164/07-01 showing unit 16471-F2. Note that the notch near the bottom of 164071-F2, seen on the neutron porosity, density and velocity traces, is correlated with an interval with increased calliper.

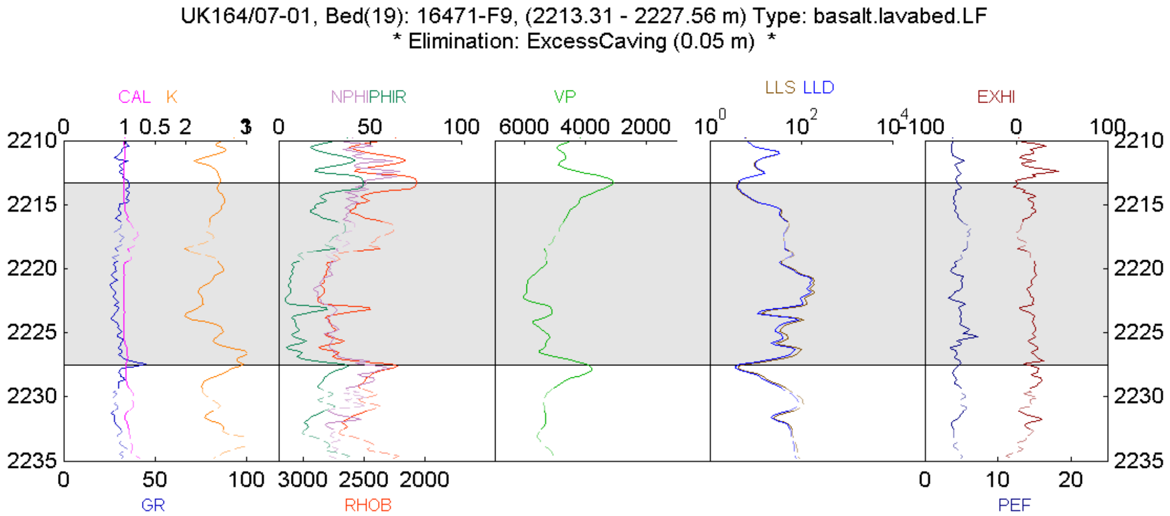

Figure 6.2. Log traces from depth interval 2210-2235 m in well UK164/07-01 showing unit 16471-F9.

In all of the three above described low frequency lava beds a slight increase of the gamma radiation (ca. 5 GAPI) is seen in the upper 1-2 m of the units.

6.1.2 High frequency lava beds

16471-F32aC (Figure 6.4): This more than 50 m thick unit consists of 3 fairly distinct layers in the upper most part characterised by velocities in the range 4000-5500 ms^{-1} in the upper 20 m and a number of less distinct layers in the bottom part, where considerable caving affects all logs adversely. The low velocity intervals (ca. 3000 ms^{-1}) in the upper part of the unit are characterised by relatively high gamma radiation (40-50 GAPI) indicating that the lava beds represented by the high velocity layers are separated by volcaniclastic material richer in potassium (and thorium).

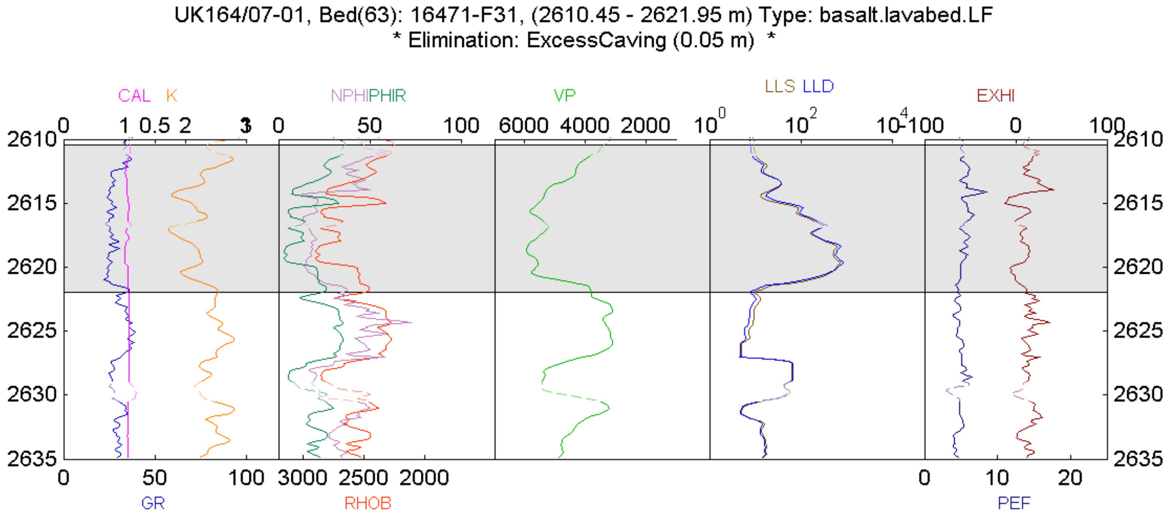

Figure 6.3. Log traces from depth interval 2605-2630 m in well UK164/07-01 showing unit 16471-F31.

16471-F50 (Figure 6.5): This 27 m thick unit comprises six distinct high velocity layers (3-7 m thick). The maximum velocity of the high velocity layers decreases with depth in the unit from ca. 6000 ms^{-1} for the uppermost layer to ca. 4500 ms^{-1} in the lowermost layers. Density, neutron porosity and the resistivities are reasonably well correlated with the velocity. At the same time gamma radiation increases downward in this unit without correlation to the porosity dependent logs. This could indicate that all the lower part of the unit consist of volcaniclastic material. The porosity fluctuations within this part of the unit could thus be related to indurations rather than different emplacement/deposition mechanisms.

The location of the lower boundary of this unit was defined to distinguish this unit from the unit below, 16471-VS II, characterised by a smooth velocity trace and seismic velocities below 4000 ms^{-1}.

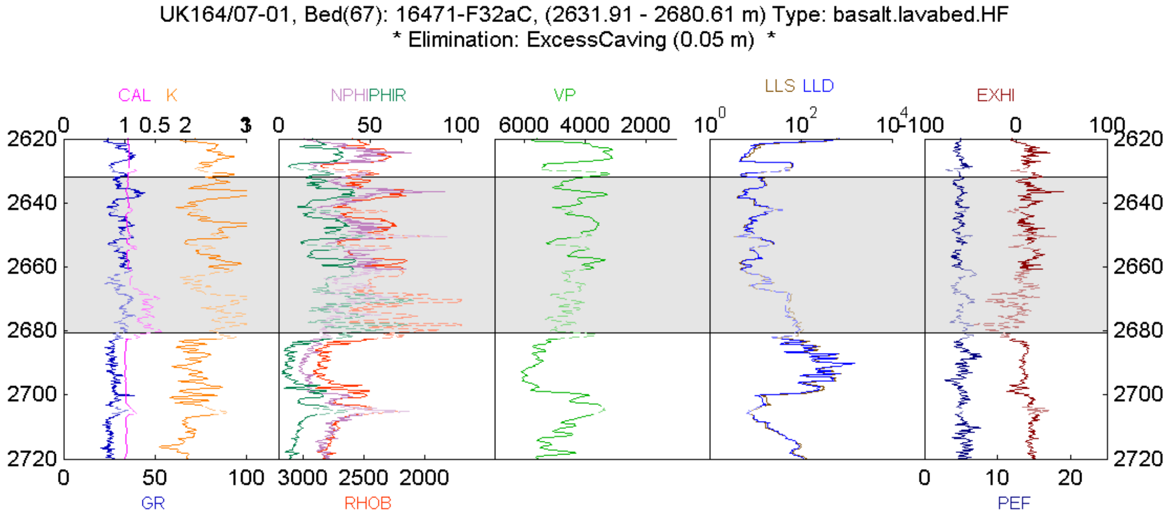

Figure 6.4. Log traces from depth interval 2620-2720 m in well UK164/07-01 showing unit 16471-F32aC.

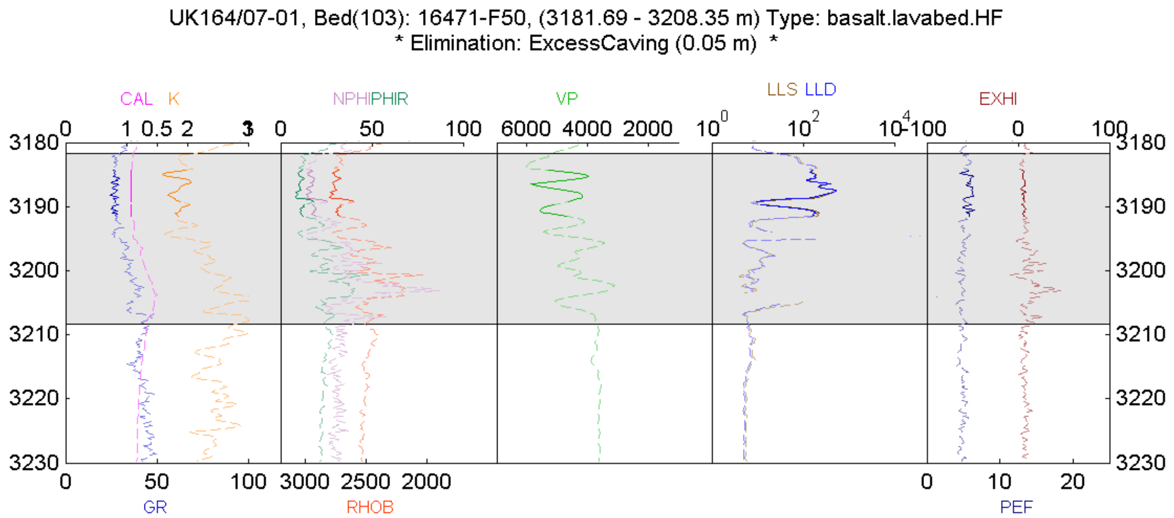

Figure 6.5. Log traces from depth interval 3180-3230 m in well UK164/07-01 showing unit 16471-F50.

6.1.3 Volcaniclastic sediments

In addition to thin intercalations of possible volcaniclastic sediments within the units of high frequency basaltic lava beds, basaltic volcaniclastic sediments have also been identified as separate units.

16471-VSA46 (Figure 6.6): This is a 5 m thick unit between two low frequency lava beds. Despite significant caving in this part of the hole, it is clearly identified as a box shaped deflection towards low porosity values on the porosity related log traces, however, best on the velocity and the resistivity traces. The maximum velocity in the unit is 4000 ms^{-1}. The GR and K traces are fairly well correlated with the porosity related traces indicating that the sediments are enriched in potassium. A side wall core from this unit is described as claystone. This supports the interpretation that this unit is of sedimentary origin. Due to the low gamma radiation combined with a setting within a volcanic succession it is most likely that the unit are dominantly volcaniclastic.

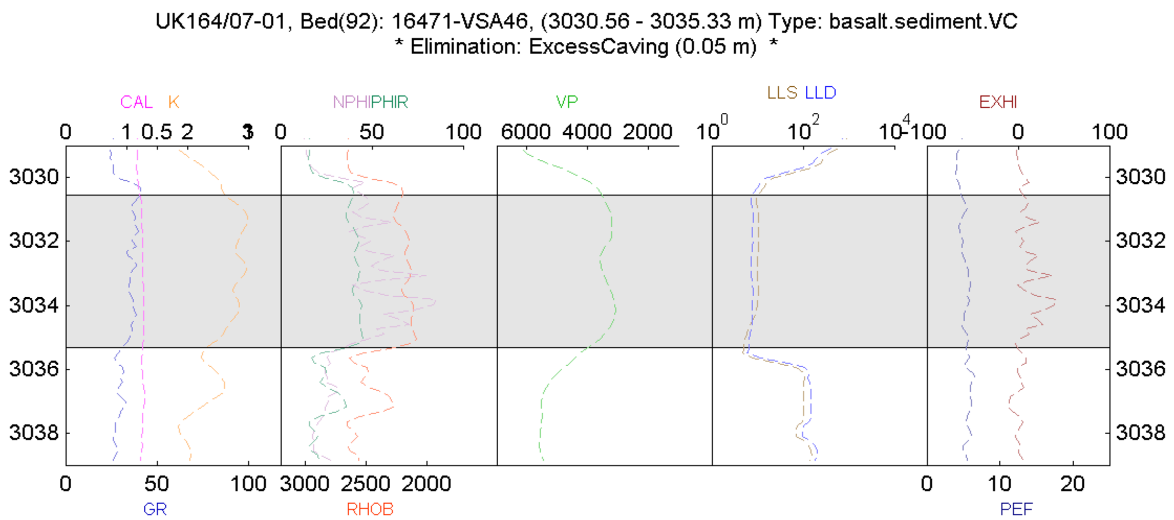

Figure 6.6. Log traces from depth interval 3030-3040 m in well UK164/07-01 showing unit 16471-VSA46.

16471-VSA38 (Figure 6.7): This is an almost 30 m thick unit of volcaniclastic sediments. Throughout this unit considerable caving has occurred. However, the log traces appear reasonably well behaved. The upper 8 m have approximately the same properties as unit 16471-VSA46. In the lower 20 m both resistivity and seismic velocity is slightly higher. The maximum velocity is ca. 4800 ms^{-1}, which is well within the range of lava beds. However, resistivity is low (<20 Ωm) compared to the parts of lava beds having similar seismic velocity. Density, porosity and gamma radiation is fairly well correlated with velocity and resistivity. The upper low velocity interval of the unit is also characterised by higher gamma radiation (and potassium concentration) as well as lower porosity. This indicates that, in this unit, either two slightly different sedimentary intervals are represented or potassium was enriched in the most porous part during alteration of the sediment.

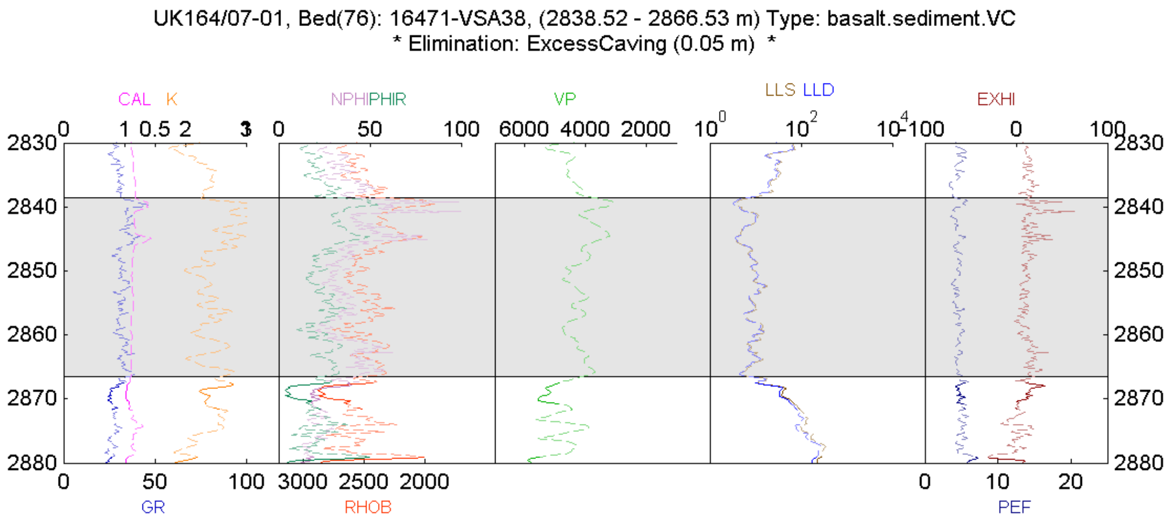

Figure 6.7. Log traces from depth interval 2830-2850 m in well UK164/07-01 showing unit 16471-VSA38.

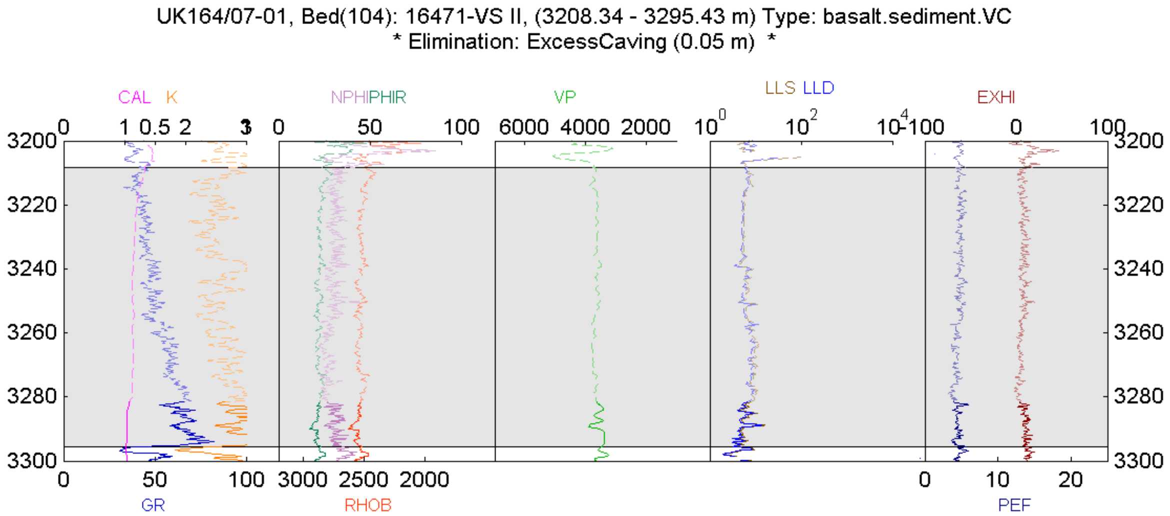

Figure 6.8. Log traces from depth interval 3200-3300 m in well UK164/07-01 showing unit 16471-VS II.

16471-VSII (Figure 6.8): The base of the volcanic unit in UK164/07-01 is represented by this unit. According to the completion log and description of sidewall cores the upper part of this unit is tuff and the lower 14 m is a basaltic conglomerate. The relatively smooth GR trace, the upwards decreasing gamma radiation (from more than 80 GAPI to ca. 30 GAPI) and indications of reworking in several sidewall cores from this unit indicates that the unit may represent a sediment composed of a basaltic volcaniclastic component increasing in concentration upwards and a potassium (and thorium rich) component decreasing in concentration upwards.

6.1.4 Basaltic intrusives

Basaltic intrusives are seen both below the volcanic succession and within the volcanic succession. The log response of one is described below.

16471-I2 (Figure 6.9): This is a fairly typical intrusive unit. The seismic velocity is comparable to the massive cores of thick lava beds (average velocity is ca. 5500 ms^{-1}). Density, porosity and resistivity are relatively well correlated to the density. A slight overall upwards decrease in resistivity is noteworthy, as this phenomenon not support the assumption of general symmetry of intrusive units. Both in this and other wells (e.g. UK164/25-01 and UK209/09-01; chapters 7 and 11) the resistivity response of intrusive units are frequently seen to be asymmetric, with lowest resistivity in the upper part of the units. If caving is taken into consideration the density and porosity traces are well correlated with the seismic velocity. Gamma radiation is low, comparable to that from lava beds, and fairly constant (21-34 GAPI).

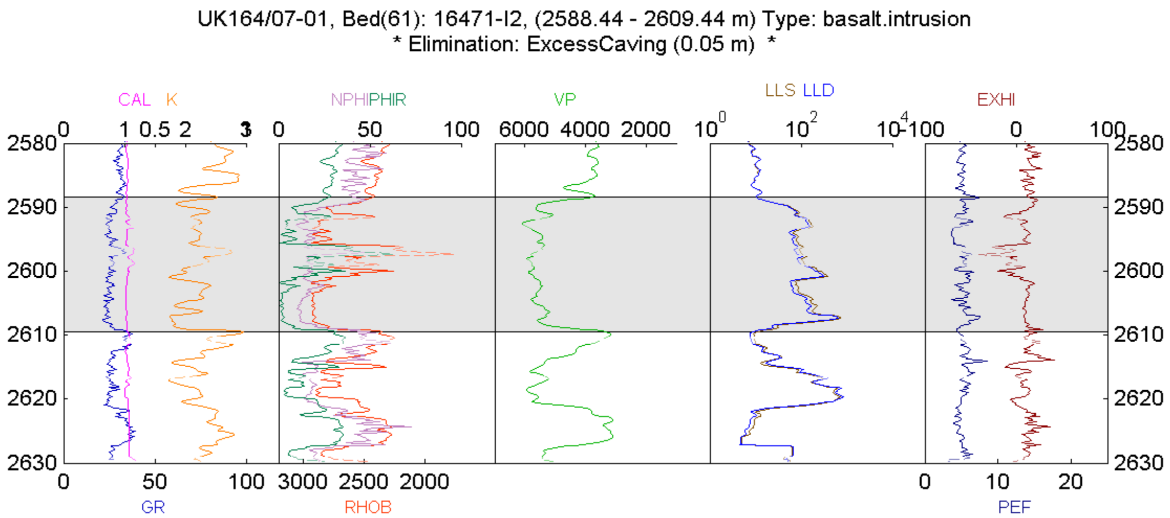

Figure 6.9. Log traces from depth interval 2620-2720 m in well UK164/07-01 showing unit 16471-I2.

6.2 Properties of basaltic rocks in UK164/07-01

Four cross plots (Figure 6.10, Figure 6.13, Figure 6.14 and Figure 6.15) illustrates the distribution of properties of basaltic rocks in UK164/07-01.

In both type of lava bed units a slight correlation between seismic velocity and gamma radiation can be seen in Figure 6.1 and Figure 6.4. At the highest velocities (ca. 6500 ms^{-1}) gamma radiation is ca. 25 GAPI, while it at the lowest seismic velocities of high frequency lava beds (ca. 3000 ms^{-1}) is ca. 40 GAPI. A few data points from lava bed with gamma radiations in excess of 40 GAPI are probably due to slight errors in the placement of the unit boundaries. To a large extent the observed trend in Figure 6.10 is associated with potassium rich zones in the upper part of the lava crusts. This may thus be indicative of alteration/soil formation just after emplacement of the individual beds.

However, a crude but distinct correlation between seismic velocity and gamma radiation can be seen in some low frequency lava beds (Figure 6.11). The trend in the figure is also seen when the average gamma radiation in lava beds and intrusives from the volcanic succession is plotted against average seismic velocity. Although it is possible that primary lava composition contributes to trend in Figure 6.12 (left) a depth dependent alteration may also contribute to the trend observed in Figure 6.12 (left) as average gamma radiation from beds also are crudely correlated to depth Figure 6.12 (right). A detailed geochemical investigation is required to distinguish all effects contributing to the trends observed in Figure 6.10 and Figure 6.13.

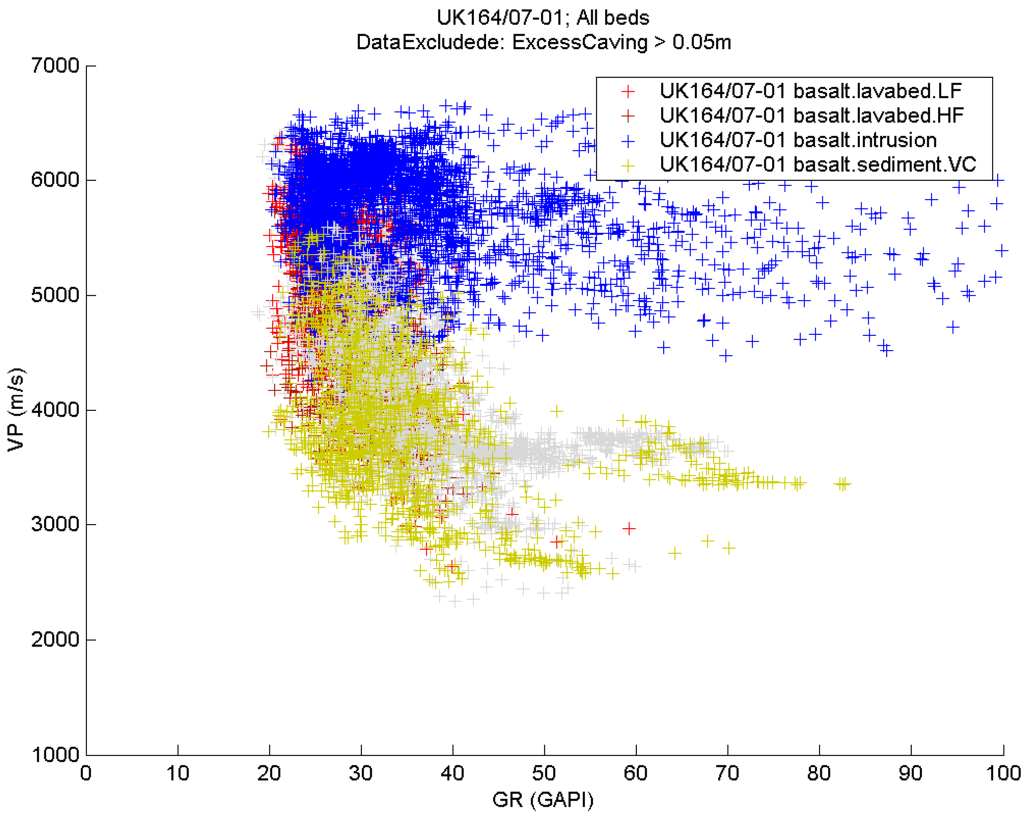

Figure 6.10. Cross plot of seismic velocity, VP, versus gamma radiation, GR, from basaltic volcanic units in UK164/07-01. The data point are colour coded according to what type of unit they belong to. Points in grey represent data points from those parts of the well where caving exceeds 5 cm. These data points are not used when calculating statistical parameters, unless specifically stated.

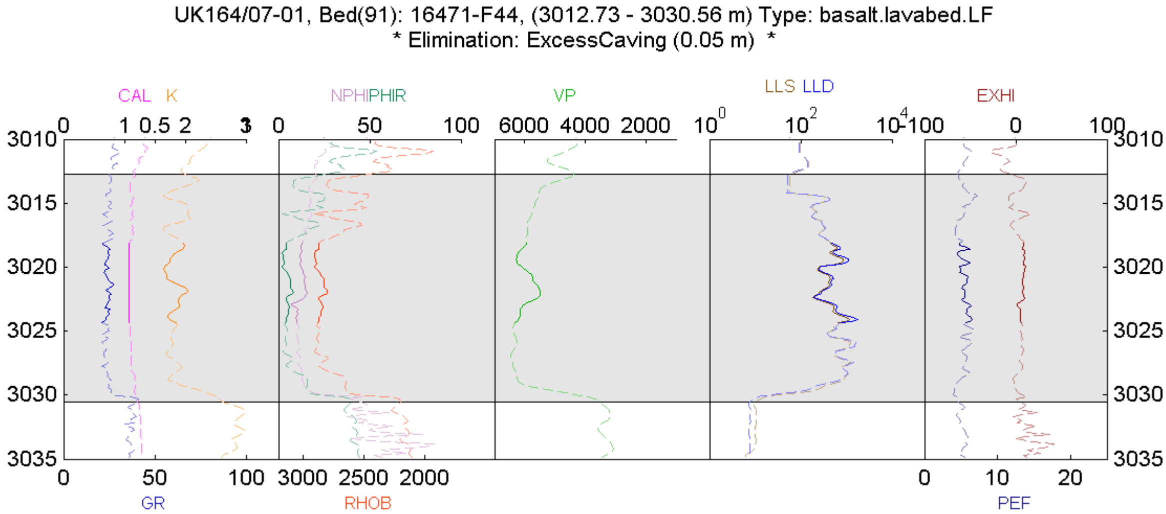

Figure 6.11. Log traces from depth interval 3010-3035 m in well UK164/07-01. Note crude corelation between gamma radiation and seismic velocity.

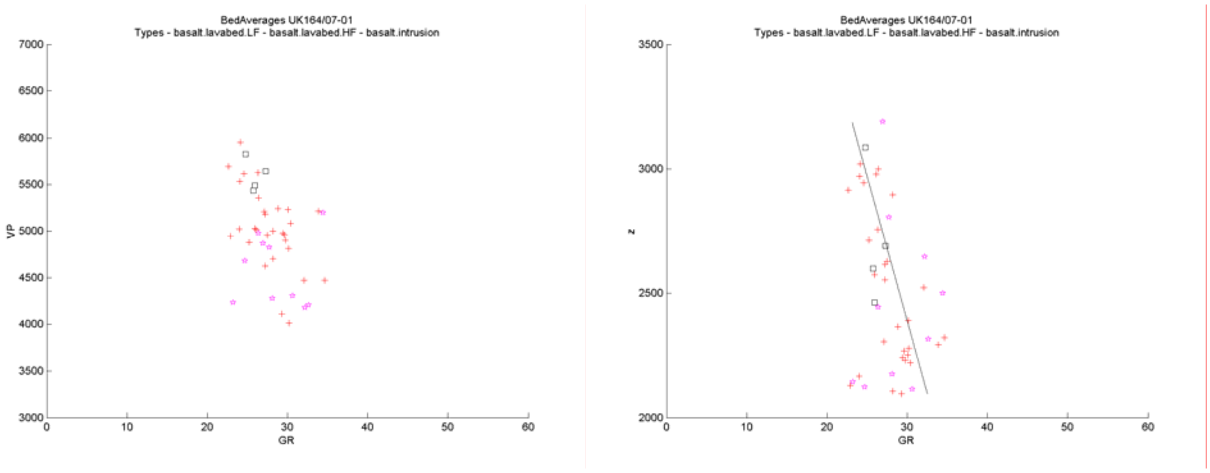

Figure 6.12. Cross plots of average values from lava beds and intrusions in the volcanic succession in 164/07-01. Left: gamma radiation (GR) versus seismic velocity (VP). Right: gamma radiation (GR) versus depth (z).

The seismic velocity for basaltic rocks in UK164/07-01 is well correlated with neutron porosity Figure 6.13. It should be noted that the neutron porosity values do not represent true porosity, but also reflect hydrogen present in hydrous minerals in the basaltic rocks. Although, there is a considerable error in the density data due to unsatisfactorily gap compensation, porosity estimated from the density log is considered preferable when absolute porosity values are required.

In the lower part of the diagram values from the volcaniclastic unit 16471-VS II and a few other units plots just outside the main trend in Figure 6.13. Actually these units define a trend of their own with considerably smaller negative trend than the massive basalt units. This is presumably to some extent an effect of the possible mixing with silisiclastic material which is apparent in the thick 16471-VS II unit Figure 6.8. Density is also fairly well correlated to seismic velocity. However, due to poor well conditions and unsatisfactorily gap compensation, the relative spread of density values is larger than the spread of neutron porosity values.

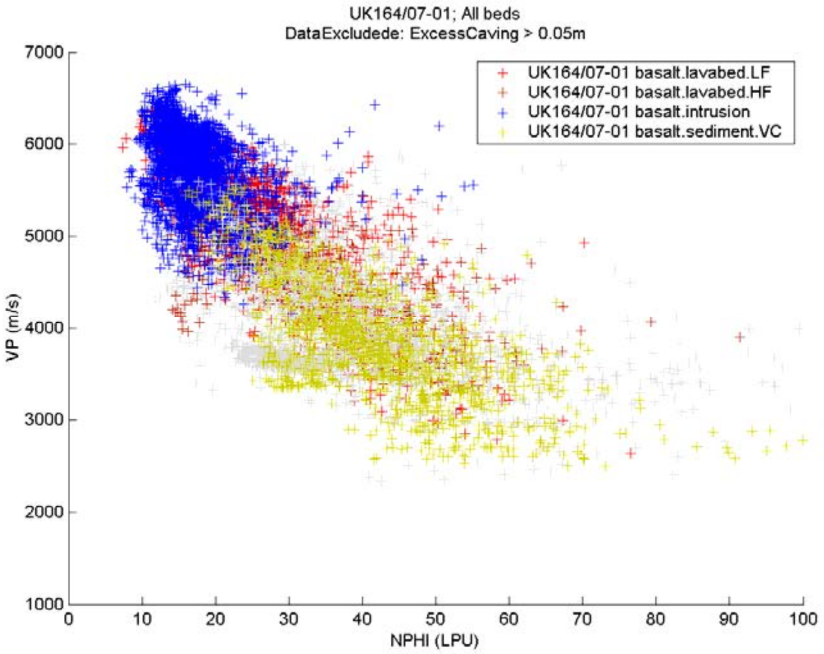

Figure 6.13. Cross plot of seismic velocity, VP, versus neutron porosity, NPHI, from basaltic volcanic units in UK164/07-01. Colour coding as Figure 6.10

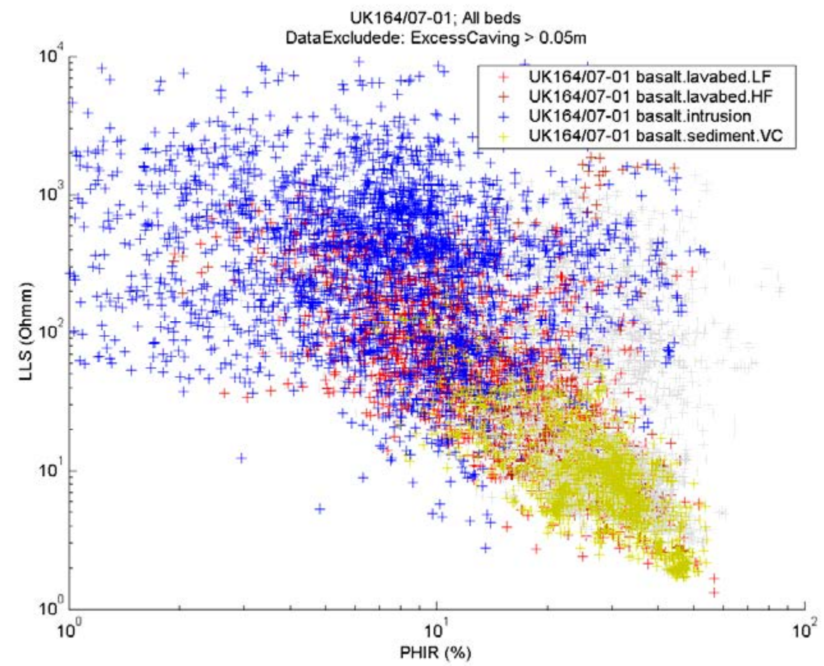

Figure 6.14. Cross plot of resistivity measured by short penetration laterolog, LLS, versus porosity calculated from the density log, PHIR,, from basaltic volcanic units in UK164/07-01. Colour coding as Figure 6.10. Note how the grey "excluded" data points are offset towards higher values (of both porosity and resistivity) than the main data swarm.

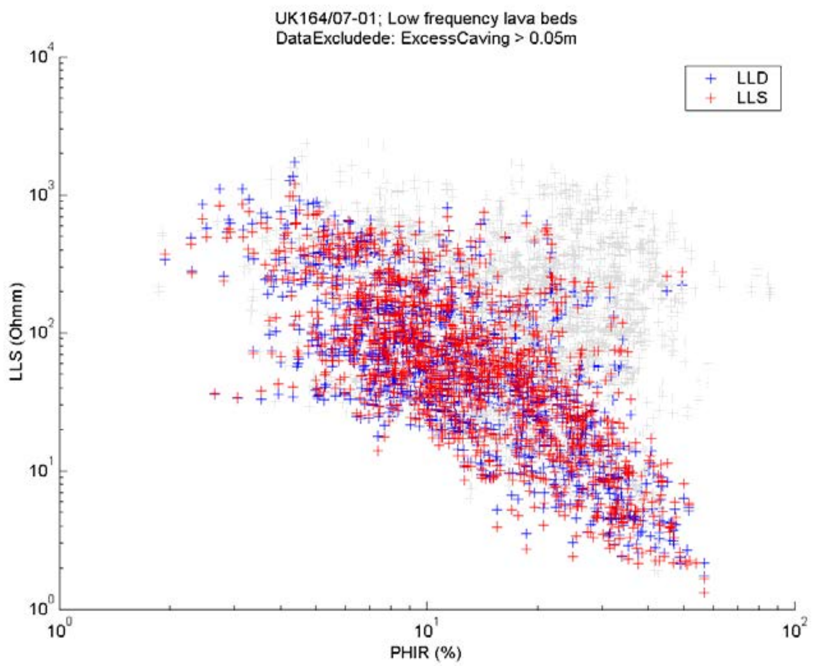

Figure 6.15. Cross plot of resistivity measured by short and deep penetration laterolog, LLS and LLD, versus porosity calculated from the density log, PHIR,, from units of basaltic lavabeds in UK164/07-01. Colour coding according to instrument type. Note how the grey "excluded" data points are offset towards higher values (of both porosity and resistivity) than the main data swarm.

7 Well UK164/25-01 and -01z

The well UK164/25-1 (59º11’45.08”N 07º08’56.11”W) was drilled in 1988 with BP as operator. The main objective was a potential Mesozoic closure. The well penetrated a ca. 200 m thick succession of Paleocene basalts and - mostly tuffaceous –sediments in the 12.25” hole at a depth of ca. 1830-2030 m. Due to drilling problems the well was side-tracked and well UK164/25-1z penetrates the same basaltic succession. The horizontal distance between UK164/25-1 and UK164/25-1z is less than 30 m in the depth interval we are concerned with in this study. The condition of the original borehole (UK164/25-1) is variable in the depth interval of interest, and considerable caving is causing reduced reliability of the measured logs. The hole-condition of UK164/25-1z is good-excellent in most of the depth interval of interest. Although the log response from the volcanic units in UK164/25-01 is influenced by the hole condition and therefore not completely representative, it has been considered worthwhile to perform a detailed correlation between UK164/25-01 and UK164/25-01z as this to some extent will illustrate the lateral variations occurring within a volcanic succession of basaltic rocks. Brief descriptions of all units in the volcanic succession in the two wells and of basaltic intrusives in the early Paleocene and Mesozoic succession below the volcanics are given below.

7.1 UK164/25-1z

The suite of log measurements in UK164/25-1z comprises

- calliper, CAL,
- natural gamma radiation, GR,
- sonic transit time (P-wave), DT,
- density, RHOB,
- neutron porosity, NPHI,
- resistivity measured with a dual induction tool, ILD and ILM,
- resistivity measured with a dual laterolog tool, LLD and LLS
- spectral gamma, K, Th and U,
- photo electric effect, PEF.

The relevant log traces from the depth interval of interest are presented as enclosure 2. However, sonic transit time is recalculated to sonic velocities and presented as the trace, VP. A part of the log from 1820-2020 m is shown as Figure 7.1.

7.1.1 Unit descriptions

In UK164/25-1z we have interpreted two intervals of effusive basaltic rocks separated by an interval of tuffaceous mudstones (Figure 7.1). In addition at least nine intrusive basaltic units are seen below the intervals of effusive basaltic rocks. The basaltic intervals are identified as such based on their uniformly low natural gamma radiation combined with high density and high seismic velocity relative to the neutron porosity. Description of side wall cores and the completion report (including a composite log) have also been used.

Within the ca. 75 m thick upper interval of effusive rocks we have separated four low porosity units (164251z-F1, -F2, -F3 and -F4, presumably effusive in origin). Two high porosity units (presumably volcaniclastic) separate units -F2 from -F3 and -F3 from -F4.

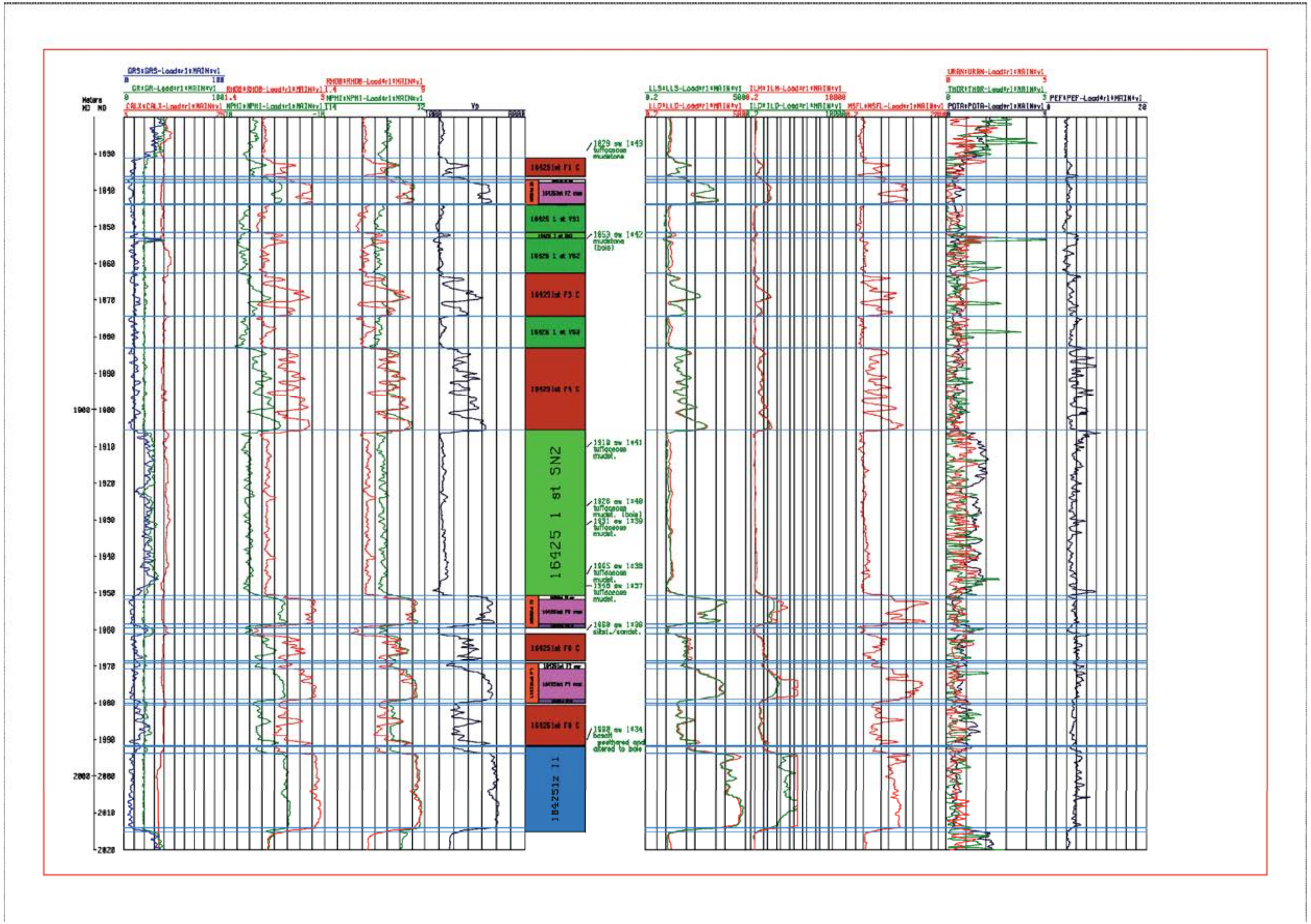

Figure 7.1. Compressed composite log showing interpretation of extrusive basaltic rocks in the well UK164/25-01z. For details see the full log (Enclosure 2).

The 4.5 m thick unit *164251z-F1* is possibly representing a thin individual flow. However, in most aspects it is different from typical low frequency lava beds. It is fairly thin, the upper crust is not very distinct; the core does not attain the low porosities generally observed in low frequency lava bed units, and the characteristic abrupt basal porosity drop is not developed at the base of unit -F1. It is tentatively classified as a high frequency lava bed unit, although only comprising one bed. However unit 16425z-F1 is almost resting directly on top of unit -F2, and it is possible that these two units should be considered a single unit. In this case unit 16425z-F1 is interpreted as an abnormal flow top.

The log pattern of the 7.5 m thick unit *164251z-F2* has a fair overall resemblance with the general log pattern for basaltic flow-units described by Planke (1994). An upper porous crust and a massive core are clearly identified on all the porosity-related logs. However, in some aspects its log pattern is distinctly different from that of typical low frequency lava beds in other wells. The core of this unit is not showing the high porosity gradients characterising flows of similar thickness in 209/05-1. If it not was for a fairly porous zone in the lower part of the core of 164251z-F2, we would say that the porosity of the core is constant. The density and the sonic velocity is higher (for the same apparent porosity) than in the flows of similar thickness in 209/05. There is very little separation between the induction logs.

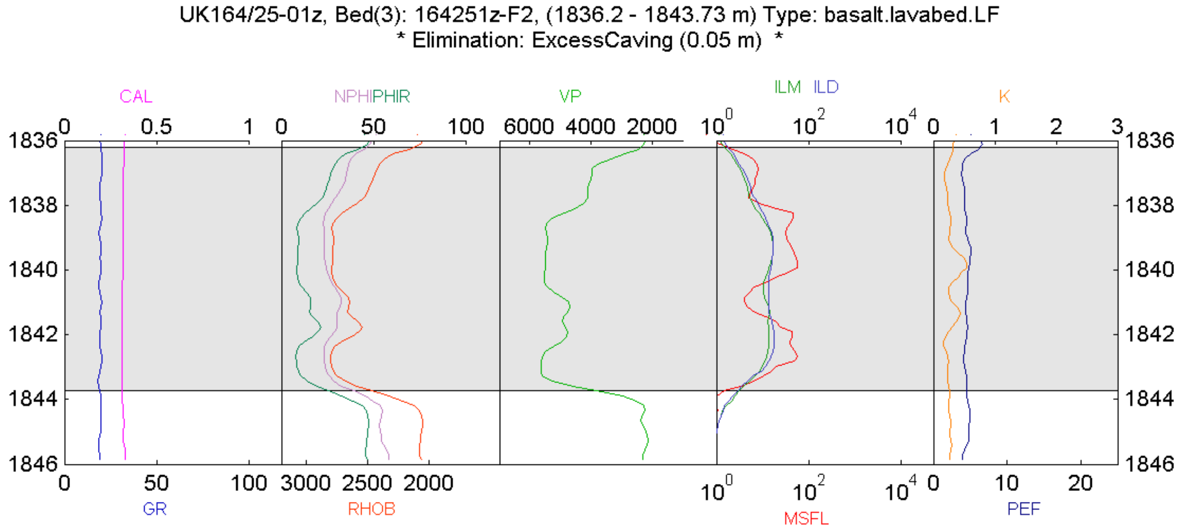

Figure 7.2. Log traces from depth interval 1836-1846 m in well UK164/25-01z showing unit 16425z-F2.

Unit *16425z-F3* is an 11.4m thick high frequency lava bed unit. Three distinct low porosity layers (ca. 1, 3 and 2 m thick) separated by thin intervals of high porosity (comparable to volcaniclastic sediments) are interpreted from the logs in this unit. It is thus likely that unit -F3 comprises three basaltic lava beds that possibly are interbedded by sediments.

The 22.5 m thick unit *16425z-F4* is also a unit of high frequency lava beds. Six distinct low porosity layers (1-3 m thick separated by thin high porosity layers are observed within unit -F4. However in contrast to unit -F3, porosity dependent parameters of the high porosity layers of this unit generally not attain values comparable to volcaniclastic sediments.

The sediment units *16425z-VS1*, *-VS2* and *-VS3* separating -F2, -F3 and -F4 are interpreted as volcaniclastic mudstones. The natural gamma radiation of these mudstones is low, fairly constant (7-12 GAPI) and fall in exactly the same range as the gamma radiation from the flow units F1, F2, F3 and F4. Concentrations of K, Th and U from the spectral gamma are also all falling in the same range as in the flow units of the upper basaltic interval in UK164/25-1z. Seismic velocities and densities of units -VS1 -VS2 and -VS3 fall on the same general trend as that of the flow-units (Figure 7.9). However, porosity is higher and density and velocity and resistivities are lower than for lava bed units. The separation of the two laterologs (Figure 7.1) might be the result of invasion of drilling fluids into these formations. If so indicating that units 16425z-VS1 -VS2 and -VS3 are permeable, compared to the lava beds. Although this is quite realistic, the observed separation are more likely to be a Groningen effect caused by imperfect processing of resistivity measurements in the presence of large resistivity contrasts.

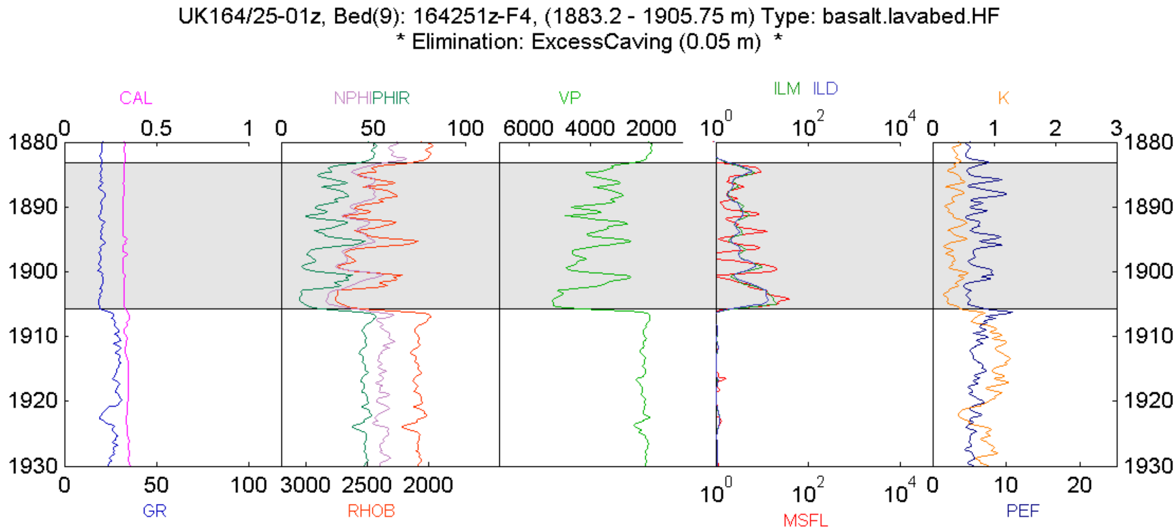

Figure 7.3. Log traces from depth interval 1880-1930 m in well UK164/25-01z showing unit 16425z-F4.

A ca. 50 m interval of tuffaceous mudstones (1905-1949 m) is treated as one unit, *164251z-SN2*. It resembles the volcaniclastic units, 164251z-VS1 and -VS2 in most respects, and five side wall cores from this unit are all described as tuffaceous mudstones. The most significant differences are that the natural gamma radiation of 164251z-SN2 is somewhat higher (25-30 GAPI) than that of the basaltic volcaniclastic sediment-units (and the flow-units); especially the potassium concentration (0.75-1%) is higher than in the basaltic volcaniclastic sediment-units and the flow-units (less than 0.5%). Both the gamma radiation and the potassium content of 164251z-SN2 are somewhat lower than in mudstones above the two upper basaltic intervals. The log pattern of this unit is therefore considered to support the description of the side wall cores.

Unit *164251z-F5* (1950-1959 m) is a low frequency lava bed. It has only a thin (1 m) not very obvious upper crust. The core is about 8 m thick and very massive. The apparent porosity is mostly below 20 LPU and the density is ca. 2800 kg/m^3. A slightly porous zone is seen at 1956 m, in the lower part of the unit. The induction logs display considerable separation in most of the core, but not in the low-porosity zone around 1956 m.

The log pattern of unit *164251z-SN3* (1959.3-1961.6m) resembles that of unit 164251z-SN2 in almost all aspects. However, the measured bulk density is about 200 kg/m^3 lower than in 164251z-SN2 indicating a significantly lower fraction of basaltic material in 164251z-SN3 than in164251z-SN2. A side wall core from 1960 m described as silty sandstone confirms this interpretation.

Unit *164251z-F6* (1962-1970 m) is different from any of the previously described basaltic units. The fluctuations of the measured parameters are larger (and more frequent) than in units composed of a single lava bed and significantly smaller than between individual beds in units interpreted as composed of several lava beds. All the way from top to bottom, the unit it is generally more porous (ca. 30-50 LPU), has lower sonic velocities and is more dense than units we have interpreted as basaltic lava beds and less porous and more dense than units interpreted as volcaniclastic sediments. The resistivity is high compared to saturated sediments, but low compared to lava beds (ca. 1-10 Ωm). Unit 164251z -F6 is characterised by laterolog separation of the same magnitude as seen in "normal sediments" above and below in the well. This separation may be caused by improper correction for bed distortions and may be an example of the Groningen effect. However, it could also be caused by invasion of drilling fluids into the unit indicating that it is fairly permeable compared to lava beds. We suggest that unit 164251z-F6 is a dense, volcanic breccia or low porosity volcaniclastic sediments rather than a lava bed (or a composite of lava beds).

The log pattern of unit *164251z-F7* (1970-1979 m; Figure 7.4) corresponds closely to the log patterns described by Planke (1994) in ODP boreholes from East Greenland and Norway continental margin. The apparent porosity decreases gradually downwards through the upper 2.5 m of the unit, from ca. 45 LPU at the top to 25 LPU ca. 2.5 m below the top. Minimum porosity (20 LPU is found approximately 1.5-2 m above the bottom of the unit. In this unit the boundary between the upper crust and the core is somewhat arbitrary on most of the logs. The overall maximum change of gradient within the unit of neutron porosity, bulk density and seismic velocity may be used as a guide. The subdivision of this flow into an upper crust and a core is best seen as a distinct separation of the induction logs within the core.

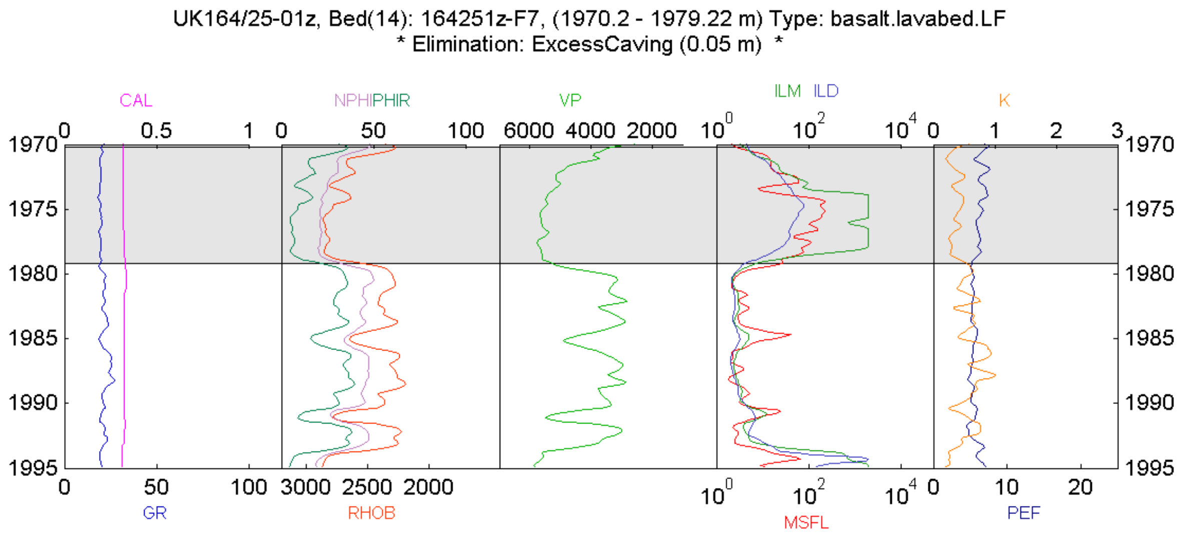

Figure 7.4. Log traces from depth interval 1970-1995 m in well UK164/25-01z showing unit 16425z-F7.

Unit *164251z-F8* (1979-1994 m; Figure 7.5) is comparable to unit 164251z-F6. Overall the porosity is slightly lower in 164251z-F8 than in -F6, and related logs varies correspondingly. The natural gamma radiation and the potassium concentration are slightly higher (28-27 GAPI/0.2-1%) than in the other typical basaltic units in this well (18-22 GAPI/0.2-0.6%) including the high-porosity units 164251z-VS1, -VS2 and -VS3). A side wall core at 1990 m, described as basalt, is sampled in one of two intervals with low neutron porosity and natural gamma radiation. This side wall core is therefore not representative of the unit as such. The higher natural radiation and potassium concentration in unit 164251z-F8 – and to less extent -F6 – indicates together with the relatively high porosity that these two units represents volcaniclastic material that have been added some potassium-rich material during transport and emplacement. Alternatively the two units represent volcanic products of a slightly more evolved magma than that producing the rest of the basaltic successions in this well.

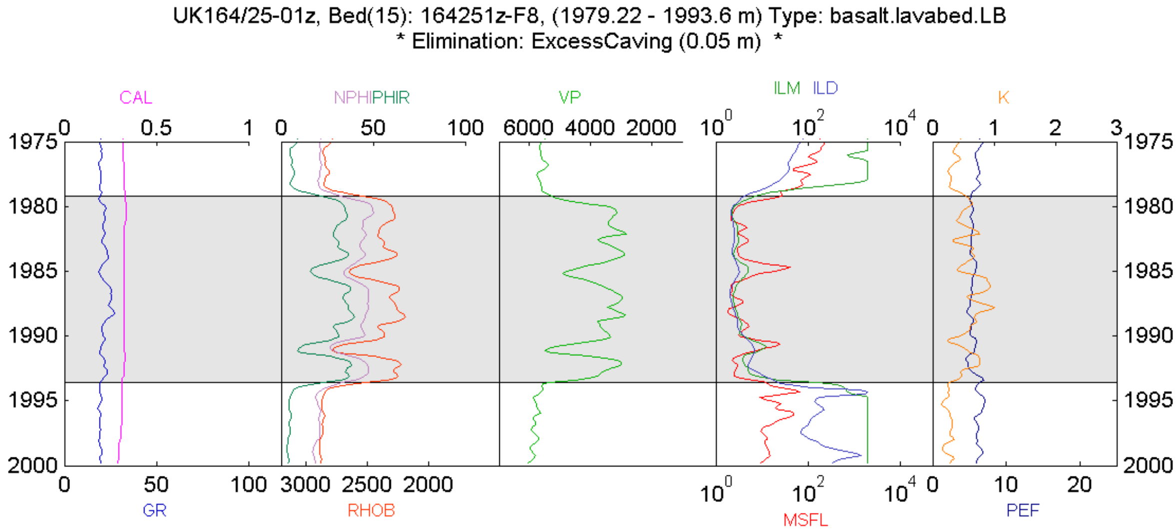

Figure 7.5. Log traces from depth interval 1975-2000 m in well UK164/25-01z showing unit 16425z-F8.

Unit *164251z-I1* (Figure 7.6) has a simple log pattern. Very narrow gradient zones are seen both at the top and bottom of this unit. Neutron porosity, bulk density and sonic travel time is almost constant throughout the unit. Similar log patterns have been attributed to hypabyssal intrusions in other wells (e.g. Boldreel, in press); it is thus interpreted as an intrusive unit (sill). The resistivity (e.g. MSFL) is less constant and may indicate subtle variations within the unit. The separation between the two induction logs is large, but the sensitivity of the deep penetration induction log is unfortunately not good enough to allow a quantification of the separation.

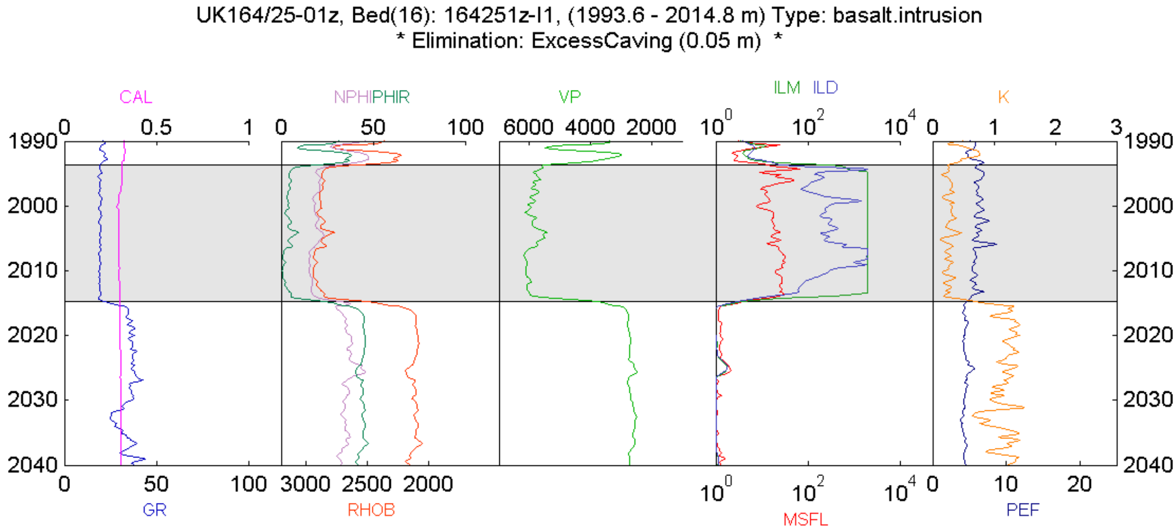

Figure 7.6. Log traces from depth interval 1990-2040 m in well UK164/25-01z showing unit 16425z-I1.

Eight more intrusive basaltic units have been interpreted at various levels deeper in the well (Enclosure 2). A combination of low gamma radiation, high density and high seismic velocities is characterising these units. Data points from the intrusives fall generally along the same trend as the lava beds and volcaniclastic units higher in the well. It should be noted that some of the intrusive units are distinctly different from the rest in several intrinsic parameters. This is best seen in cross plots (e.g. Figure 7.8, Figure 7.9).

7.2 UK164/25-1

The suite of log measurements in UK164/25-1 comprises

- calliper, CAL,
- natural gamma radiation, GR,
- sonic transit time (P-wave), DT,
- density, RHOB,
- neutron porosity, NPHI,
- resistivity measured with a dual induction tool, ILD and ILM,
- resistivity measured with a dual laterolog tool, LLD and LLS
- spectral gamma, K, Th and U,
- photo electric effect, PEF.

However, the DT- log and the electrical logs are only run down to ca. 1930 m. The relevant log traces from the depth interval of interest are presented as enclosure 2. However, sonic transit time is recalculated to sonic velocities and presented as the trace, VP. A part of the log from 1820-2020 m is shown as Figure 7.12.

The resistivity logs and the sonic logs are missing below 1900 m, due to problems with the stability of the borehole. The quality of the other logs is of inferior quality (compared to the logs from the deviated well UK164/25-01z). In the interval from 1800-1900 m most logs are of moderate to poor quality as caving also is a problem throughout this interval.

7.2.1 Unit descriptions

In the description of the basaltic log units in this well we focus on comparison with the deviated well, as the two wells provide a possibility to compare lateral lithological changes occurring over less than 100 m.

Unit *164251-F1* (1832-1845 m) is characterised by a gradual overall increase of neutron porosity from the top to the bottom. The other porosity related logs display a corresponding trend. The natural gamma radiation is increasing in the top 2-3 m. Subtle internal layering is apparent in all logs except the “chemical logs”. The upper crust are characterised by high porosity and increased natural gamma radiation (>10 GAPI). The lower part of the unit is characterised by separation of the induction logs.

Unit *164251-VS1* (1845-46 m) is a thin high porosity/low density interval. Gamma radiation is in the same range as the typical basaltic units of this well (7-12 GAPI). We interpret this layer as volcaniclastic sediments.

Unit *164251-F2* (1846-1849 m) is interpreted as a thin individual flow separated from the overlying unit by a thin caved interval. The unit is not well defined as the logs are strongly influenced by caving of the borehole at this level.

Unit *164251-VS2* (1849-1854 m) is a high porosity/low density interval, presumably volcaniclastic sediments. A thin interval, *164251-SN1*, within this unit is characterised by gamma radiation around 40 GAPI. 164251-SN1 is presumably a non-volcanic sediment. We use it, as marker believing it is identical to 164251z-SN1.

Unit *164251-F3* (1854-1880 m) is interpreted as a high frequency lava bed unit. It comprises a number of low porosity layers. Two or three fairly distinct layers separated by thin intervals of high neutron porosity (comparable to volcaniclastic sediments) are seen in the lower part of the unit. Layers with high bulk density and seismic velocity in the upper part of this unit are not matched by resistivity and porosity anomalies. The upper part of this unit could thus be volcaniclastic rather than lava beds. In the thickest individual bed the induction logs are separated.

Unit *164251-VS3* (1880-1883 m). The unit has high porosity, fairly low density and is otherwise also comparable to units -VS1 and -VS2

Unit *164251-F4* (1883-1906 m; Figure 7.7) is a high frequency lava bed unit with at least five distinct low porosity layers separated by thin high porosity layers that can be identified within this unit according to the neutron porosity, bulk density and high resolution resistivity (MSFL) logs. One of these layers is not seen on the sonic log and the medium and deep penetrating resistivity logs. The high porosity layers of this unit do attain values comparable to volcaniclastic sediments.

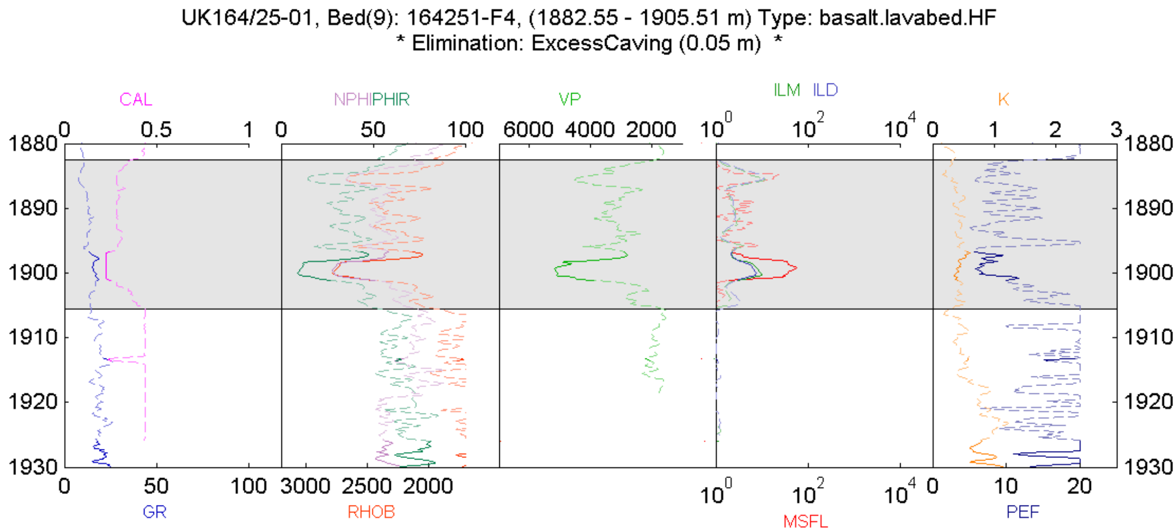

Figure 7.7. Log traces from depth interval 1880-1930 m in well UK164/25-01z showing unit 16425z-F4.

Unit *164251-SN2* (1906-1950) is not well defined due to the poor quality of the logs in this interval. However, the top is fairly distinct and picked based on a slight increase in the natural gamma radiation close to the top of an extremely caved part of the well. The base of the unit is also picked based on change in the level of natural gamma radiation.

Below unit 164251-SN2 we have interpreted five high density low porosity basaltic units, *164251-F5*, *164251-F6*, *164251-F8* and *164251-I1*. The units 164251-F5, 164251-F6 and 164251-F8, are separated by thin intervals with high gamma radiations at 1958-59 m and 1965-67 m. Both intervals are associated with low neutron porosity and high bulk density. The spike at 1958-59 m is associated with significant caving. Units, 164251-F5, and 164251-F6 are interpreted as comprised of basaltic lava beds. The boundary between the two units is however not well defined in this well due to the quality of the logs. Unit 164251-F6 lies in the same depth interval as unit 164251z-F6 in the deviated well (see enclosure 5).

Unit 164251-F8 is characterised by higher natural gamma radiation, higher porosity and lower bulk density than the basaltic units above. Gamma radiation and potassium concentration are comparable to the same measurements from unit 164251-F8 in the deviated well, UK164/25-01z.

Unit 164251-I1 (1992-2017 m) is characterised by very high density (2850 kg/m^3), low natural gamma radiation and neutron porosity. This combined with the blocky log pattern indicates that the unit is a hypabyssal intrusion.

Four additional intrusive units (*164251-I2*, 2341-2350; *164251-I3*, 2425-2612; *164251-I4*, 2806-2808 and *164251-I5*, 2813-2819 m) are interpreted due to high density (2600-2760 kg/m^3) and low gamma radiation (11-12 GAPI in the two upper and around 25 GAPI in the two lower).

7.3 Correlation between UK164/25-01 and UK164/25-01z

A tentative stratigraphic correlation between UK164/25-01 and UK164/25-01z is shown in Table 7.1 (more details can be found in the graphical presentation enclosure 5). The distance between the two bore-holes is small (ca 5 m at 1830 m increasing to ca. 30 m at 2800 m), so we would expect the correlation to be simple.

Generally, there is no problem correlating the basaltic units between the two wells. However, there are significant differences between units we consider stratigraphic equivalents. Some of these differences may be explained by different hole conditions in the two wells during logging and variable instrument performance in general. Comparing the measured gamma radiation from the two wells, it can be observed that the measured radiation in UK164/25-01 generally is less than in the same interval in UK164/25-01z. The problem seems to be worse at low radiations. The difference in gamma measurements is presumably due to instrument calibration. We expect the values from the deviated hole to be closest to the correct values

Despite the problems with some of the logs we are still able to compare the two wells fairly detailed:

In well UK164/25-01z units 164251z-F1 and -F2 are clearly separated. However, in UK164/25-01 they appear to be merged to a single unit, 164251-F1.

Unit 164251-F2 has no obvious counterpart in well UK164/25-01z.

Unit 164251-F4 (interpreted as a high frequency lava bed unit by correlates excellently with unit 164251z-F4.

Overall, units 164251-F5 to 164251-F8 correlates well to 164251z-F5 to 164251z-F8.

The intrusives 164251-I1 to 164251-I2 correlates excellently to 164251z-I1 to 164251z-I2 and the depths matches indicating this are sub-horizontal sills.

Units 164251-I3 and 164251z-I3 are comparable. Both the log pattern and values of measured data (except natural gamma radiation) compare well (Enclosure 5). However, they are offset by 40 m. indicating significant dip of the intrusive. The exact dip can not be calculated as well direction survey only is available for UK164/25-01z.

The induction logs may be used as a tool to distinguish between dykes on the on hand and sills and lava beds on the other hand. The resistivity measured with induction tools separate so the ILM measurements tend to be higher than ILD measurements in sills and lava beds, while ILM measurements tend to be lower than ILD measurements in dykes (Figure 7.11). The separation of the induction logs in sills and lava beds is may be caused by shoulder effects due to the high resistivity contrast at the top of sills and lava beds, and the separation of the induction logs in dykes are presumably to some extent a geometric effect. However, vertical fractures in sills and lava beds and horizontal fractures in dykes would give a similar response. Modelling and possibly reprocessing of the logs is required to investigate the possible influence of fractures in detail.

In order to quantify how significant the differences are between the volcanic successions in the two wells we compare the vertical acoustic transmission (along the well trajectory). With vertical acoustic transmission we refer to the amount of energy that would be transmitted directly through the unit assuming the only energy loss is due to reflection. It is calculated by multiplication of transmission coefficients. The transmission is a meaningful physical value, which relates to the objectives of the SeiFaBa project, and it is simple to compare the transmission through the same unit in the two wells (Table 7.1; Figure 7.17).

If the sonic logs in the two wells are properly calibrated and otherwise representative and the calculated acoustic transmission of a unit varies significantly between the two wells we can safely assume that the unit's acoustic character changes between the two wells. However, if the calculated transmission loss is the same, it is possible the units are identical. There may still be significant differences that can be attributed to "bedding style". These differences would be manifest in the "stratigraphic filters" (See chapter #0). However, as stratigraphic filters just like logs are series, not single numbers, they are not necessarily any better than the raw logs for strata comparisons.

For the layers where we have been able to calculate the vertical acoustic transmission, there are considerable differences between the two wells. The differences are largest for units with low transmission (lava beds) and smallest for volcaniclastic and siliciclastic sediments. There are presumably considerable "well influences" due to the different "quality" of the two holes on the measurements of bulk density and acoustic velocity. Some of the observed differences should thus be ascribed to "well influences", which is difficult to quantify. However, if the transmission values presented in Table 7.1 and Figure 7.17 are representative, there is a significant change in acoustic properties over 50 m indicating that transmission through the basaltic succession in UK164/25-01 an UK164/25-01z not is completely described by 1D scattering. A complete description should include 3D scattering due to lateral variations of acoustic properties of the basaltic rocks.

Table 7.1. Comparison of acoustic transmission through the same intervals in UK164/25-01 and UK164/25-01z.

UK164/25-01							UK164/25-01z					
Bed	Z_{top}	H_{tot}	T_a	T_{ac}	T_a'		Bed	Z_{top}	H_{tot}	T_a	T_{ac}	T_a'
							164251z-F1	1831.1	4.5	0.9552		
164251-F1	1831.9	12.8	0.8281	0.8281	0.9854		164251z-VS1	1835.5	0.7	0.9961	0.9011	0.9898
							164251z-F2	1836.2	7.5	0.9470		
164251-VS1	1844.7	1.0	0.9961									
164251-F2	1845.8	3.7	0.9347	0.9253	0.9897		164251z-VS2a	1843.7	9.2	0.9109	0.9109	0.9899
164251-VS2a	1849.4	2.8	0.9939									
164251-SN1	1852.3	1.3	0.9991	0.9991	0.9994	1	164251z-SN1	1852.9	1.1	0.9981	0.9981	0.9983
164251-VS2b	1853.6	0.5	0.9974	0.7110	0.9883		164251z-VS2b	1854.0	9.2	0.9801		
164251-F3	1854.1	25.8	0.7185				164251z-F3	1863.2	11.4	0.8427	0.8106	0.9928
164251-VS3	1879.9	2.6	0.9922				164251z-VS3	1874.6	8.6	0.9815		
164251-F4	1882.6	23.0	0.7858	0.7858	0.9896		164251z-F4	1883.2	22.5	0.8328	0.8328	0.9919
164251-SN2	1905.5	44.1	NaN		NaN		164251z-SN2	1905.8	44.8	0.8855		0.9973
164251-F5	1949.6	8.4	NaN		NaN		164251z-F5	1950.6	8.7	0.9257		0.9911
164251-SN3	1958.0	1.0	NaN		NaN		164251z-SN3	1959.3	2.3	0.9539		0.9801
164251-F6	1959.0	17.2	NaN		NaN		164251z-F6	1961.6	8.6	0.9055		0.9885
			NaN		NaN		164251z-F7	1970.2	9.0	0.9827		0.9981
16425	1976.2	15.4	NaN		NaN		164251z-F8	1979.2	14.4	0.8696		0.9903
164251-I1	1991.6	25.3	NaN		NaN		164251z-I1	1993.6	21.2	0.9712		0.9986
164251-I2	2340.7	9.0	NaN		NaN		164251z-I2	2338.9	9.2	0.9874		0.9986
164251-I3	2434.8	187.5	NaN		NaN		164251z-I3	2463.5	49.5	0.9688		0.9994
							164251z-I4	2877.3	3.2	0.9900		0.9969
							164251z-I5	2897.3	122.2	0.9271		0.9994
							164251z-I6	3044.5	41.9	0.8751		0.9968
							164251z-I7	3257.0	45.5	0.8418		0.9962
							164251z-I8	3337.8	7.0	0.9931		0.9990
							164251z-I9	3417.9	14.2	0.7440		0.9794

Units have been groupe to ensure best possible correelation (see enclosure 5). Table headings: Z_{top}: Meassured depth to the top of the unit. H_{tot}: The thickness of the unit. Ta. Transmission trough the unit. T_{ac}. Transmission trough a group of units. T_a': Normalised transmission.

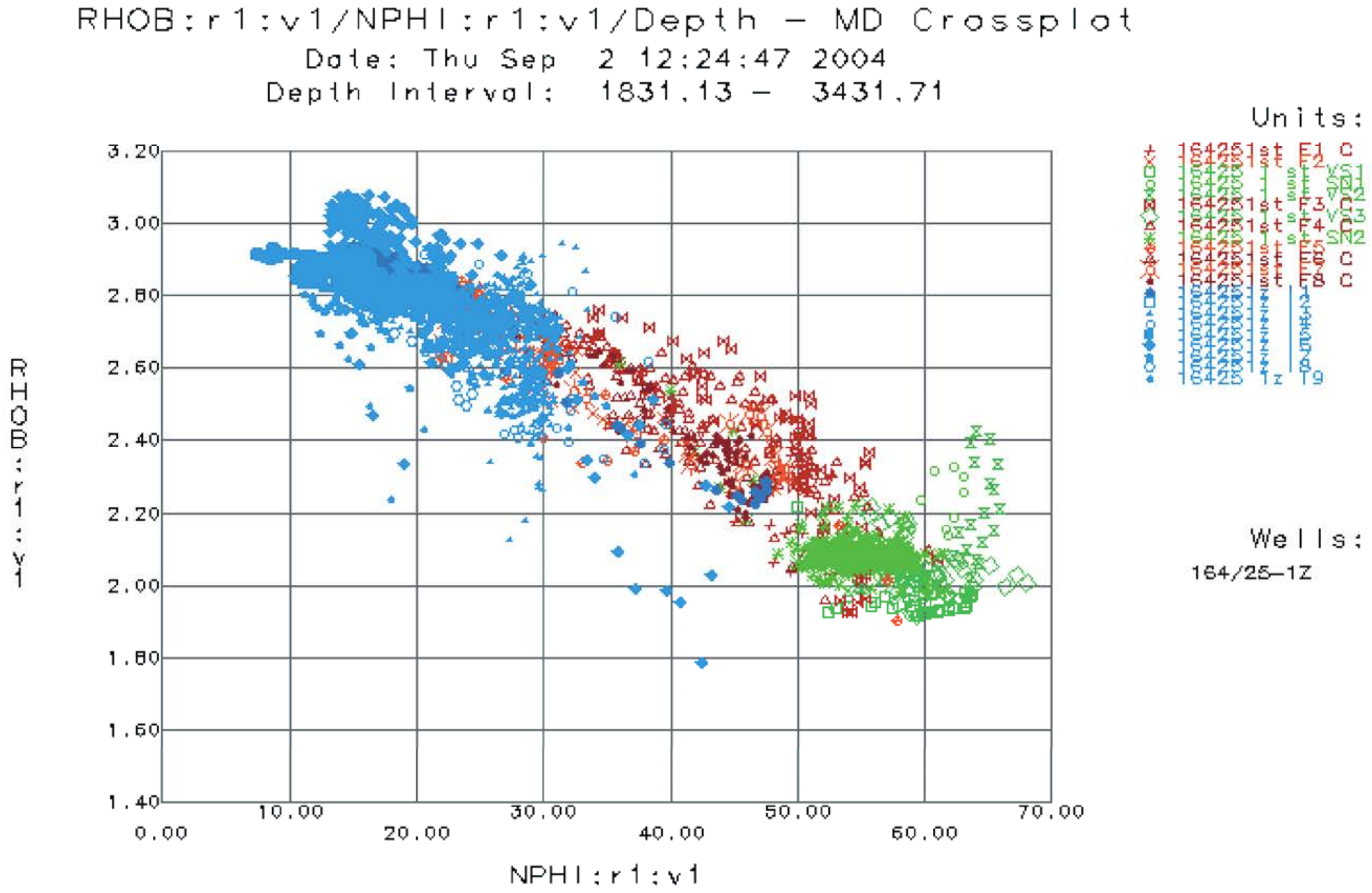

Figure 7.8. Cross plot of neutron porosity (NPHI) versus measured bulk density (RHOB) in UK164/25-01z. All basaltic units indicated in enclosure 2 are plotted in the diagram.

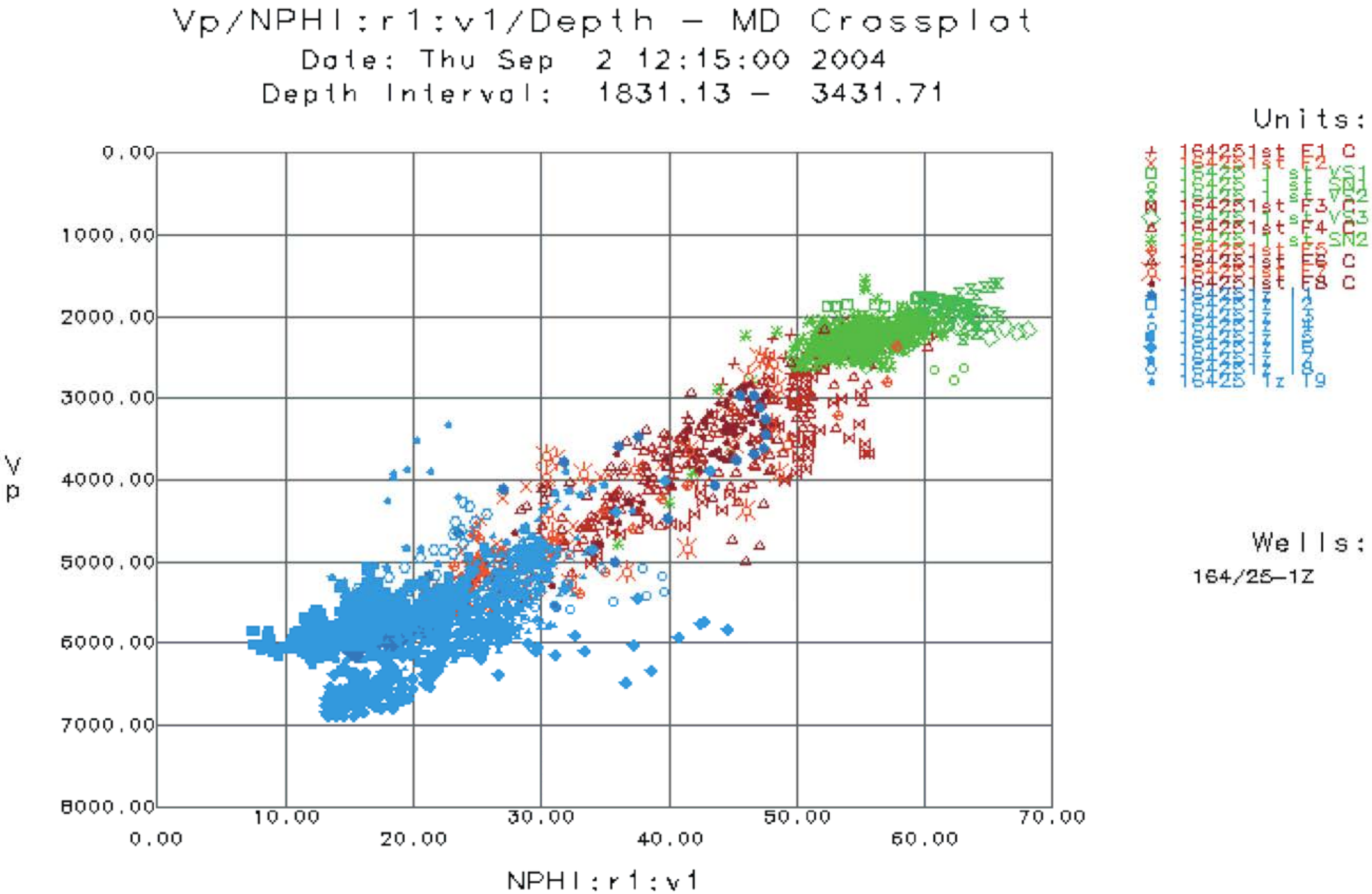

Figure 7.9. Cross plot of neutron porosity (NPHI) versus acoustic velocity (VP) in UK164/25-01z. All basaltic units indicated in enclosure 2 are plotted in the diagram.

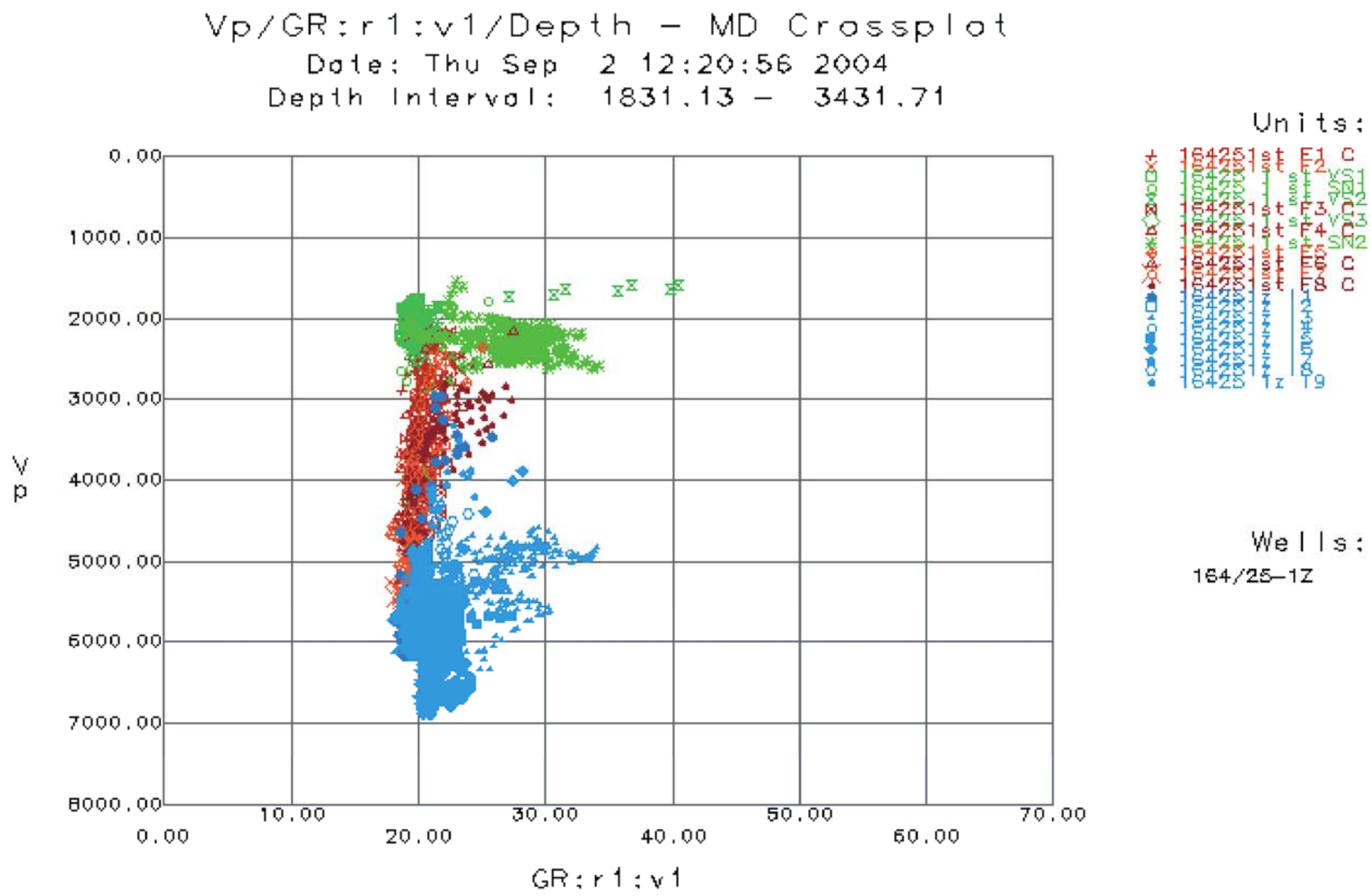

Figure 7.10. Cross plot of gamma radiation (GR) versus acoustic velocity (VP) in UK164/25-01z. All basaltic units indicated in enclosure 2 are plotted in the diagram.

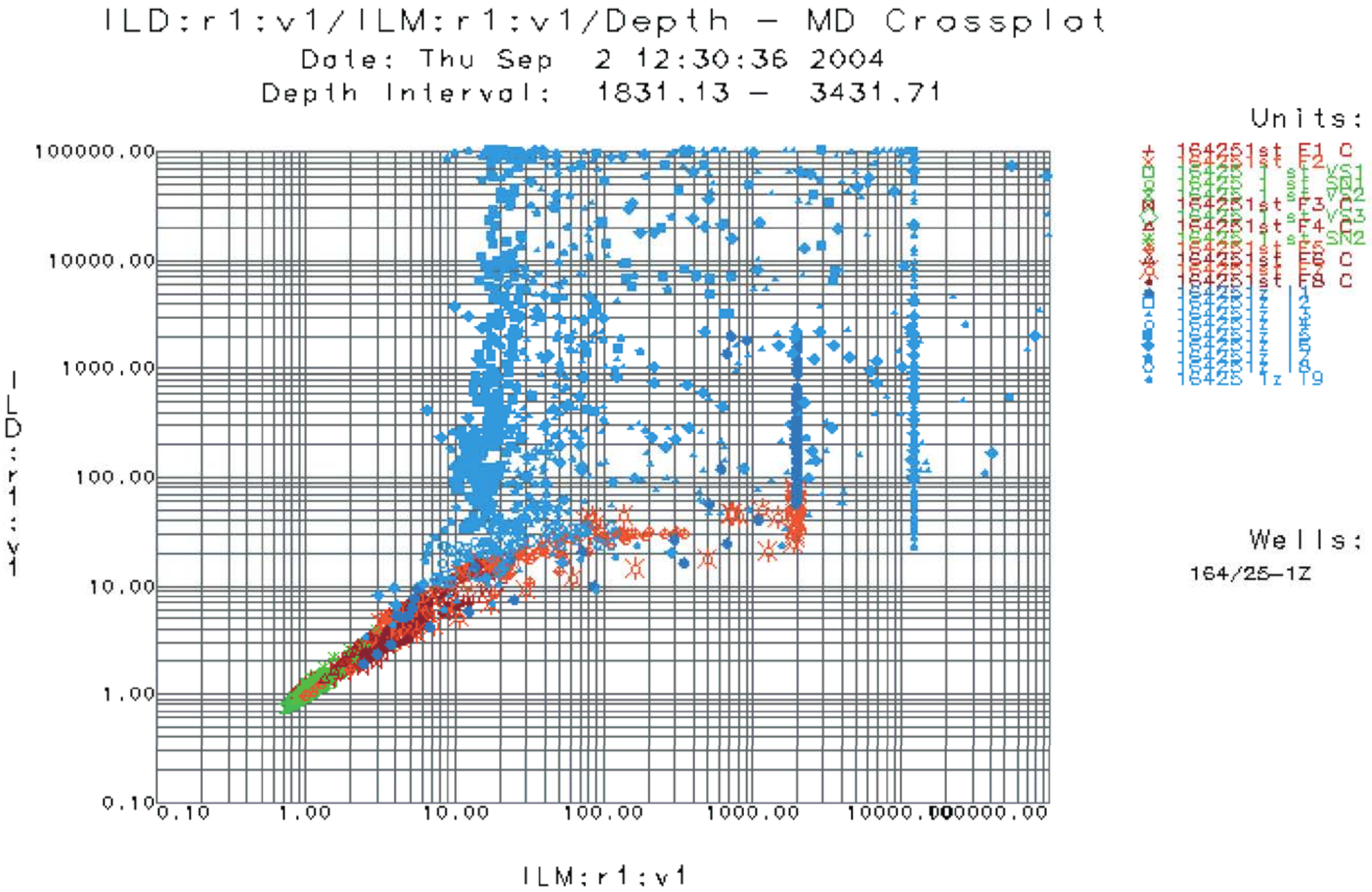

Figure 7.11. Cross plot of medium penetration (ILM) versus deep penetration induction logs (ILD) in UK164/25-01z. All basaltic units indicated in enclosure 2 are plotted in the diagram.

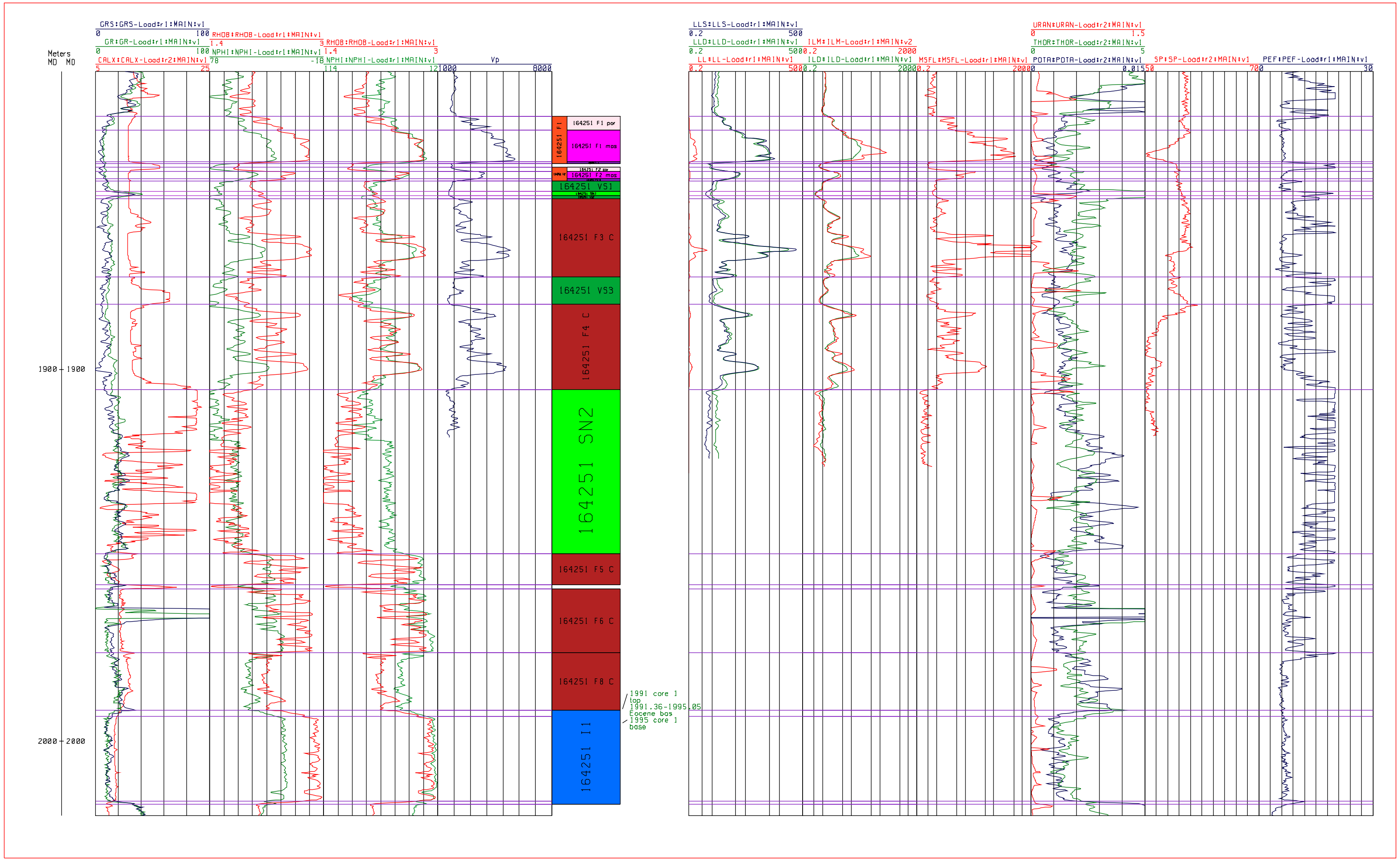

Figure 7.12. Compressed composite log showing interpretation of extrusive basaltic rocks in the well UK164/25-01. For details see the full log (Enclosure 2).

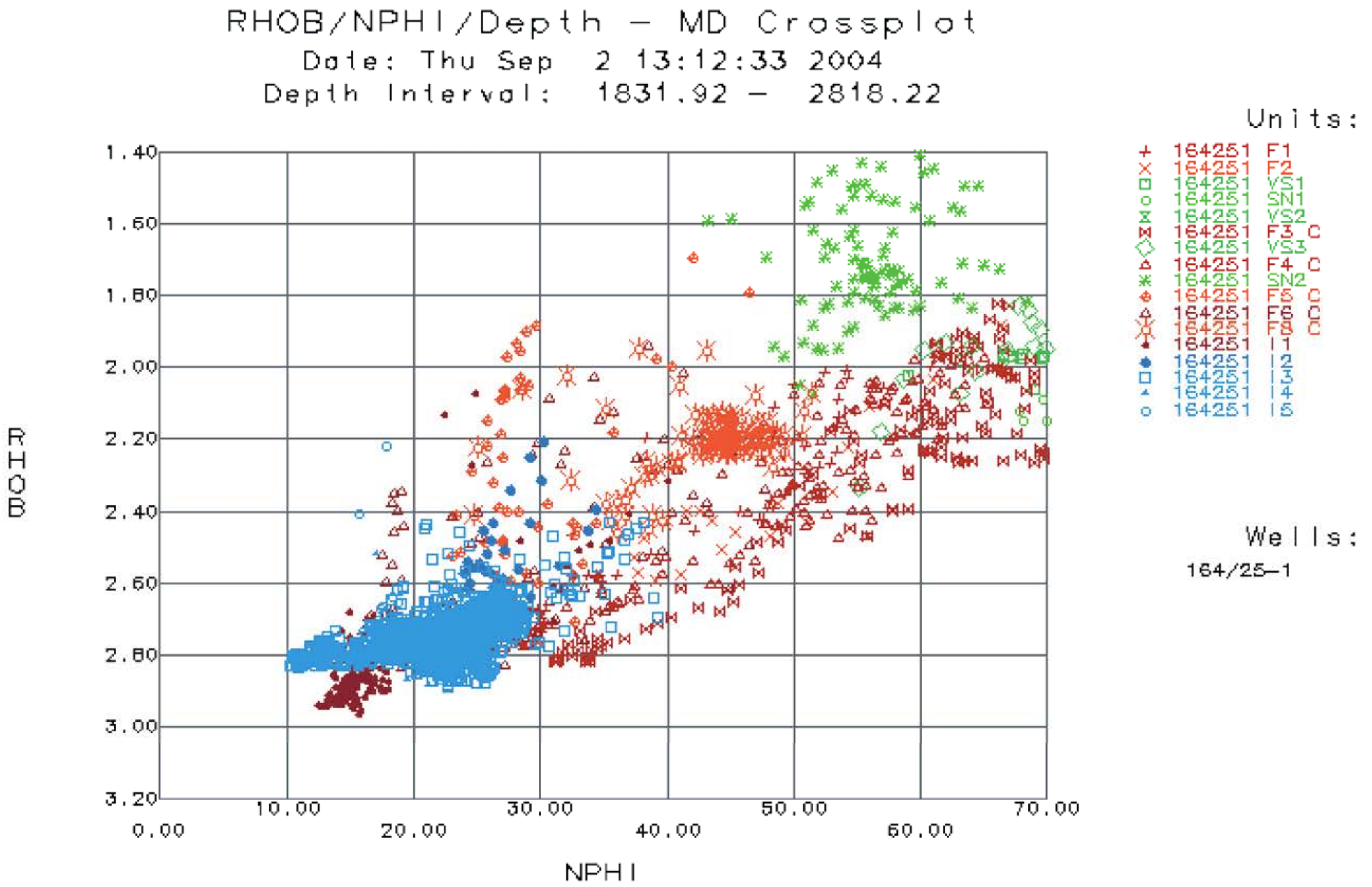

Figure 7.13. Cross plot of neutron porosity (NPHI) versus measured bulk density (RHOB) in UK164/25-01z. All basaltic units indicated in enclosure 2 are plotted in the diagram.

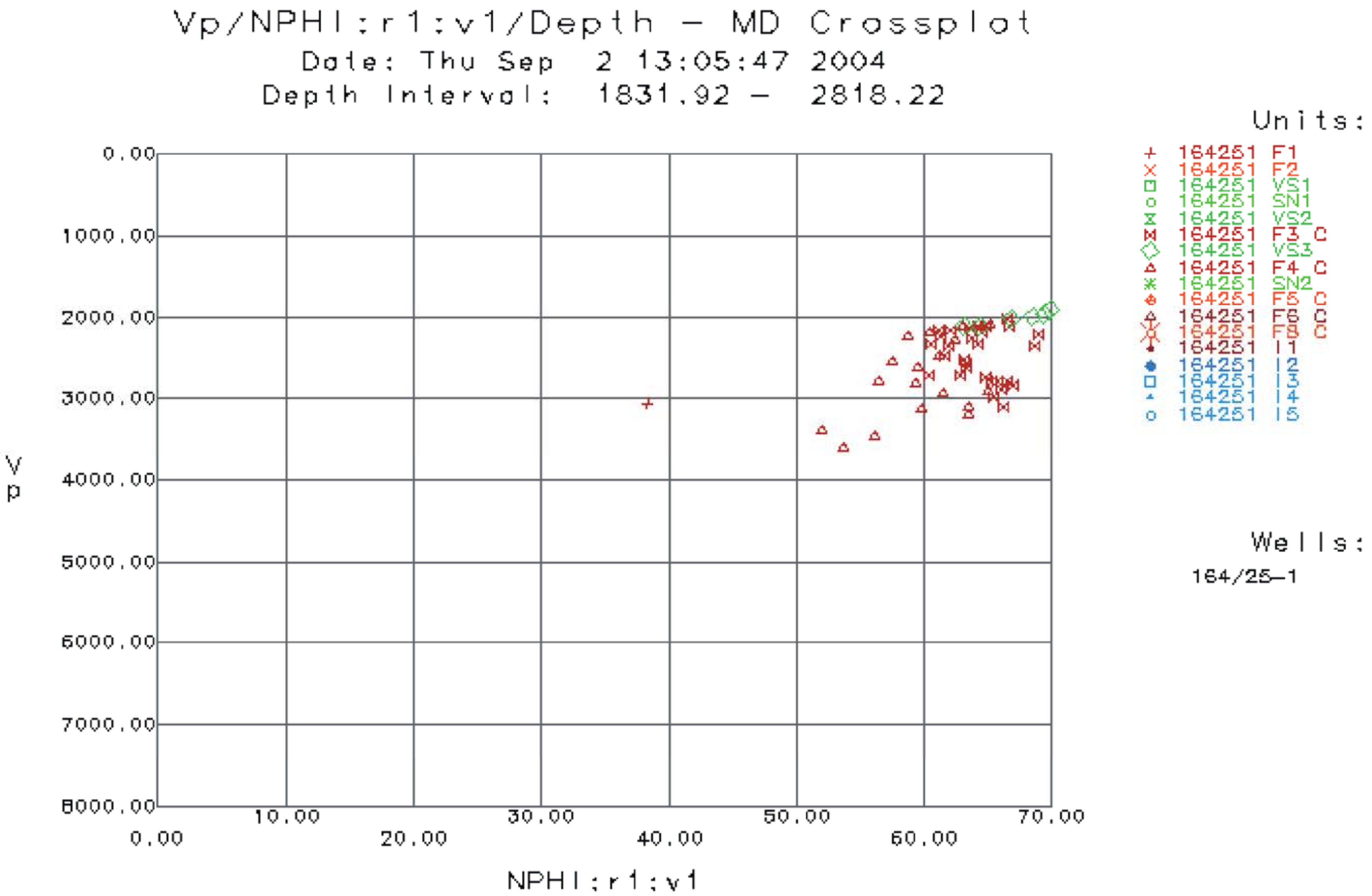

Figure 7.14. Cross plot of neutron porosity (NPHI) versus acoustic velocity (VP) in UK164/25-01z. All basaltic units indicated in enclosure 2 are plotted in the diagram.

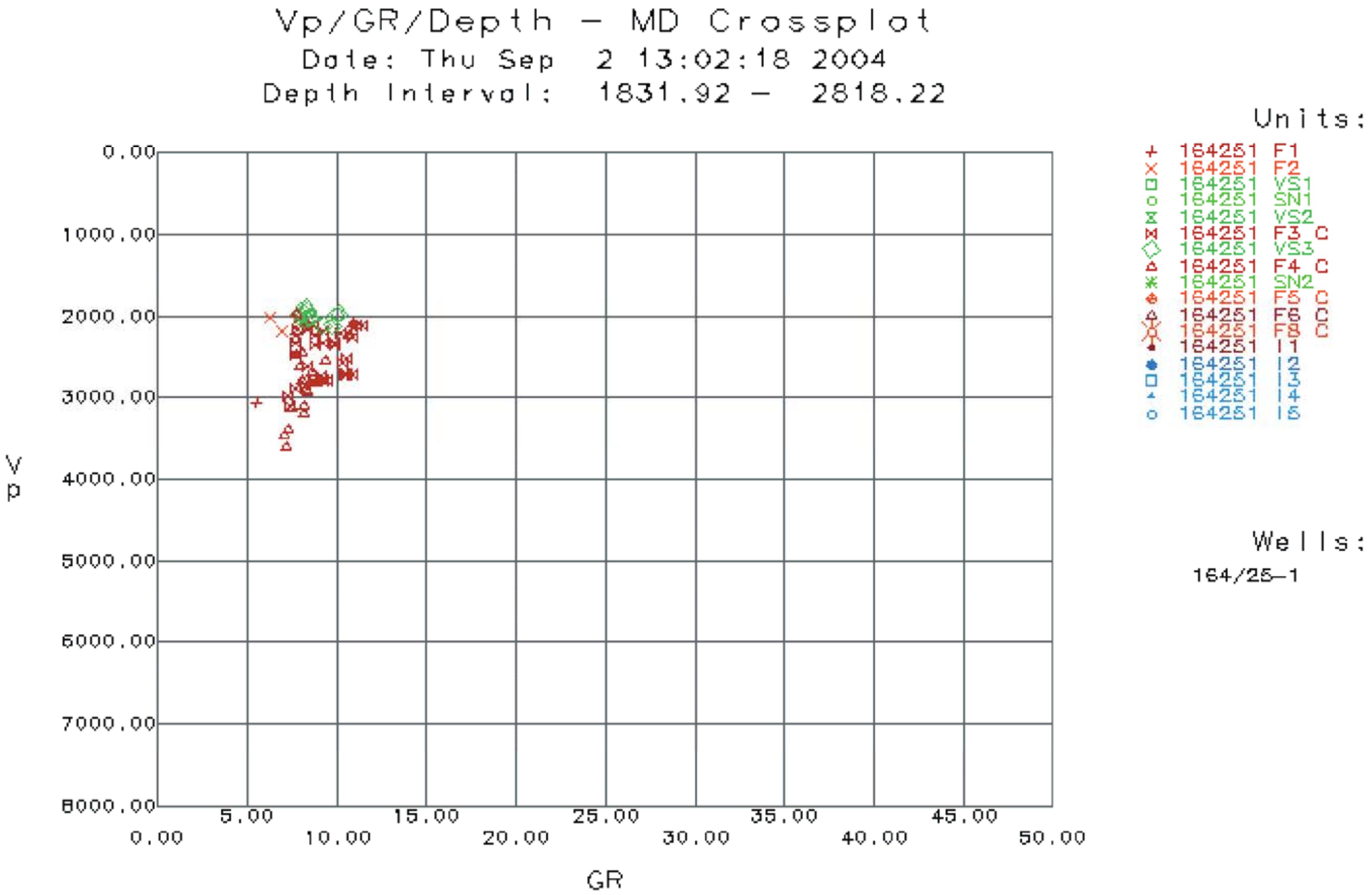

Figure 7.15. Cross plot of gamma radiation (GR) versus acoustic velocity (VP) in UK164/25-01z. All basaltic units indicated in enclosure 2 are plotted in the diagram.

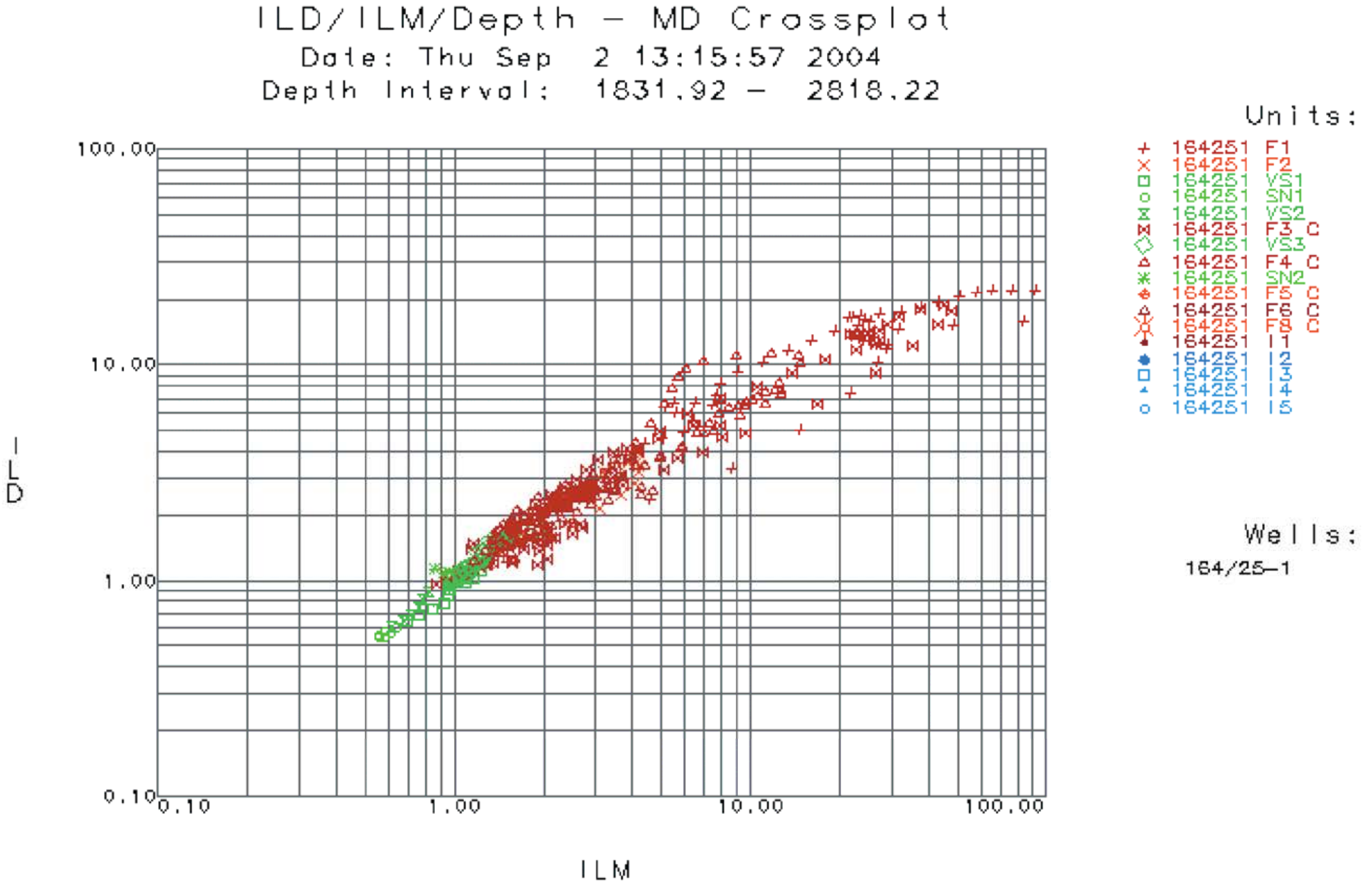

Figure 7.16. Cross plot of medium penetration (ILM) versus deep penetration induction logs (ILD) in UK164/25-01z. All basaltic units indicated in enclosure 2 are plotted in the diagram.

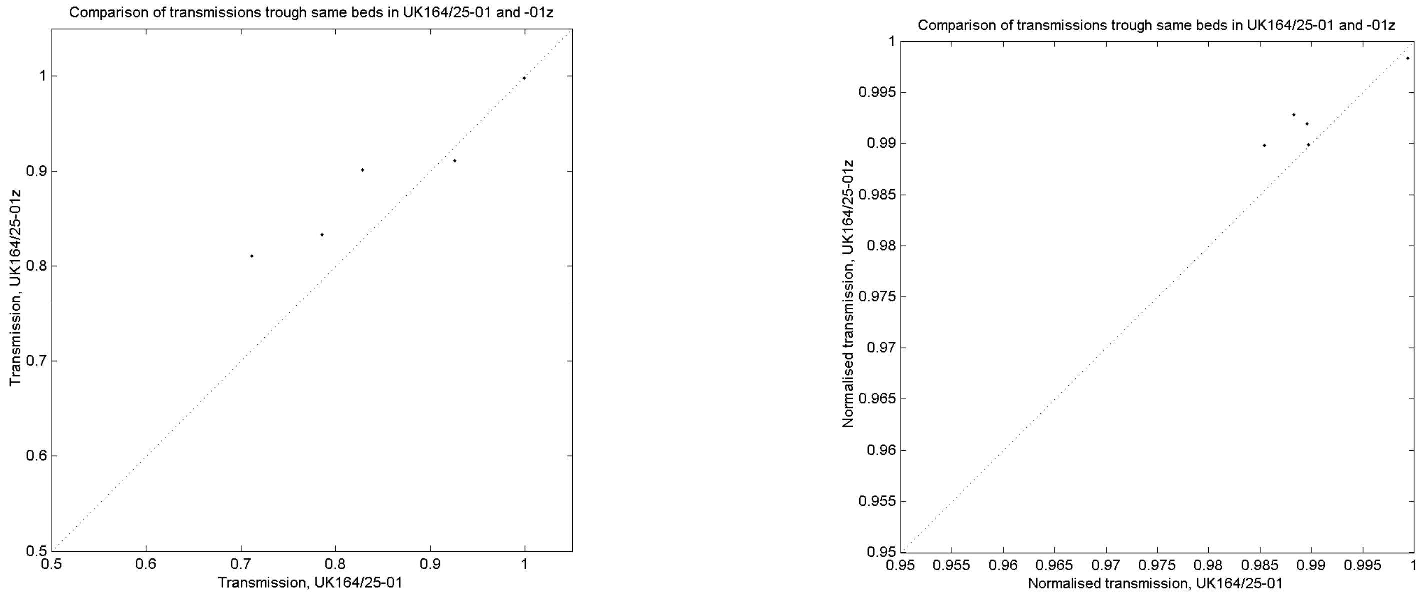

Figure 7.17. Comparison of transmission through basaltic intervals in UK164/25-01 and UK164/25-01. In the right diagram the actual calculated transmissions of through unit in the two wells are plotted against each other. The left diagram transmissions are normalised. The data are from Table 7.1.

8 Well UK205/09-01

The well UK205/09-01 (60º48’23.3”N 3º22’21.8”W) was drilled in 1989. Total depth of the well was 4722 m (TVDSS). The completion report from UK205/09-01 was not available for this study. Previous studies of the well indicate that Paleocene basaltic lava beds were penetrated in this borehole (Naylor et al. 1999; Ellis et al. 2002). Naylor et al. reported three lava beds in the volcanic succession of UK205/09-01. Ellis et al. report ca. 70 m of basaltic rocks. The latter is in agreement with the current study, which found four lava beds with a cumulated thickness of 66.5 m. Based only on the wireline logs, we suggest that four basaltic lava beds are present in the interval between 2610 and 2810 m (MD) in the 12.25” section of the hole. No other basaltic units are identified in this well with any certainty. One thin high velocity/high density interval could possibly be volcaniclastic sediments (tuffs).

The calliper in the interval of interest (2610-2810 m) indicates a fairly stable borehole. With one exception, caving is below (25 mm) within intervals interpreted as basalts. Caving above 50 mm, significantly affecting most of the logs (most adversely the density log), is seen within one of the lava bed units (depth interval 2650-2665 m; Figure 8.1).

In the depth interval of interest, the suite of log measurements in UK205/09-01 comprises

- calliper, CAL,
- natural gamma radiation, GR,
- sonic transit time (P-wave), DT,
- density, RHOB,
- neutron porosity, NPHI,
- resistivity measured with a dual induction tool, ILD and ILM,
- spontaneous potential,
- spectral gamma, K, TH and U,
- photo electric effect, PEF.

Except in the above mentioned interval with excessive caving all available logs are apparently of good quality. The induction logs appear to have been processed to reduce bed effects. The relevant log traces from the depth interval of interest are presented as enclosure 4.

8.1 Unit descriptions

Four several meters thick and a number of thin intervals in this well are characterised by bulk density higher than 2300 kg m-3 and seismic velocities above 4000 ms-1. However, only the four thick intervals are in addition to high seismic velocities also characterised by high neutron porosities (compared to the density and velocity). The four thick intervals are all characterised by a low and constant natural gamma radiation (between 25 and 30 GAPI) within the range expected for basalts. The resistivities of these intervals are high (typically above 100 Ωm).The thin intervals with bulk densities above 2300 kg m-3 and seismic velocities above 4000 ms-1 are in addition to a low neutron porosity (relative to the density when compared to the four thick high velocity intervals) also characterised by natural gamma radiation in the interval above 40 GAPI, and resistivities below 10 Ωm (compared to resistivities above 100 Ωm in the four thick high velocity intervals). Four basaltic lava beds are thus seen in this interval. One of the thin high velocity/high density intervals might be of volcaniclastic origin (Figure 8.2). However, it is not characterised by a low gamma radiation compared to sediments above and below, and a firm lithological interpretation of this interval based only on the available logs is not considered realistic. It thus appears that four units of basaltic lava beds are found in well UK209/05-1 (Figure 8.1).

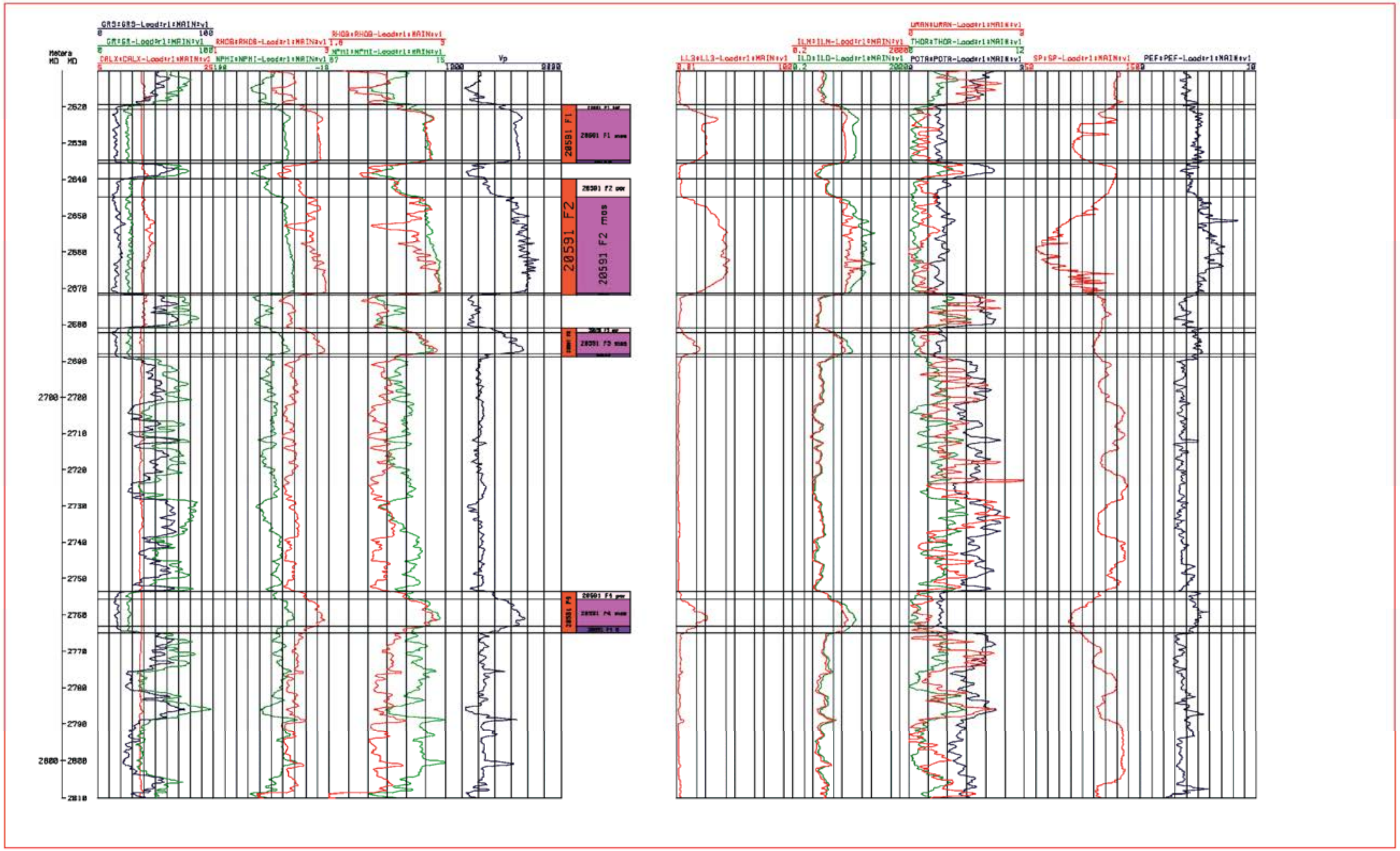

Figure 8.1. Log traces in the depth interval of interest (2600-2800m) in UK205/09-01

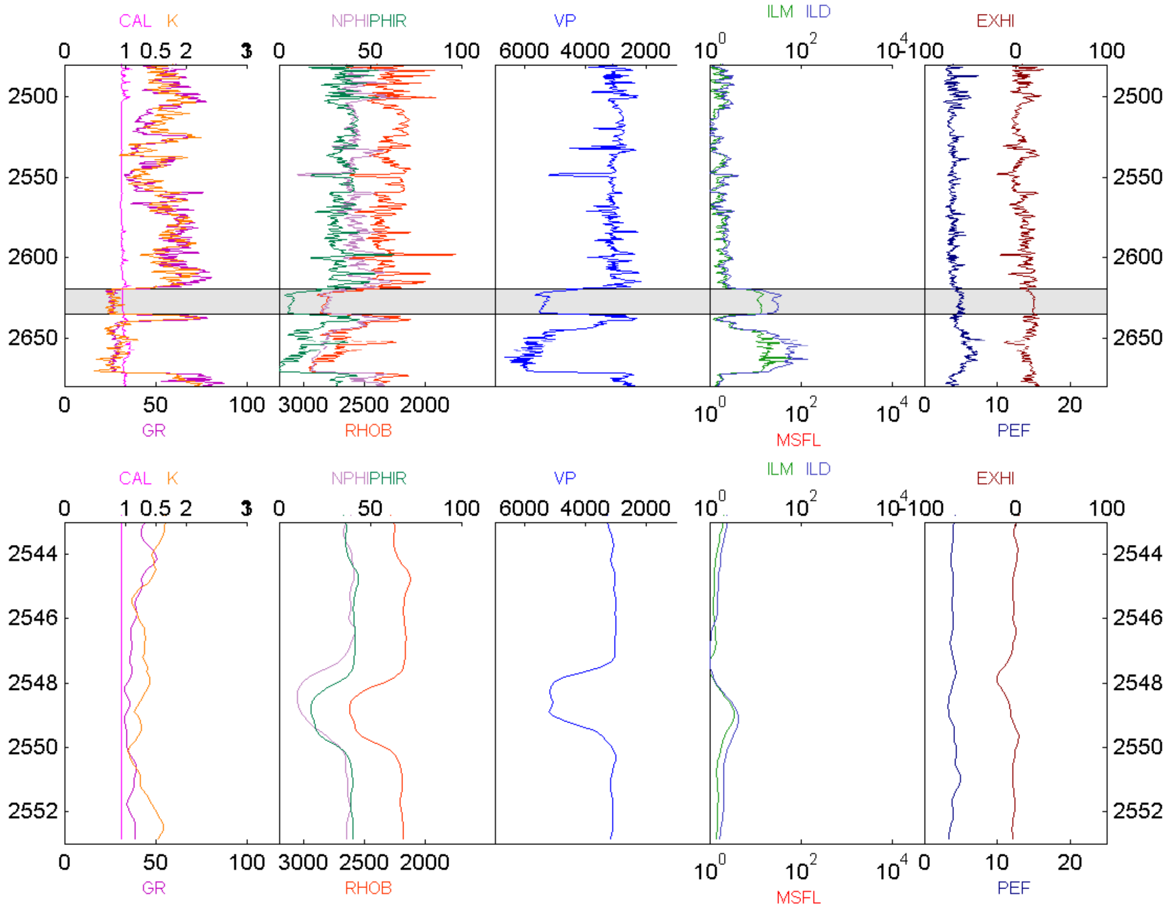

Figure 8.2. Upper row of panels: log traces from depth interval 2500-2650 m in well UK205/09-01. The uppermost basaltic lava bed, unit 20591-F1 is highlighted. Lower row of panels: Detail around thin high velocity/high density interval at 2548-2550 m. Note different separation of the NPHI and RHOB traces in the lava bed, unit 20591-F1 and the thin high velocity/high density interval at 2548-2550 m. This interval is not a lava bed, but could possibly be a thin volcaniclastic sediment bed.

In three of the four basaltic units in this well the neutron porosity is around 40 LPU in the top of the interval and decreases monotonously (but with variable gradient) to a minimum value around (10-20 LPU). From here it increases monotonously back to ca. 40 LPU. In the uppermost unit a local porosity minimum is found in the upper 3 m of the unit. Otherwise the overall porosity description above is valid also for this unit. By analogy to previous work in other wells (e.g. Planke 1994; Delius 1995; Boldreel 2002) each of the four intervals is thus considered a single basaltic lava bed.

Unit 20591-F1: The least porous part (22 LPU) of unit 20591-F1 is ca. 3 m below the top of the 15.4 m thick flow (Figure 8.3 NPHI log). Another minimum (25 LPU) is found less than 1 m above the base of the flow. A distinct upward increasing porosity trend (0.35 LPU/m) is seen in a zone (2624-2635 m) extending from the lower minimum to just below the upper porosity minimum. The uppermost 1.5 m of flow 20591-F1 (2619.55-2620.90) constitutes a distinct zone of high apparent porosity (ca. 40 LPU), the upper crust. A thin high porosity zone just above the base of the lava bed, the lower crust, is also distinct. The apparent porosity distribution of flow 20591-F1 described above is also reflected in the density (RHOB), sonic travel time (DT) and resistivity logs (ILM and ILD). A distinct separation (ca. 0.3 decade) is seen between the two induction logs throughout most of the flow.

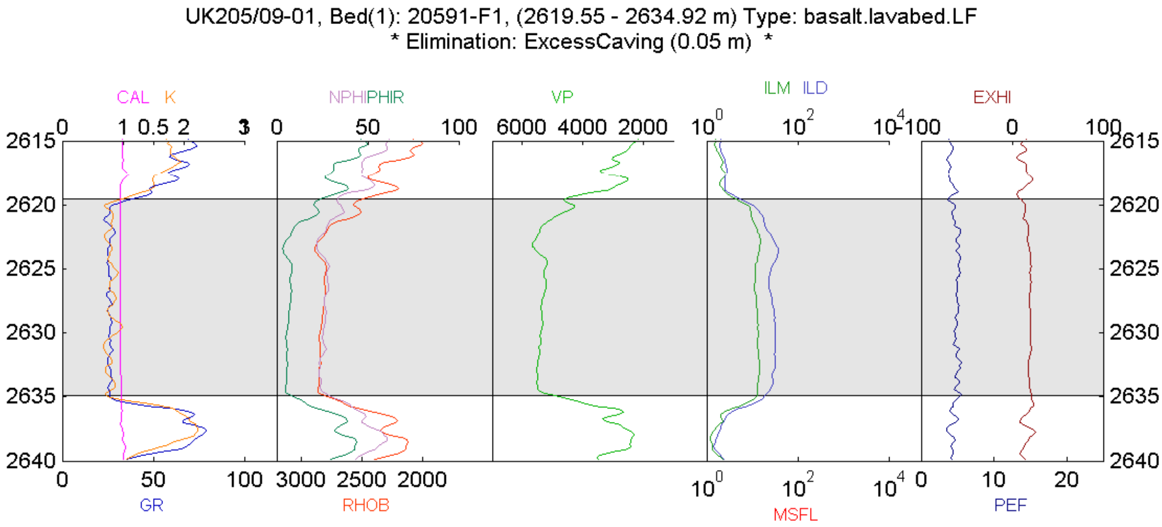

Figure 8.3. Log traces from depth interval 2615-2640 m in well UK205/09-01 showing unit 20591-F1.

Unit *20591-F2* (Figure 8.4) is twice as thick (31.6 m) as unit 20591-F1. But otherwise it has mostly the same characteristics as unit 20591-F1. However, due to caving data from the central part of the flow is not reliable. There is only one distinct porosity minimum (18 LPU), ca. 1 m above the bottom of the flow. Most of the matrix is characterised by an upward increasing porosity trend (2644.95-2671.80 m) with a gradient of ca. 0.35 LPU/m. The neutron porosity in the upper crust (2639.76-2644.95 m) is high and fairly constant (45-50 LPU). The low porosity lower crust is ca. 0.5 m thick. The density (RHOB), sonic travel time (DT) and the resistivity logs (ILM and ILD) are all highly correlated to the porosity (NPHI). As in unit 20591-F1 there is also a distinct separation between the two induction logs (0.3-0.4 decade) in unit 20591-F2. However, the separation is only seen within the massive core.

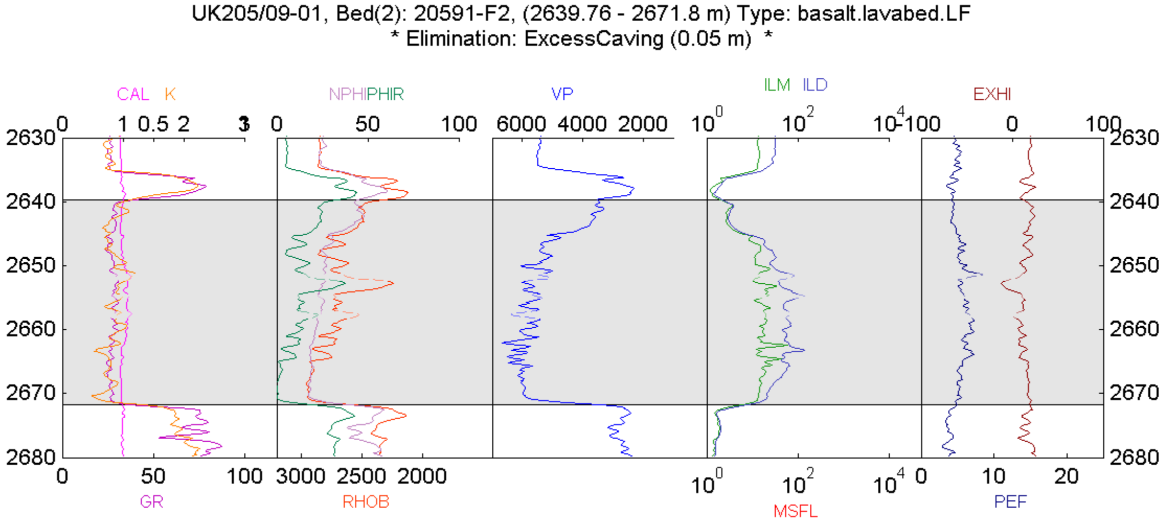

Figure 8.4. Log traces from depth interval 2630-2680 m in well UK205/09-01 showing unit 20591-F2.

Unit *20591-F3* (Figure 8.5) is thinner than the units' 20591-F1 and -F2 (7.2 m). However, it does resemble these flows in many aspects. The upper crust (ca. 2680.88-2682.13 m) is characterised by upwards increasing porosity. A distinct zone with constant high porosity are not seen in the top of the crust of unit 20591-F3. A porosity minimum is found close to the bottom of the massive core (2 m above the base of the unit). In the massive core above the porosity minimum the porosity decreases gently (2682.13-2688.69 m; gradient 2.8 LPU/m), and no distinct boundary is seen between crust and core. The separation between the two induction logs in the massive core is ca. 0.3-0.4 decade.

Unit *20591-F4* (Figure 8.6) is 9.8 m thick. In most aspects it is comparable to flow 20591-F3. However, unit 20591-F4 has a fairly distinct 1.5-2.5 m thick basal crust with high apparent porosities (ca. 30-40 LPU). In addition the minimum porosity is more or less in the middle of the central massive zone, not close to the base as in 20591-F1, F2 and F3.

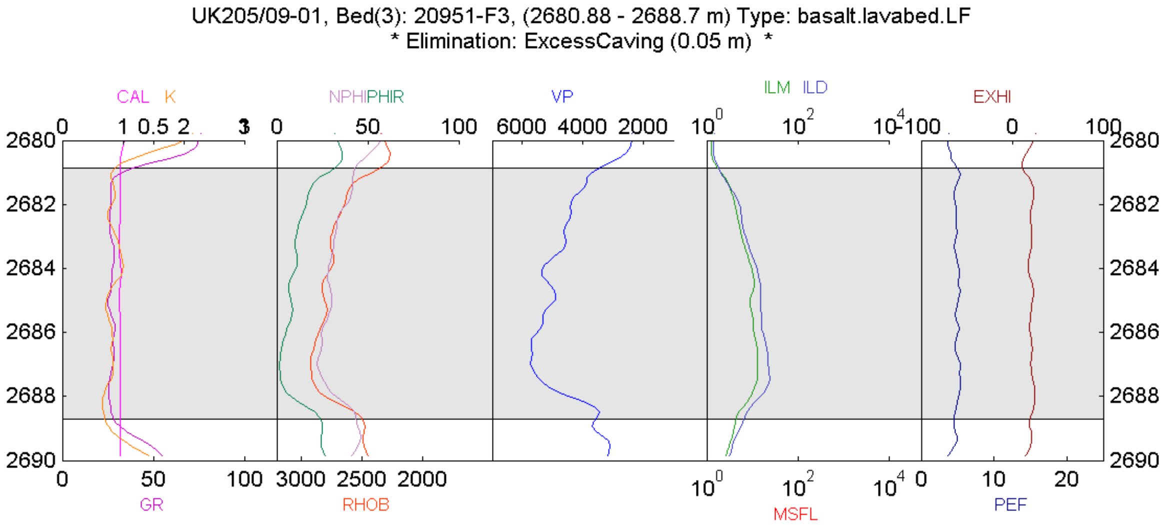

Figure 8.5. Log traces from depth interval 2680-2680 m in well UK205/09-01 showing unit 20591-F3.

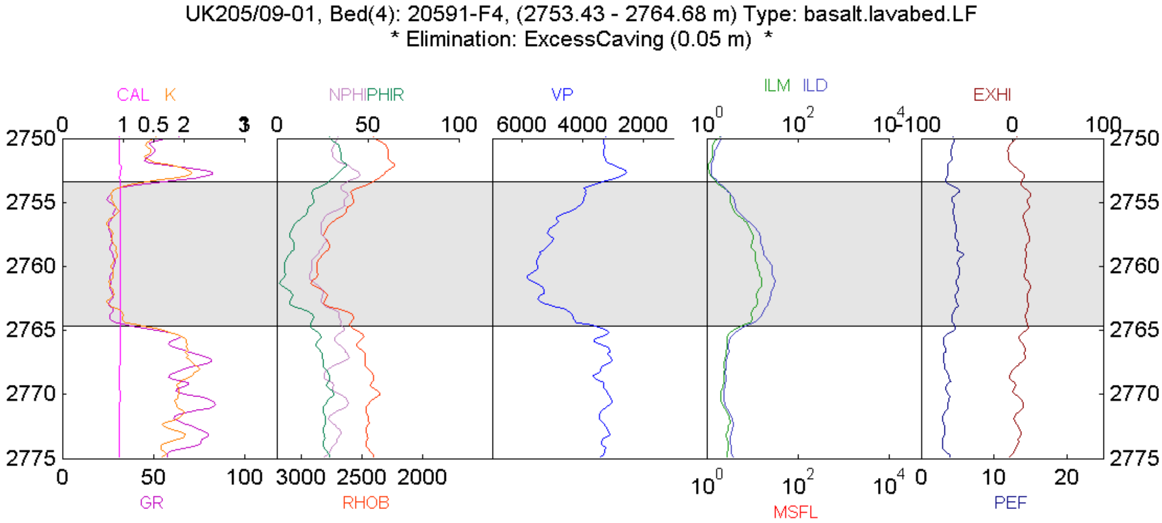

Figure 8.6. Log traces from depth interval 2750-2775 m in well UK205/09-01 showing unit 20591-F4.

As the four basaltic lava beds in UK205/09-01 is emplaced in shaley sediments with distinctly higher gamma radiation than the basalts, the boundaries of the lava beds may be picked precisely using only the GR trace, and a cut-off value of 32 GAPI would successfully separate the basaltic lava beds from sediments in this well.

Ambiguities, whether there are volcaniclastic sediments between individual lava beds, which may arise in pure basalt succession, where the upper boundary of lava beds mainly is picked based on the porosity related log traces, is thus not present in this well. We are therefore fairly certain that the zones of constant velocity in the upper part of the upper crust in units' 20591-F1 and -F2 are integrated parts of the lava beds.

The lack of any significant anomaly on the gamma radiation trace in the upper part of the basaltic lava beds in UK205/09-01 indicates that there has been little soil formation (lateritisation) on top of these lava beds. Therefore the zones of constant velocity in the upper part of the upper crust in units' 20591-F1 and -F2 most probably represents brecciated flow tops of aa' type lava flows. Based on the variation of the gamma radiation from the basalts and the magnitude of gamma radiation from the sediments above, it is estimated that at most 5-10 % of siliciclastic sediment can be mixed into this part of the lava beds, presumably less.

The descriptions of the log patterns of the four basalt flows in UK209/05-1 confirm previous work (e.g. Planke 1994; Delius et al. 1995; Boldreel 2002) that basaltic lava beds based on the log response can be divided into an upper porous crust, a massive core and a lower porous crust. In a purely basaltic succession the lower boundary are conveniently identified by an abrupt upward increase in velocity (e.g. Planke 1994). Based on the interpretation of the basaltic lava beds in UK205/09-01, it is possible that this approach may exclude the lower porous zone from the lava bed (Figure 8.1). An alternative (or supplementary) approach is to use the marked increase in (apparent) resistivity at the base of lava beds (Delius et al. 1995). Although the measured resistivities may be wrong due to bed effects, the location of the lower boundary is well defined. Precise identification of the upper boundary based on porosity related logs may be even more difficult than identification of the base. The approach used in this report is to place the boundary at a depth of local maximum curvature on the porosity related logs where the porosity decreases. Based on the log traces from UK205/09-01 this may place the boundary slightly too high. Supplementary to this it is in other of the investigated wells sometimes possible to use the GR trace to identify the top of alteration profiles related to soil formation, and even in the most pure basaltic successions occasional thin volcaniclastic sediment layers may commonly be identified by high gamma radiation compared to that of the basaltic succession the sediments are embedded in.

8.2 Properties of basaltic rocks in UK205/09-01

Within the four basaltic lava beds in UK205/09-01 there is a weak tendency that the gamma radiation increases as the velocity decreases and the porosity increases (Figure 8.7). This is most obvious in unit 20591-F2, and is most likely due to alteration as the variation occurs within individual beds.

The seismic velocity is well correlated with the measured neutron porosity (Figure 8.8) and density.

In Figure 8.9 the resistivity measurements, ILD and ILM, are plotted against the density derived porosity, PHIR. The data points are not distributed along a linear trend (in the log-log diagram) as would be expected for a material obeying Archie's equation (that is material without matrix conductivity). Three explanations are possible. Either the matrix has significant conductivity (Bussian 1983), and the basaltic lava beds are electrically anisotropic, as there is a difference between the deep penetration and the medium penetration induction log (Boyeldieu & Winchester 1982). Secondly, processing of the induction logs has not totally removed shoulder bed effects. Finally, the porosity estimates based on the density log may be incorrect. This would be most serious at low porosities where a small error in the matrix density used for correction may lead to significant error in the porosity. Based on the "well behaved" linear trends between resistivities measured with an MSFL tool and porosity in other wells (UK164/25-01, Glyvursnes-01 and Vestmanna-01), the two last explanations are considered most likely.

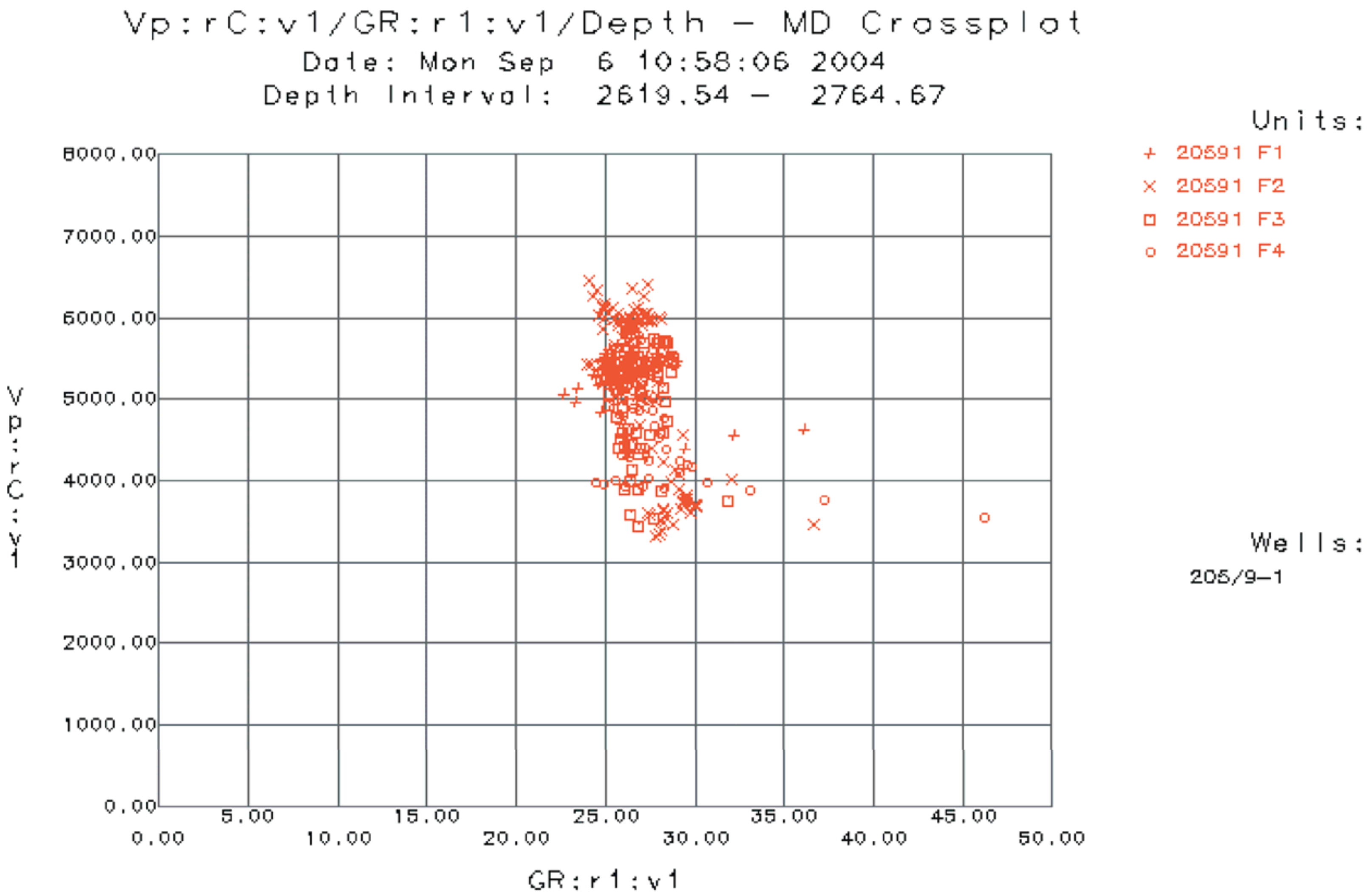

Figure 8.7. Cross plot of seismic velocity, VP, versus natural gamma radiation, GR, from basaltic volcanic units in UK205/09-01. The data points are coded according to what unit they represent. Data points from intervals with caving in excess of 5 cm is not shown.

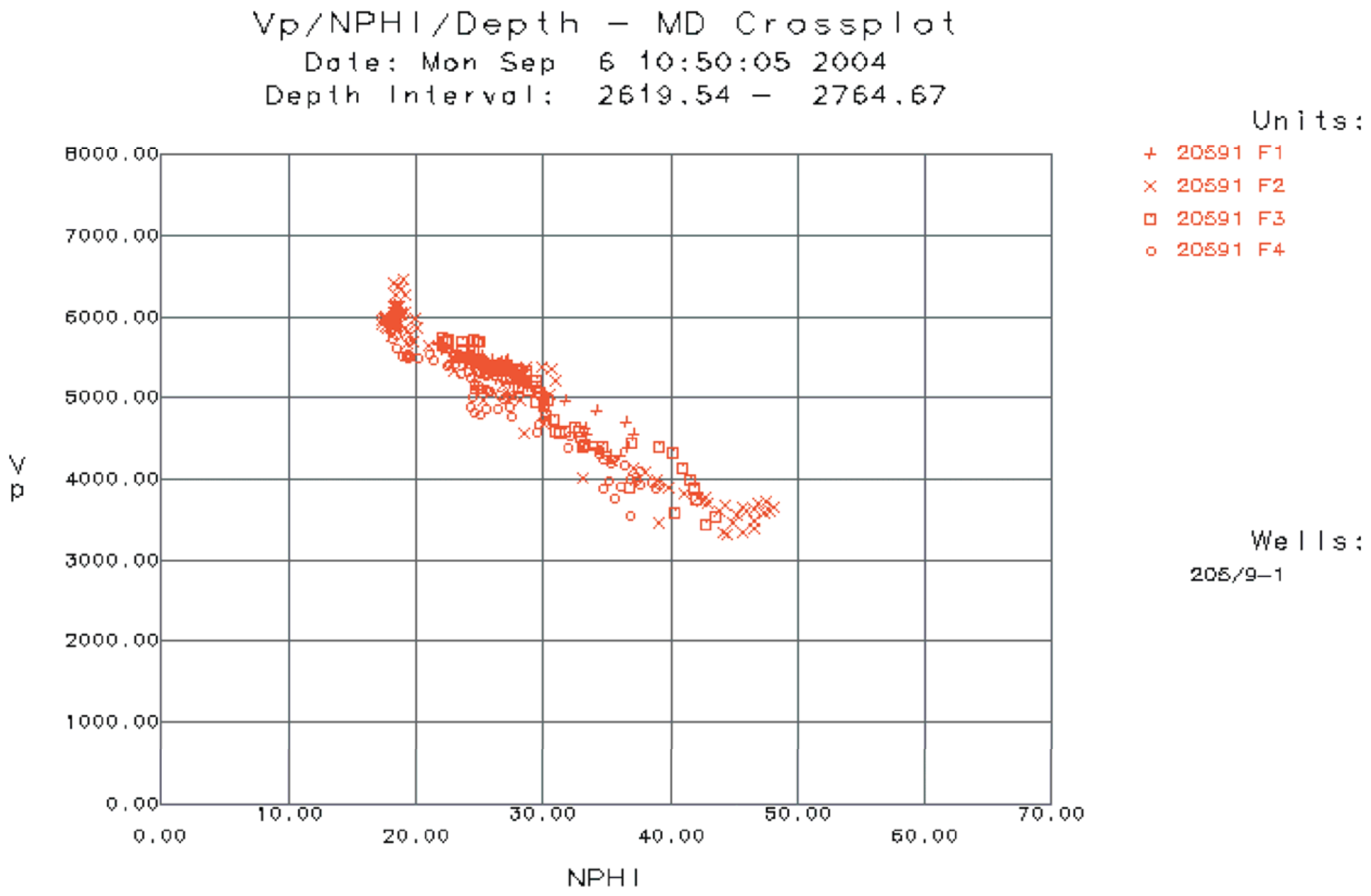

Figure 8.8. Cross plot of seismic velocity, VP, versus neutron porosity, NPHI, from basaltic volcanic units in UK205/09-01. The data points are coded according to what unit they represent. Data points from intervals with caving in excess of 5 cm is not shown.

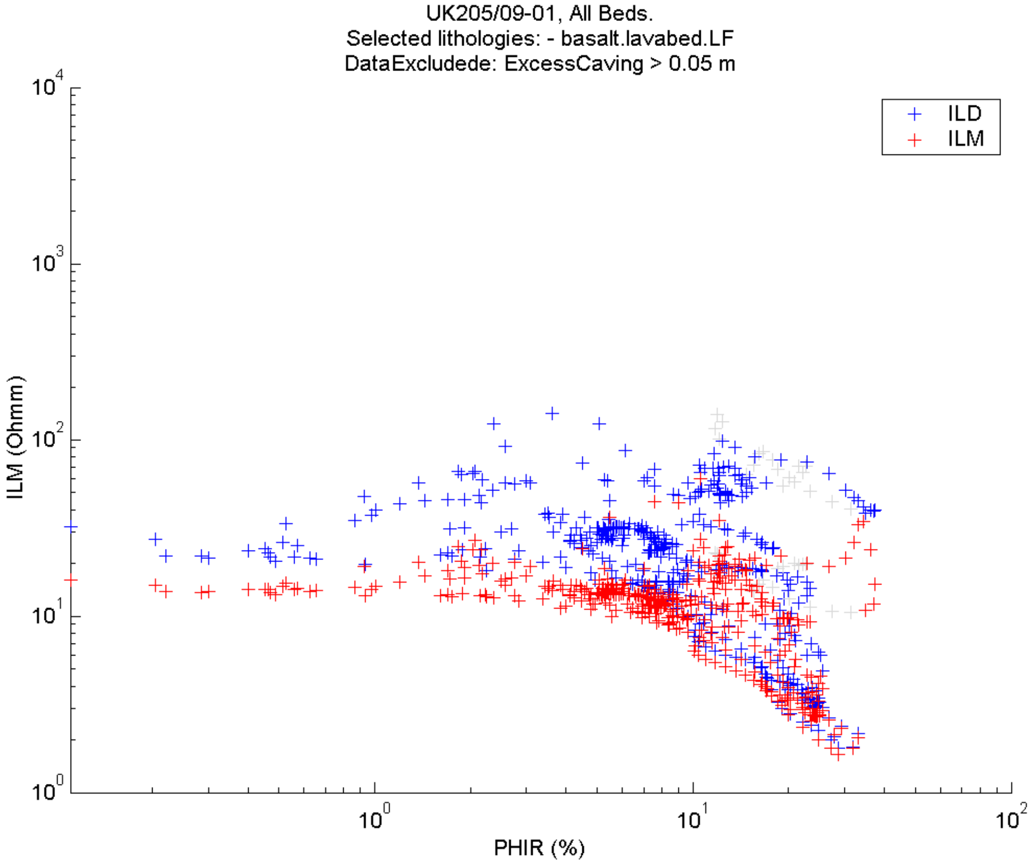

Figure 8.9. Cross plot of porosity, PHIR (calculated from the density logs assuming a matrix density of 2500 kg m^{-3}), versus resistivities measured with the deep penetration induction tool, ILD, and, medium penetration induction tool, ILM, from basaltic volcanic units in UK205/09-01. The data points are coded according to what tool they represent. Data points from intervals with caving in excess of 5 cm is not shown.

9 Well UK209/03-01

The well UK209/03-01 (61º51'24.651N 00º34'34.332"W) was drilled in 1980, with Lower Tertiary and Mesozoic targets on the flanks of a high generated by regional faulting and subsequent igneous intrusion. The well penetrated a ca. 830 m succession interpreted as Paleocene basaltic volcanics. In addition a few basaltic intrusions (presumably of Paleocene age) intrude the Cretaceous section below the volcanic succession. The well is placed on the flank of a volcanic centre (The Erlend volcanic complex; Gatliff et al. 1984). The top of the volcanic succession lies at 1244m (MD) in the top of the 12.25" hole, which continues to TD. Overall, the borehole conditions in the volcanic succession are fair, with caving exceeding 50 mm in less than 10 % of the volcanic succession.

The suite of log measurements in the depth interval of interest in UK209/03-01 comprises

- calliper, CAL,
- natural gamma radiation, GR,
- sonic transit time (P-wave), DT,
- density, RHOB,
- neutron porosity, NPHI,
- resistivity measured with a deep penetration induction tool, ILD,
- resistivity measured by a shallow penetration spherically focused tool, SFLU and
- spontaneous potential, SP.

The spontaneous potential log is not considered useful for this study. The log measurements appear otherwise to be of fair quality. The spherically focussed log are characterised by pronounced high resistivity within lava beds and is assumed to provide a fairly realistic measure of resistivity variations within all formations. Within the lava beds the resistivity measured by the deep penetration induction tool is considerably lower than that measured by the spherically focussed tool. This is commonly seen in wells penetrating basaltic successions, and it is presumably an artefact caused by lower sensitivity of the induction tool (Goldberg 1997), although different conductivities of formation and drilling fluids also may play a role.

The relevant log traces from the depth interval of interest are presented as enclosure 4. However, sonic transit time is recalculated to sonic velocities and presented as the trace, VP. A part of the log from 1220-1420 m is shown as Figure 9.1.

9.1 Unit descriptions

The uppermost ca 50 m of the basaltic succession in UK209/03-01 is comprised by five distinct low frequency lava beds separated by low velocity/density units. Below, an approximately 40 m thick low velocity (ca. 2000 ms^{-1}) unit is found interpreted as volcaniclastic sediments - possibly with a single thin basaltic lava bed.

The lowermost ca. 730 m of the volcanic succession in UK209/03-01 is generally characterised by fairly low mean velocities, ca. 3000 ms^{-1} in the top increasing downwards to above 4000 ms^{-1}. According to the completion report and description of side wall cores from the lower 730 m of UK209/03-01 this succession is basaltic.

9.1.1 Low frequency lava beds

The low frequency lava beds in the upper part of the volcanic succession in UK209/03-01 are fairly thin (4-11 m) and the top of the lava beds are generally not well defined as both the gamma radiation and the porosity related physical properties changes gradually across the top of the lava beds.

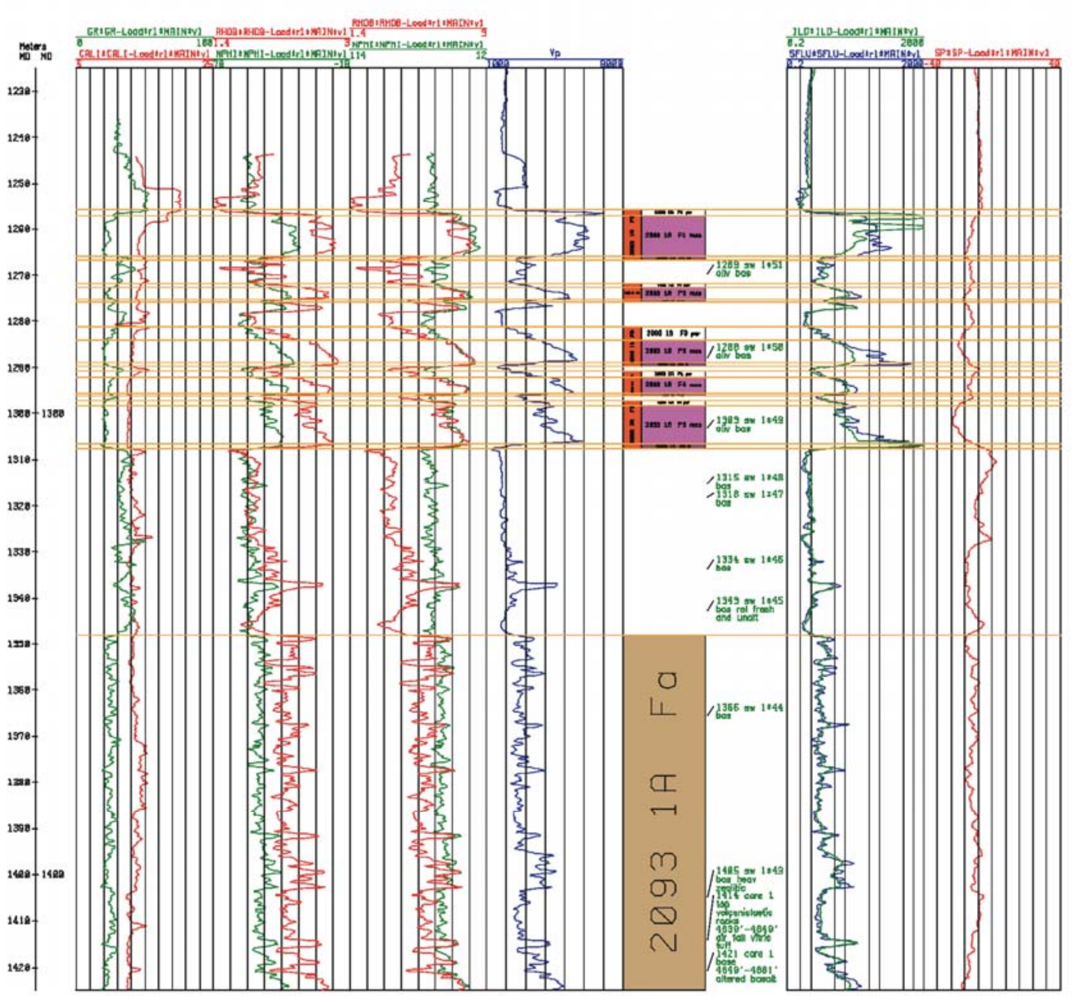

Figure 9.1. Log panels and interpreted units from the depth interval 1220-1420 m in UK209/03-01.

Unit *20931-F3* (Figure 9.2) is characterised by a fairly continuous increase in seismic velocity from ca. 2200 ms^{-1} just below the interpreted top of the lava bed to ca. 5600 ms-1 approximately one meter above the bottom of the unit. A ca. 3 m thick upper crust with high porosity is distinct on the density, neutron porosity and the spherically focussed resistivity traces, but not on the velocity trace.

Unit *20931-F5* (Figure 9.3) is ca. 10 m thick, characterised by high seismic velocities. At least three zones of higher porosity are seen within this unit. These porosity zones are reflected in all the porosity related logs. Due to the porosity zones this unit has a superficial resemblance to a high frequency unit. However, due to the overall upward decrease in seismic velocity and high average and maximum velocities ($V_{Pmax} \approx 5900\ ms^{-1}$) we classify the unit as a low frequency lava bed.

In the low frequency lava beds in this well the gamma radiation is decreasing downwards through each bed to some extent following the porosity related logs indicating that the variation of gamma radiation with lava beds gamma radiation reflect porosity dependent alteration of the lava beds.

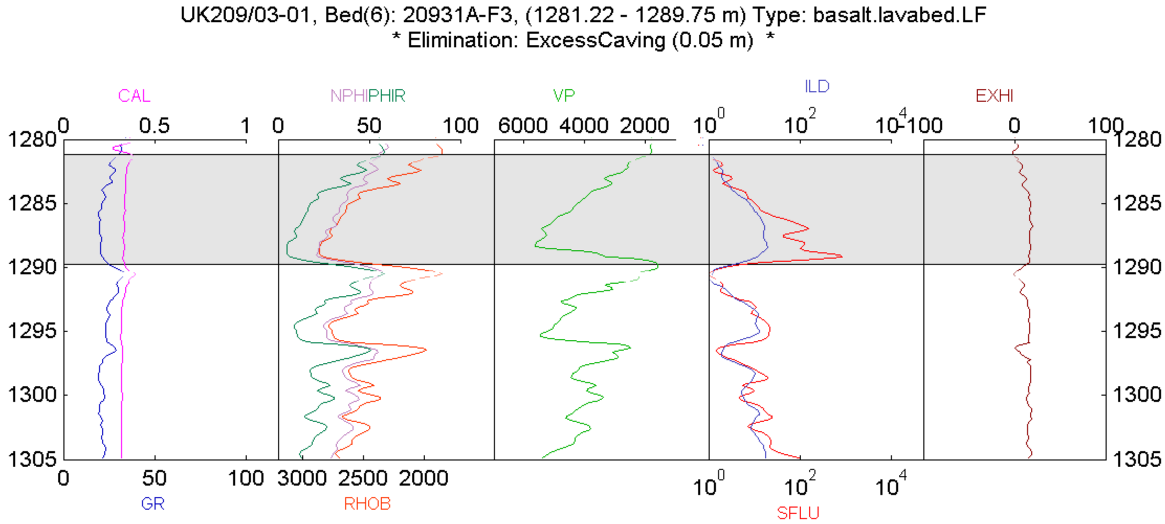

Figure 9.2. Log traces from depth interval 1280-1305 m in well UK209/03-01 showing unit 20931A-F3.

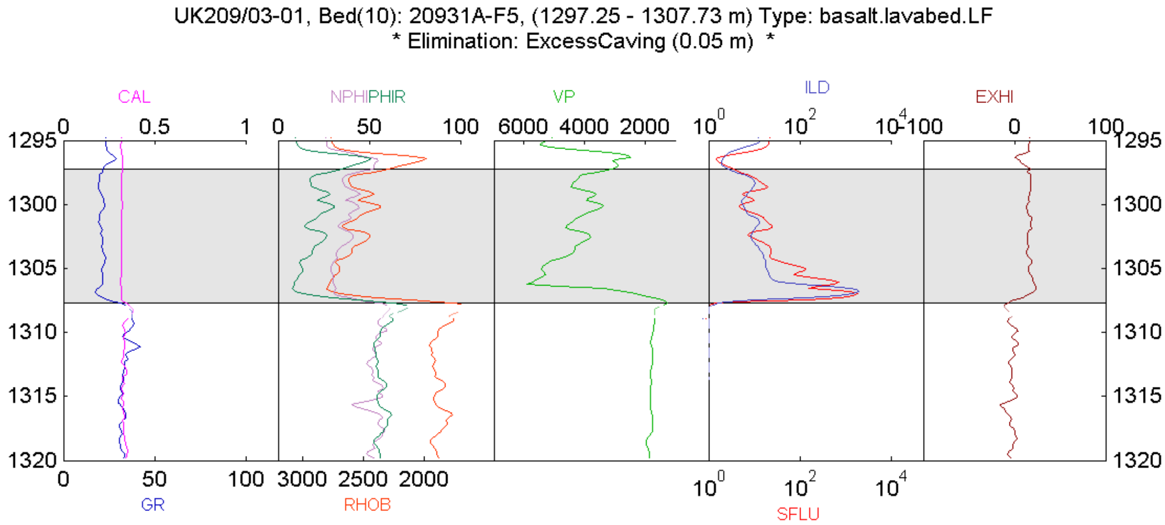

Figure 9.3. Log traces from depth interval 1295-1320 m in well UK209/03-01 showing unit 20931A-F5.

9.1.2 High frequency lava beds

The 700 m of high frequency lava beds (from 1348.1 to 2079.5 m) are characterised by short period oscillations (typical wavelength around 2 m) on all porosity related log traces. The total range for the porosity related logs is smaller than in the low frequency basalts (Figure 9.4). Especially local velocity maximima are not as large as in the low frequency lava beds, typically around 5000 ms^{-1}, The lowest velocities are ca 3000 ms-1 in the uppermost part of the high frequency basalts in this well and increases downwards to ca. 4000ms^{-1}.

Based on small changes in the level of the gamma radiation the high frequency lava beds in UK209/03-01 is divided into three units, the ca. 160 m thick *20931A-Fa*, characterised by a gamma radiation of 23.5 ± 2.74 GAPI, the 550 thick 20931A-Fb (subdivided into *20931A-Fb1*, *20931A-Fb2*, *20931A-Fb3*) characterised by gamma radiation of ca. 20.2 ± 1.81 GAPI and the thin lower unit *20931A-Fc* characterised by gamma radiation of 24.3 ± 3.85 GAPI.

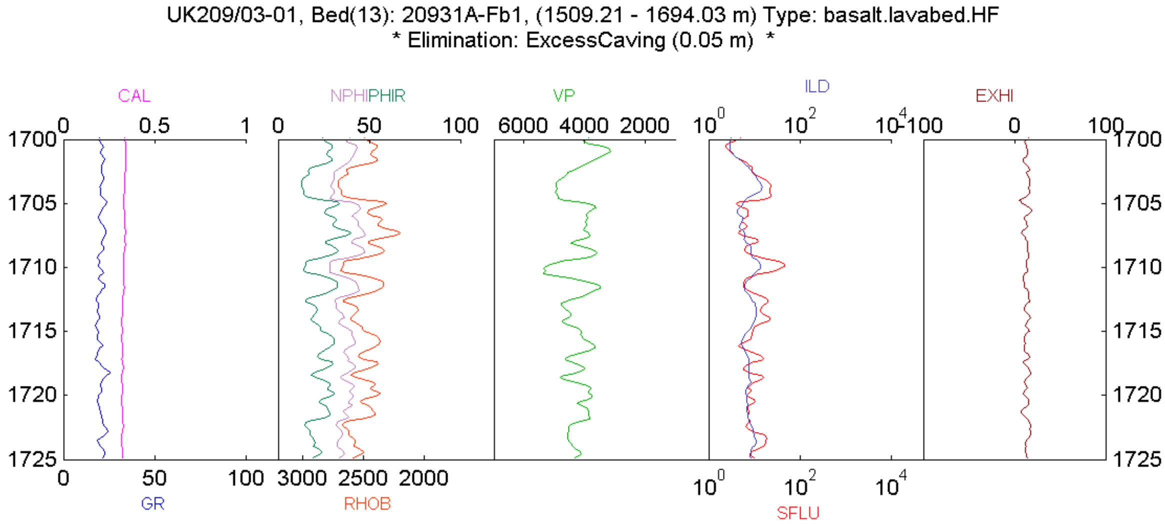

Figure 9.4. Log traces from depth interval 1700-1725 m in well UK209/03-01 showing a small part of unit 20931A-Fb1.

9.1.3 Volcaniclastic sediments

Thin (1-5 m) units of volcaniclastic sediments are interpreted to be intercalated with the low frequency lava beds 20931A-F1 to -F5 in the top of the volcanic succession (e.g. 20931A-VS2; Figure 9.1 and Figure 9.5). They are characterised by slightly increased gamma radiation (relatively to the lava beds), and fairly constant seismic velocity around 2500ms^{-1}. Indications of internal bedding are seen in some of these sediment layers. Caving is generally significant within these sediment layers.

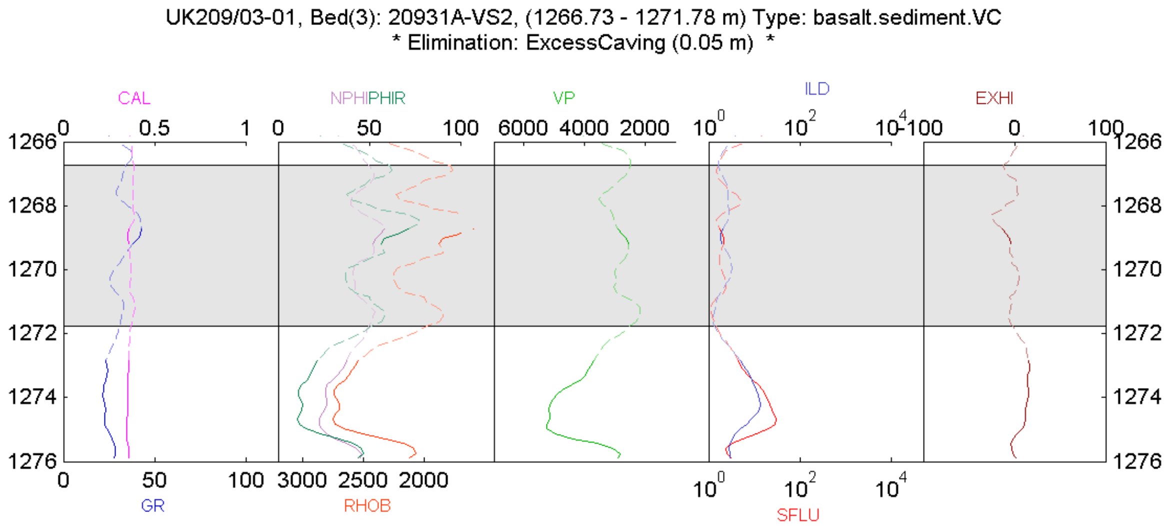

Figure 9.5. Log traces from depth interval 1266-1276 m in well UK209/03-01 showing unit 20931A-VS2. Internal bedding at the meter scale is indicated by the fluctuating but correlated log traces.

A side wall core in one of the sediment units mentioned above is described as olivine basalt indicating the possibility that some of these units may be flow top breccias associated with the underlying lava bed.

A 40 m thick sediment unit, *20931A-VS6*, is seen between the upper succession of low frequency lava beds and lower succession of high frequency lava beds (Figure 9.6). Gamma radiation from this sediment layer is considerably higher (typically 30- 40 GAPI) than that from lava beds or the sediments intercalated with the upper lava beds. Seismic velocity is ca. 2000 ms-1 and the other porosity related log traces are deflected correspondingly relatively to values in lava beds. A very thin high velocity layer at ca 1335 m is presumably a lava bed. Three side wall cores in this unit are all described as basaltic. In the completion report the unit is described as tuffaceous siltstone/claystone.

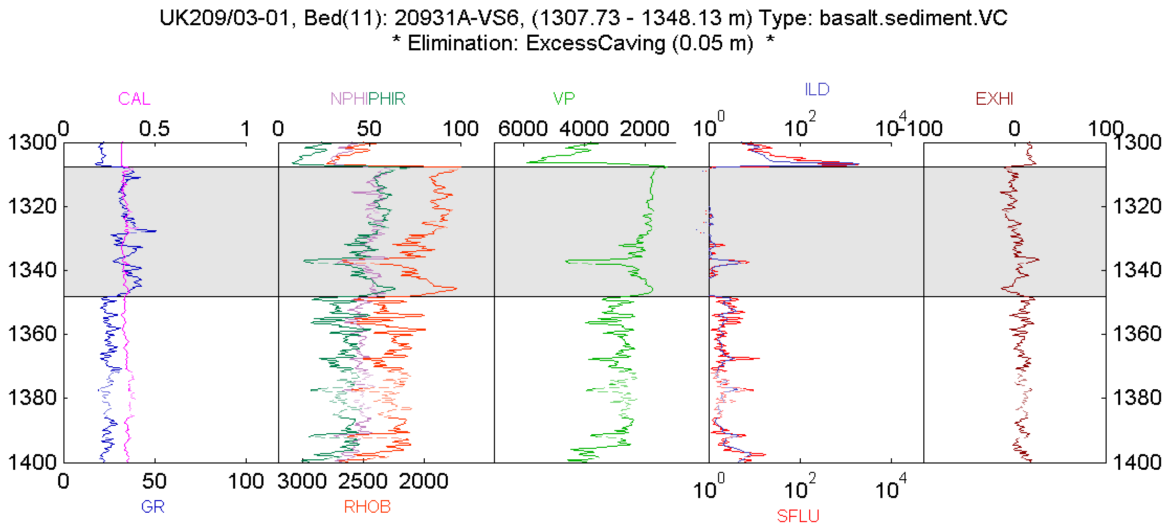

Figure 9.6 Log traces from depth interval 1300-1400 m in well UK209/03-01 showing unit 20931A-VS6.

9.1.4 Intrusives

A few thin (1-7 m; Figure 9.7) high velocity intercalation with intrinsic properties, which mostly are within the range of typical basaltic rocks, are recognised within the Cretaceous sediments below the volcanic successions. These thin units are interpreted as intrusives, partly due to fairly symmetric porosity distributions (Figure 9.7 and Figure 9.8) and partly due to the stratigraphic position.

9.2 Properties of basaltic rocks in UK209/03-01

It is seen from Figure 9.9 that the gamma ray fluctuations in the lava bed units generally are uncorrelated to the seismic velocity. This is a bit surprising as a quite distinct correlation between gamma radiation and seismic velocity is seen at bed level (Figure 9.3 and Figure 9.4). There are some indications that gamma radiations in the high frequency lava beds are higher at low seismic velocities. This is presumably indicating the presence of unidentified sediment intercalations in the units of high frequency lava beds. The volcaniclastic sediments cluster around two velocities ca. 1900 ms^{-1} (unit 20931A-VS6) and ca. 2800 ms^{-1} (most units between the upper low frequency basalts). This highlights the possibility mentioned above that units 20931A-VS1, -VS2, -V3 and -VS5 could be misinterpreted and actually constituted top breccias of the underlying lava bed. However, in cross plots these four units are clearly plotting in a cluster separate from the low frequency basalts (Figure 9.9, Figure 9.10 and Figure 9.11). It is thus likely that two different types of volcaniclastic sediments are observed in UK209/03-01. The geological explanation for the two types is not revealed by the available data.

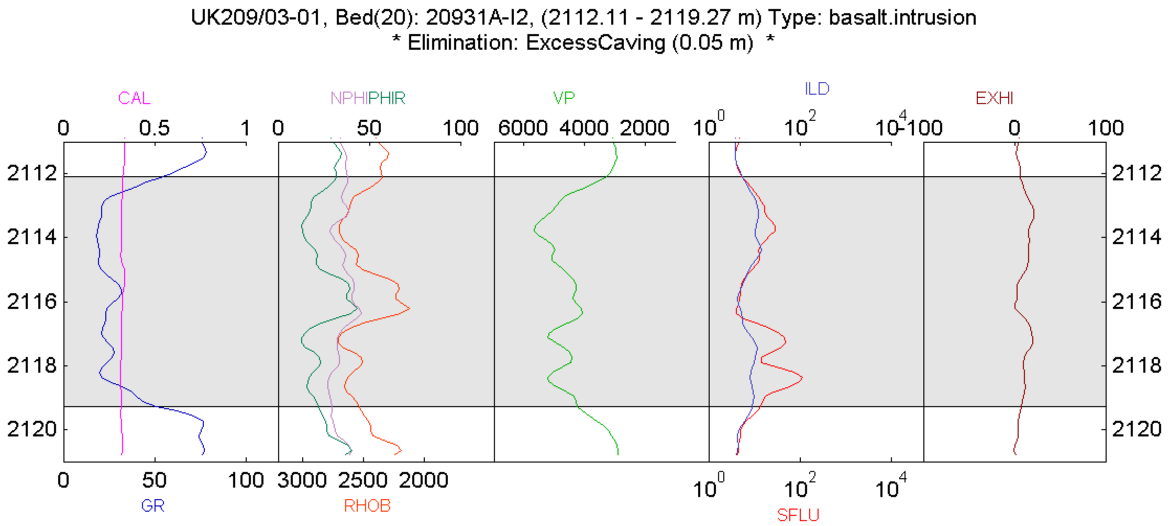

Figure 9.7. Log traces from depth interval 2111-2121 m in well UK209/03-01 showing unit 20931A-I2.

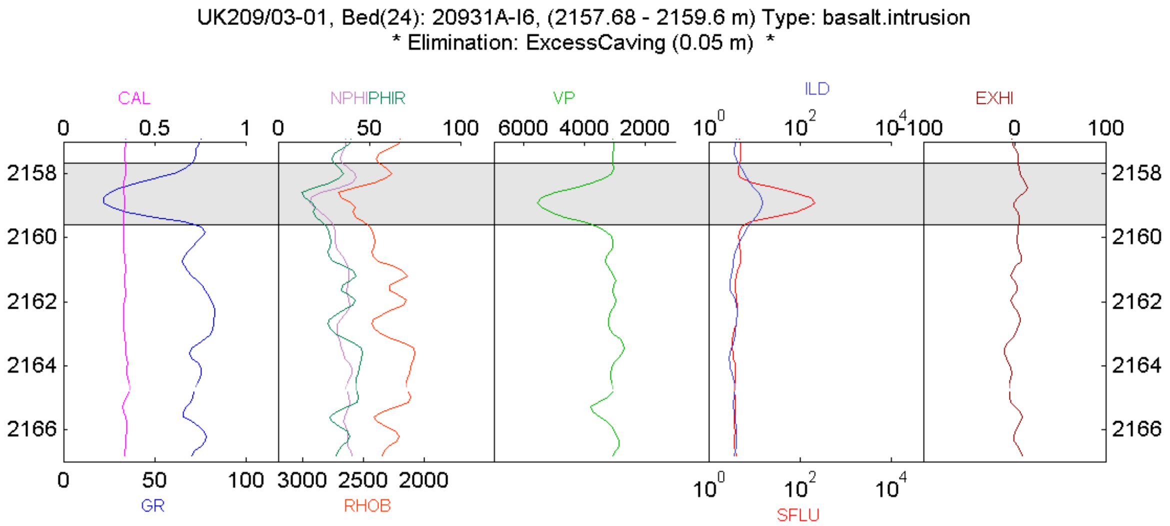

Figure 9.8. Log traces from depth interval 2157-2167 m in well UK209/03-01 showing unit 20931A-I6.

The data points from the intrusions show a considerable scatter in Figure 9.9. This scatter is at least to some extent an effect of the strategy used within this project to pick unit boundaries, and the different vertical resolution of the gamma tool (ca. 0.2 m) and the sonic tool (ca. 0.5m). As the pick of units boundaries is based on inflection of the seismic velocity trace, it is likely to be outside the intrusion, and the higher resolution gamma tool measures the radiation of the side rock at a few points close to the boundary. This effect is generally not seen in the volcanic successions, where the gamma radiations not change much from unit to unit. In addition, in thicker beds we may work around this problem by discarding samples close to the top and bottom of the units. Although the interpretation strategy probably is the most important reason for the scattering of data points from intrusions in Figure 9.9, mobilisation of incompatible elements (especially K) may also be involved in this scatter (see chapter 6).

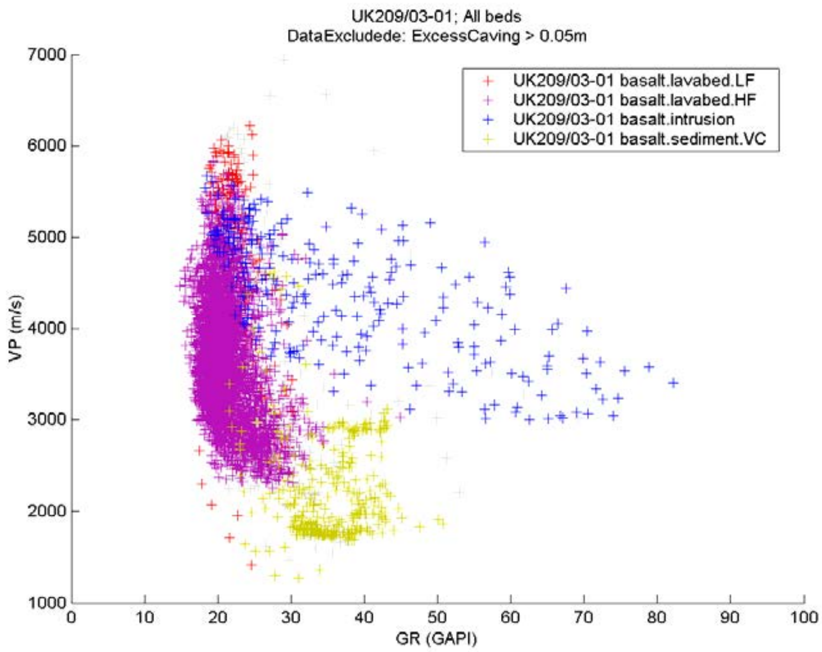

Figure 9.9. Cross plot of seismic velocity, VP, versus gamma radiation, GR, from basaltic volcanic units in UK209/03-1. The data point are colour coded according to what type of unit they belong to. Points in grey represent data points from those parts of the well where caving exceeds 5 cm.

The seismic velocity is fairly well correlated to both the porosity estimates, NPHI and PHIR (Figure 9.10 and Figure 9.11). However, differences between the two porosity estimates can be identified by comparing the two figures.

1. Neutron porosity is rarely below 20 LPU, even in the massive basalts with the highest velocities. This is not in agreement with field observations or with core measurements of porosities in basalts from Vestmanna-1(Abrahamsen & Argir; 2004; see chapter 14).
2. In Figure 9.10 the intrusives are offset towards lower neutron porosity relatively to the lava beds. A similar offset are not seen in Figure 9.11. This may reflect that intrusives generally contain a smaller amount of hydrous minerals than the equivalent volcanic rocks. The PHIR trace may thus be the most reliable porosity estimate, at least at porosity estimates below ca. 25 % porosity.
3. In the volcaniclastic units the two porosity estimates are high, around 50 LPU using the neutron porosity log, and from 40-60 % using the estimate based on the density log. As 50 % porosity is unrealistic for sediments buried to a depth of 2000 m, this indicates that neither of the two estimates are particularly realistic in the volcaniclastic sediments.

Overall it is concluded that porosities estimated from the density log is the most realistic in the more massive part of the basalts. However, neither density measurements nor neutron porosity measurements provide very realistic estimates of porosities in the basaltic rocks in UK209/03-01.

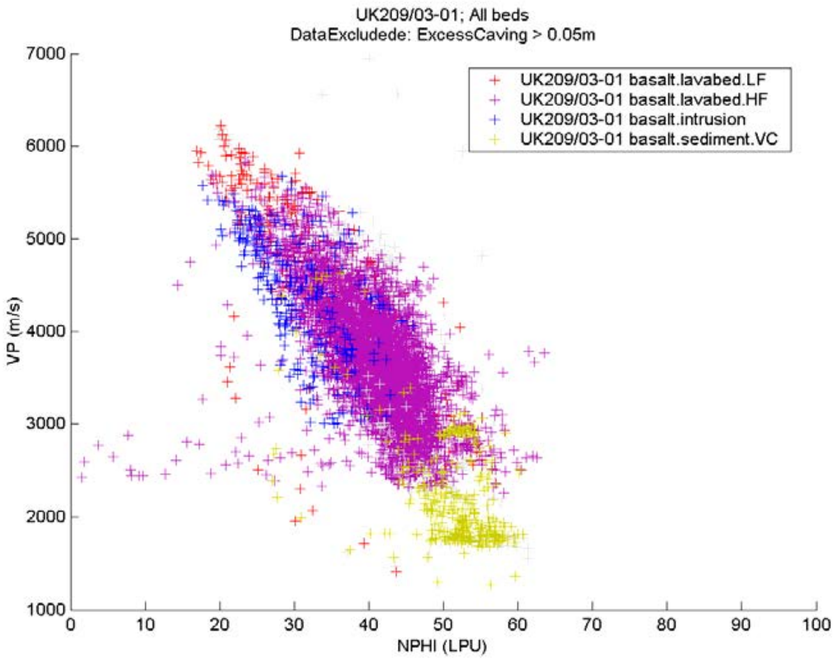

Figure 9.10. Cross plot of seismic velocity, VP, versus neutron porosity, NPHI, from basaltic volcanic units in UK209/03-01. The data point are colour coded according to what type of unit they belong to. Points in grey represent data points from those parts of the well where caving exceeds 5 cm.

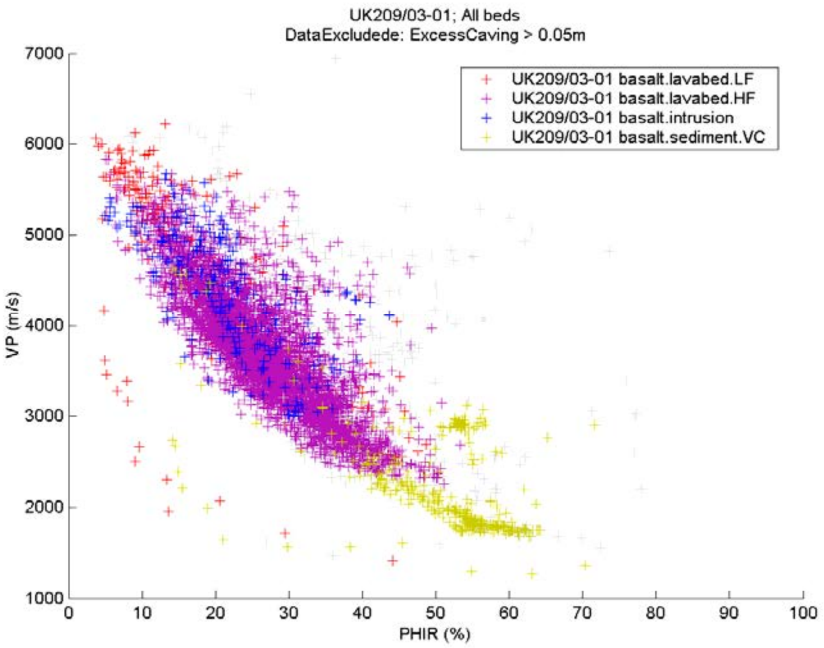

Figure 9.11. Cross plot of seismic velocity, VP, versus porosity calculated from the density log, PHIR, from basaltic volcanic units in UK209/03-01. The data point are colour coded according to what type of unit they belong to. Points in grey represent data points from those parts of the well where caving exceeds 5 cm.

The measured resistivities in lava beds are clearly porosity dependent (Figure 9.12). However at apparent porosities below ca. 10 % the data points deviates from the linear trend that would be expected for simple materials obeying Archie's equation. Comparing with wells, where the resistivity data is assumed to be more realistic (UK164/07-01, UK164/25-01z, Glyvursnes-01, and Vestmanna-01) we are worried that bed effects may dominate the resistivity measurements in UK209/03-01. However, it should be noted that the overall resistivity trend is comparable to that observed in two of the other studied wells (UK205/09-01, UK209/04-01).

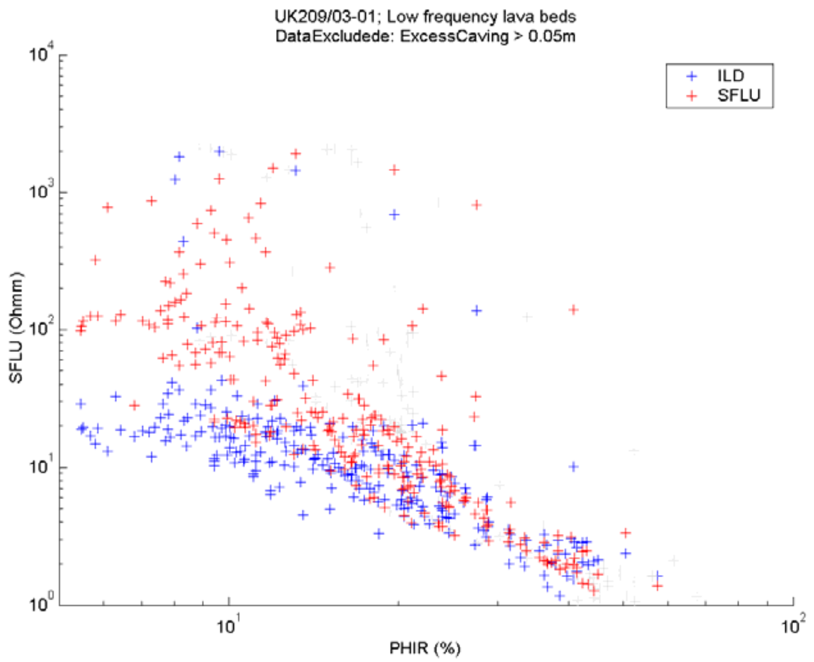

Figure 9.12. Resistivity (both SFLU and ILD) versus gamma radiation, GR, from basaltic low frequency lava bed units in UK209/03-01. The data point are colour coded according to the log tool. Points in grey represent data points from those parts of the well where caving exceeds 5 cm.

In Figure 9.13 the data hulls for seismic velocity versus density of the high frequency basaltic lava beds in UK209/03-01 are shown. This is one of the few distinct examples of depth correlated variation of physical properties seen within the investigated wells. Both density and velocity are correlated to depth in the high frequency basaltic lava beds in UK209/03-01. Velocity is the parameter with the highest depth correlation. At present, it is not clear whether this variation is caused by burial or reflects variation in primary lithology (e.g. subtle gradual change in magma composition during the eruptions forming the five units of high frequency lava beds in UK209/03-01). This could possibly be clarified by detailed investigation of the side wall cores from these units.

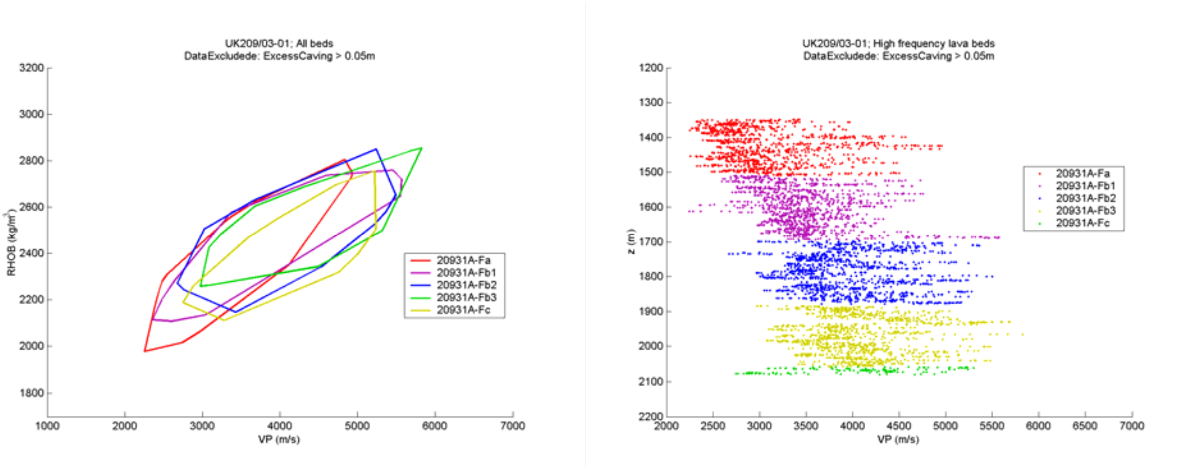

Figure 9.13. Right: Cross plot of seismic velocity, VP, versus density, RHOB, from high frequency basaltic lava bed units in UK209/03-01. Only the data hulls are shown so the gradual offset towards higher densities and velocities in the four upper high frequency lava bed units can be seen. Left: Plot of seismic velocity vs.density. The lowest unit, 20931A-Fc, is displaced towards lower densities and porosities relatively to unit 20931A-Fb3 immediately above, possibly reflecting a slightly different mineralogy. This conclusion is supported by different levels of gamma radiation in the two lowest volcanic units.

10 Well UK209/04-01

The well UK209/04-01 (61º55’17.54”N 00º17’53.69W) was drilled in 1985 with Sun Oil as operator to test possible prospects in the Paleocene (just above the volcanics) and in the Cretaceous. The well penetrated a succession of almost 500 m of Paleocene basaltic volcanic rocks (1637.5-2125.0 m) in the 12.25” hole. Volcaniclastic rocks are dominating this succession ($N/G_{Lavabed}$≈0.25). This well contains also rhyolitic rocks of Cretaceous age. These rocks are not included in the analysis in order to avoid clustering an already complex data set with an additional population of data points. Borehole conditions were not suited for high quality logging within the depth interval of interest. Caving varies mostly between 5 and 10 cm and may exceed 20 cm. This affects all log traces.

The density log is apparently the most affected. According to the completion report the recorded densities are possibly to low. However, compared to other wells investigated as a part of this study, the density measurements are rather too high than too low. To make things worse, there is some confusion in the completion report about the detector types used in the density tool. Post processing of the density log, as suggested in the processing report, is not considered feasible within the depth interval of interest.

Frequently, the velocities in the base of lava beds are rising slowly to the maximum values (e.g. Figure 10.1 and Figure 10.3), not abruptly as usually seen. This is considered a measurement error possibly due to unrealistically low gradient threshold in the picking algorithm.

The spherically focussed resistivity trace has generally no of the high frequency signal seen in the induction logs (and all the other porosity related logs). This is probably due to filtering. Otherwise, the measurements from the spherically focussed resistivity tool appear consistent with the other logs.

Although the overall quality of the log traces in this well is dubious, the data are usable. However, in order to get data of sufficient quality for statistical analysis, only data with caving in excess of 10 cm is rejected from this hole.

The suite of log measurements in the depth interval of interest in UK209/04-01 comprises

- calliper, CAL,
- natural gamma radiation, GR,
- sonic transit time (P-wave), DT,
- density, RHOB,
- neutron porosity, NPHI,
- resistivity measured with a deep induction tool, ILD, and ILM,
- resistivity measured with a spherically focussed tool, RFOC
- spectral gamma, K, Th and U,
- photo electric effect, PEF
- side wall cores (15 in the depth interval of interest)

The relevant log traces from the depth interval of interest are presented as enclosure 3. However, sonic transit time is recalculated to sonic velocities and presented as the trace, VP. A part of the log from 1800-2000 m is shown as Figure 10.1

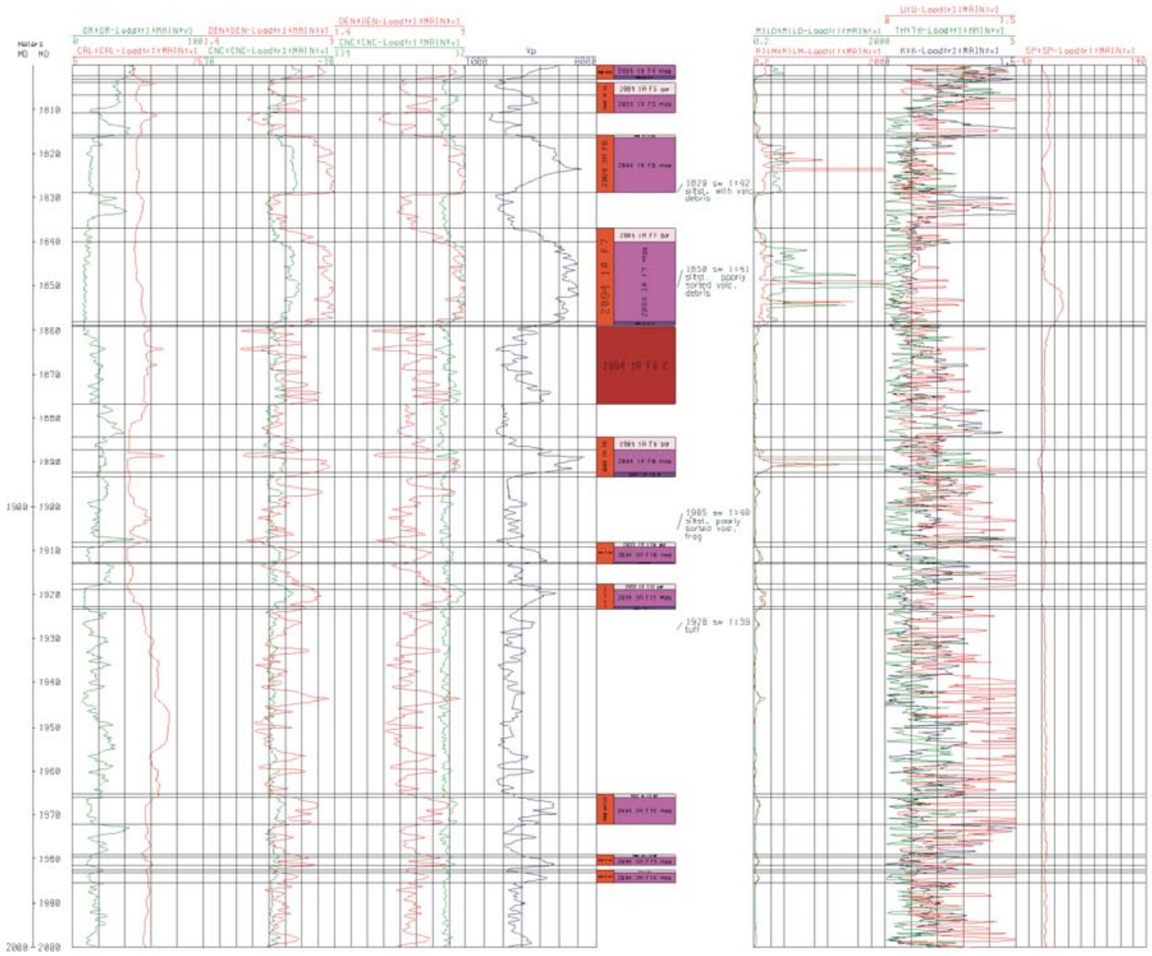

Figure 10.1. Log panels and interpreted lava bed units from the depth interval 1800-2000 m in UK209/04-01.

10.1 Unit descriptions

In UK209/04-01 we have interpreted a volcanic succession comprised of low and high frequency lava beds, and volcaniclastic sediments. The latter are based on the completion log to some extent “contaminated” by siliciclastic sediments.

10.1.1 Low frequency lava beds

Fifteen low frequency lava beds are found at various levels within the volcanic succession. While the volcanic succession and especially the lava beds in the other investigated wells are characterised by a narrow range of gamma radiation intensity, it is more variable in this well (10-40 GAPI).

Unit *20941A-F3* (Figure 10.2) is a typical low frequency lava bed. The upper crust is ca. 2 m thick, the upper one meter characterised by a fairly constant seismic velocity. The seismic velocity in the massive core is nearly constant, but with a general tendency to increase with depth within the core of the unit. Two thin more porous intervals in the massive core are apparent on the velocity trace, VP. One of these is also relatively distinct on the density and neutron porosity log. These details are not seen in the resistivity logs. The base of the unit is sharp on the porosity related log traces. It is also reflected in the natural gamma radiation and potassium concentration. The unit below (20904A-F4; see below) is interpreted as a lava bed with higher concentration of potassium than unit 20904A-F3. The deflection of the gamma radiation trace at the base of unit 20904A-F3 is thus an example that change in gamma radiation at boundaries of lava bed units not always can be considered an indication of sediments.

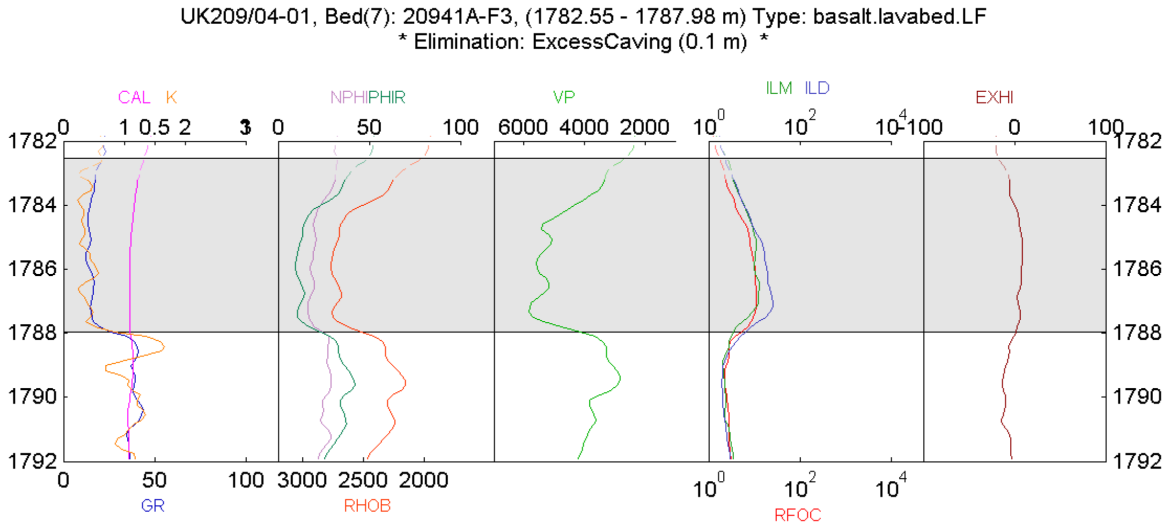

Figure 10.2. Log traces from depth interval 1782-1792 m in well UK209/04-01 showing unit 20941A-F3.

Unit *20941A-F4* (Figure 10.3). The seismic velocity within this unit is only well correlated to the other porosity related logs in the upper part of the unit. In the lower part it is uncorrelated, and the velocity measurements in this part of the unit are considered dubious. The log response from the other porosity related logs are typical for low frequency lava beds, although the upper crust is thicker than in most other low frequency lava beds. The ca. 6 m thick upper crust is characterised by neutron porosities in the interval 25-30 LPU. There is a distinct porosity decrease from 25 to 15 LPU at the boundary of the upper crust and the massive core.

Both the upper and lower boundary of this unit is distinct on the chemical logs. Natural gamma radiation and potassium concentration is fairly constant within the unit and higher than in most of the other lava beds from this well suggesting that the original lava composition of this unit was slightly more evolved than the lava responsible for most of the units in the well.

Unit *20941A-F7* (Figure 10.4) is a more than 20 m thick lava bed with a relatively thin upper crust (3 m). The unit is characterised by high seismic velocity (in excess of 6000 ms^{-1} in some parts of the core). The other porosity related log traces are reasonably well correlated with the velocity, and all but the spherically focussed log indicate that fairly high frequency “porosity layering” is present in the massive core of this lava bed.

10.1.2 High frequency lava beds

Only two units of high frequency lava beds have been interpreted in this well, and both are somewhat atypical.

Unit *20941A*-F1 (Figure 10.5) is a 22 m thick unit with several velocity maxima. Generally the velocity is lower than in low frequency lava beds and the other porosity related logs are well correlated with the velocity log. We have classified this unit as a unit of high frequency lava beds. However, the log response could also arise from a single thick inflated lava flow with several vesicle zones with in the massive core. The ca. 5 m thick interval below 1640 m with velocities above 4000 ms-1 could in this case be interpreted as separate tongues of lava on top of the inflated lava bed (lava break outs). We have retained this unit as a unit of high frequency lava beds due to the relatively low velocities at the internal maxima (4000-5500 ms-1) and the relatively narrow velocity range.

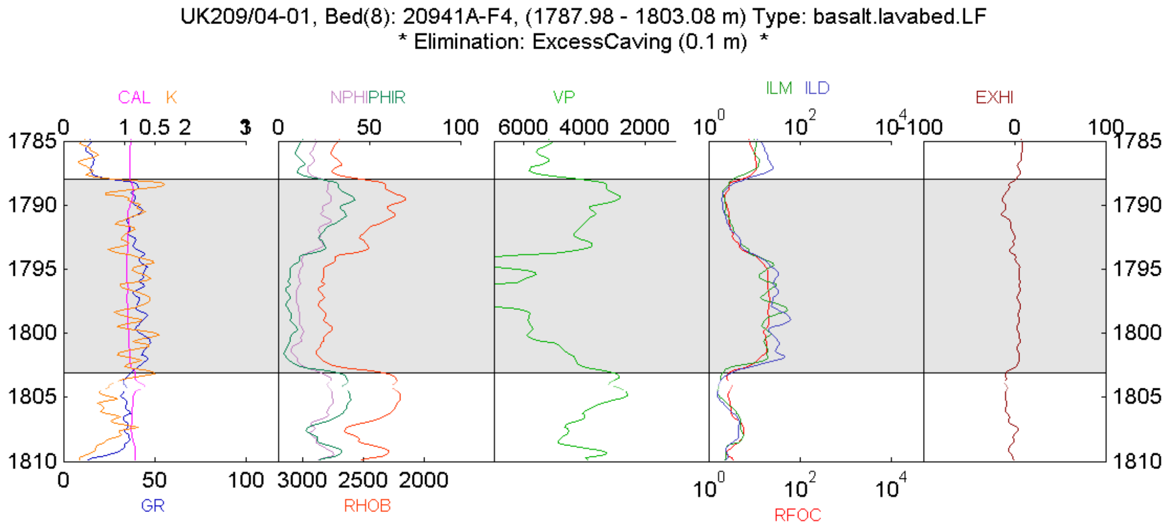

Figure 10.3. Log traces from depth interval 1785-1810 m in well UK209/04-01 showing unit 20941A-F4.

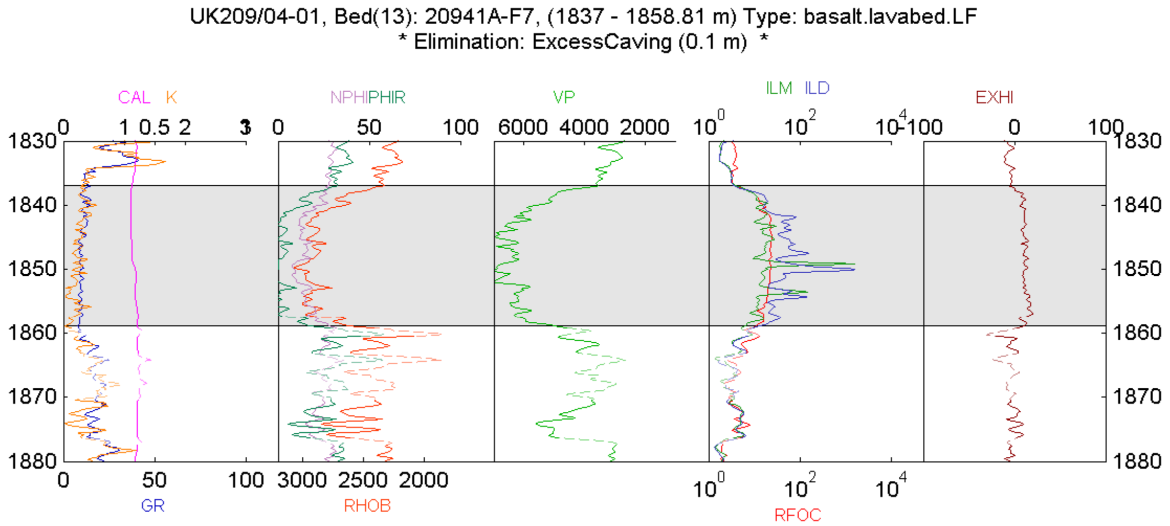

Figure 10.4. Log traces from depth interval 1830-1880 m in well UK209/04-01 showing unit 20941A-F7.

Unit *20941A-F8* (Figure 10.6). This 18 m unit comprises 7 “high velocity” layers of 2-3 m thickness characterised by maximal seismic velocities in the range 4000-5500 ms-1. This is considerably lower values than in the low frequency lava beds in this well. The other porosity related log traces in this unit and the natural gamma trace are all fairly well correlated with the velocity trace. In some aspects including the fluctuating gamma radiation, this unit resembles units of volcaniclastic sediments. Cuttings from the centre of the unit are described as “claystone, pink-brick read, quartz, mafic grains, tuff”. Although, it is possible that the log response and cutting description indicate a brecciated lava flow, we classify this unit as a unit of high frequency lava beds based on the velocity range and the velocity fluctuations.

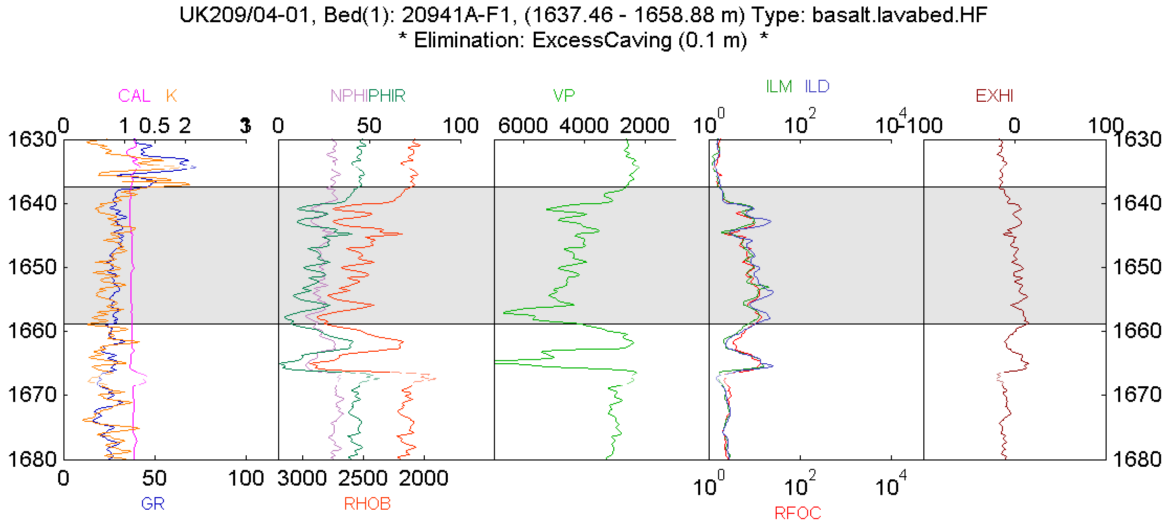

Figure 10.5. Log traces from depth interval 1630-1680 m in well UK209/04-01 showing unit 20941A-F1.

10.1.3 Volcaniclastic sediments

We have interpreted ca. 350 m of volcaniclastic sediments in this well. Partly as thick (10-100 m) fairly homogeneous units and partly as thin layers in between units of lava beds.

Unit *20941A-VS3a* (Figure 10.7, lower row of panels) is an almost 70 m thick unit characterised by low seismic velocities. In the bottom the velocities is ca 2500 ms^{-1} increasing upwards to ca. 3000 ms^{-1}. In a few thin high velocity layers within the unit the velocity exceeds 3500 ms^{-1}. Velocity fluctuations within this unit are small compared to units of lava beds (Figure 10.7 upper row of panels). Neutron porosity is not well correlated with the velocity in this unit. It is fairly high (ca. 25-35 LPU) and constant throughout the unit. However, density and the resistivity traces are well correlated with the seismic velocity. Gamma radiation is fairly low within this unit, comparable to the basaltic lava beds in this well. Two side wall cores from this unit are both described as basalt.

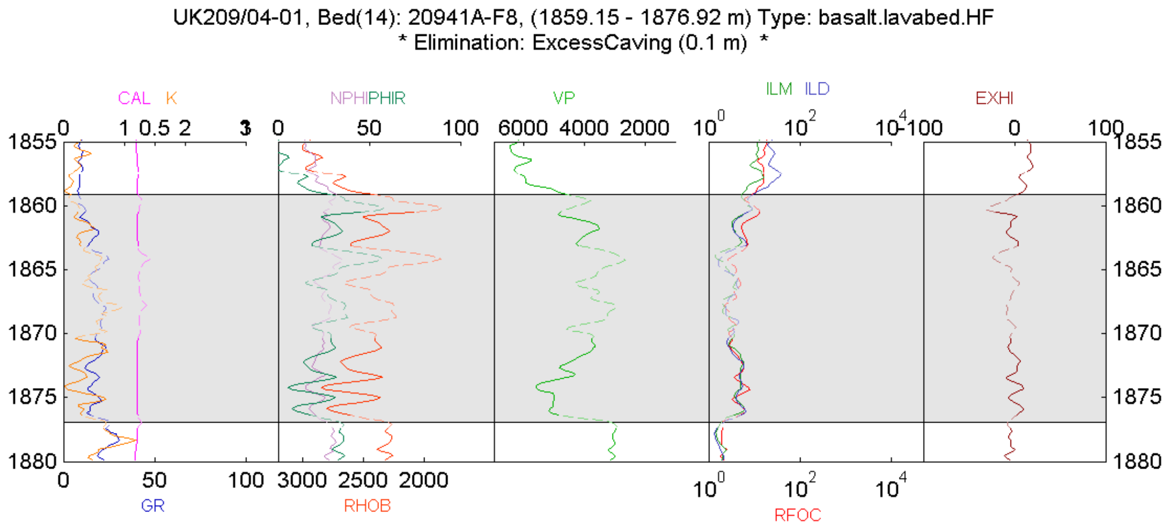

Figure 10.6. Log traces from depth interval 1855-1880 m in well UK209/04-01 showing unit 20941A-F8.

Unit *20941A-VS6* (Figure 10.8) is an 8.1 m thick sediment layer in between two low frequency lava beds. Seismic velocities of the unit vary from ca. 2600 ms^{-1} in the top to ca. 3600 ms^{-1} in the bottom of the unit. The natural gamma radiation and potassium concentration are high (compared to lava beds) in the upper three quarters of the unit indicating possible contamination with potassium rich material from elsewhere. A side wall core from this part of the unit is described as “siltstone with volcanic debris”. Natural gamma radiation and potassium concentration in the lower part of the unit are the same as in the lava bed below, and this part of the unit is considered a sediment of local origin. However, it should not be ruled out that the lower part of the unit can be interpreted as a highly brecciated flow top of the lava bed below. The position of the lower unit boundary was selected at the point of maximum change of gradient on the velocity trace.

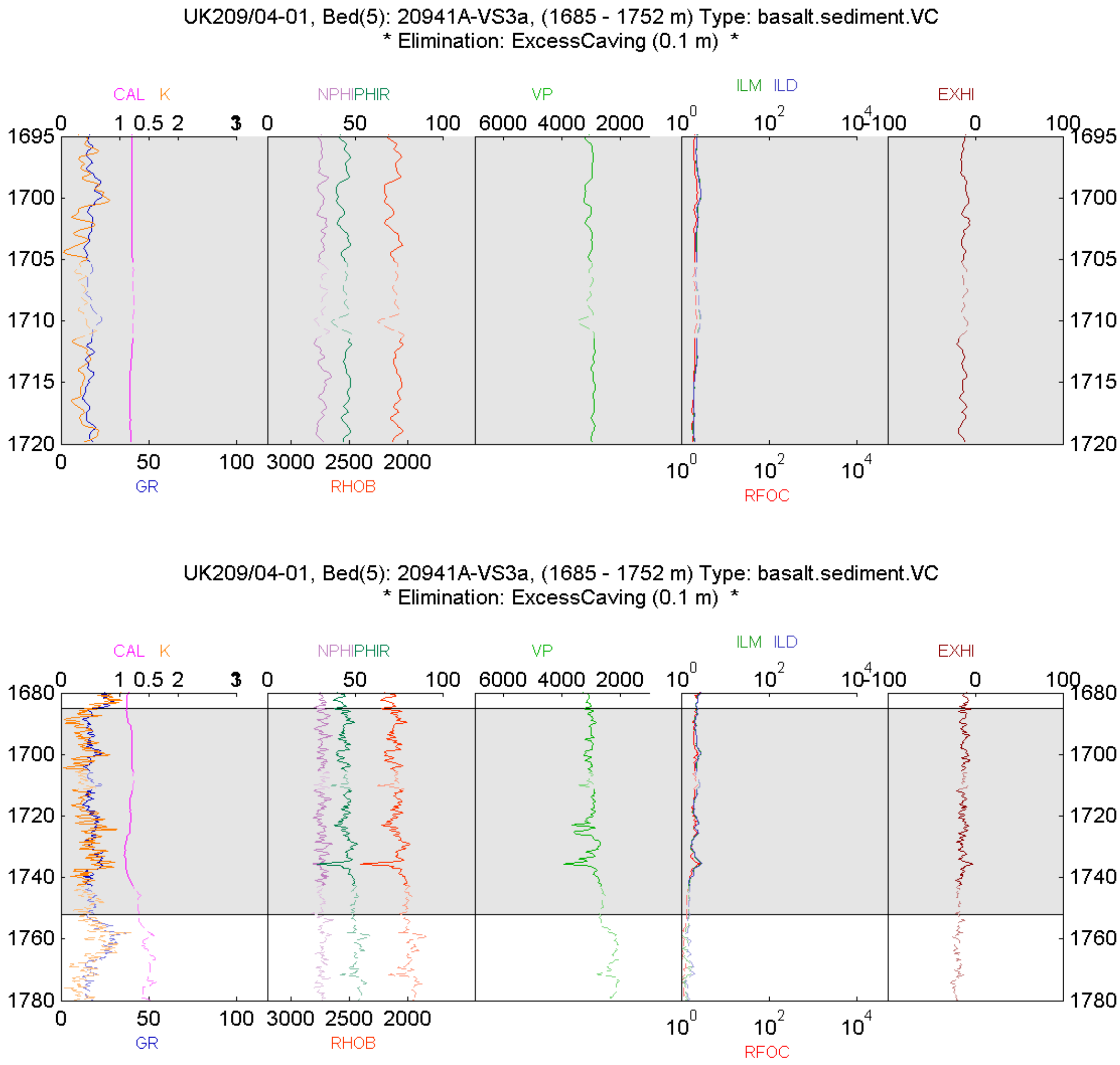

Figure 10.7. Log traces showing unit 20941A-VS3a from well UK209/04-01. Lower panel (depth interval 1680-1780 m) show the complete unit. Upper panel (depth interval 1695-1720 m) show details from the upper part of the unit.

10.1.4 Intrusives

Two basaltic intrusives are identified in the Upper Cretaceous section of the well.

Unit *20941A-I1a,b* (Figure 10.9) is characterised by seismic velocities in the range 5000 ms^{-1} to 7000 ms^{-1}, and low natural gamma radiation except for a ca. 2 m thick interval in the central part of the unit, where gamma radiation reaches values above 50 GAPI indicating a possible xenolith. The relatively poor correlation between the apparent location of unit boundaries on the natural gamma trace and the velocity trace is possible reflecting contact metamorphism.

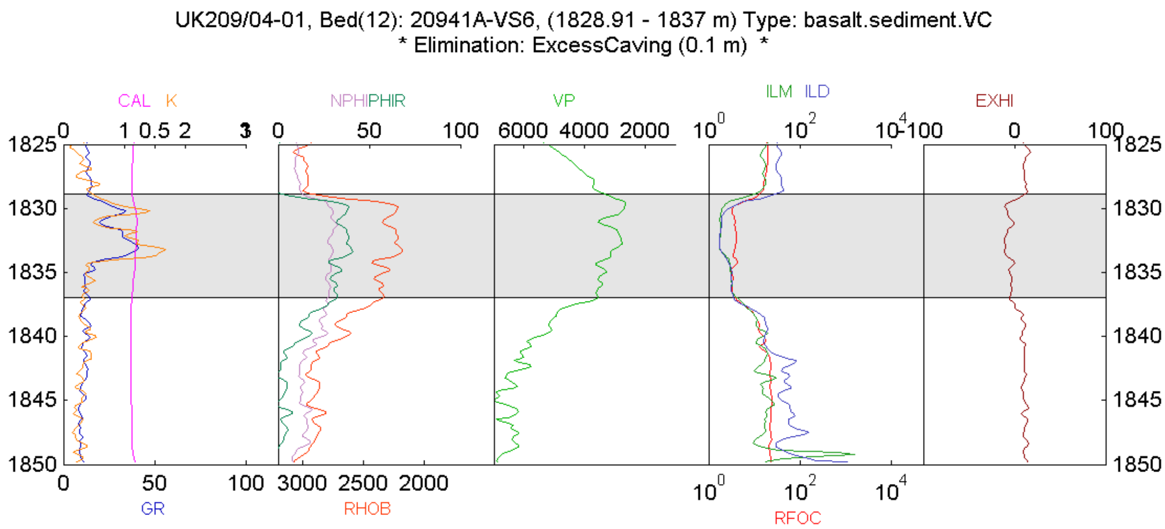

Figure 10.8. Log traces from depth interval 1825-1850 m in well UK209/04-01 showing unit 20941A-VS6.

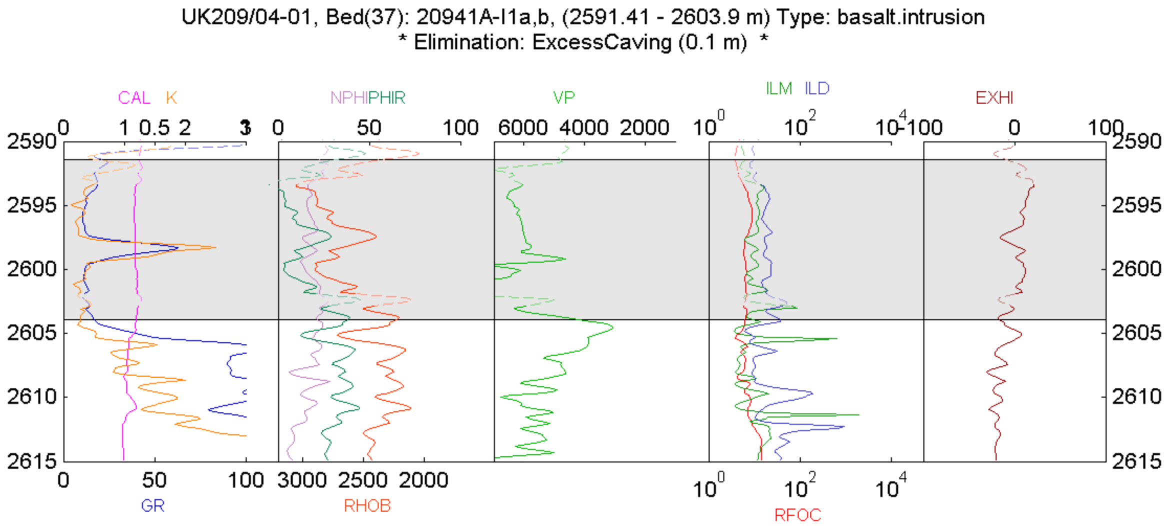

Figure 10.9. Log traces from depth interval 2590-1615 m in well UK209/04-01 showing unit 20941A-I1a,b.

10.2 Properties of basaltic rocks in UK209/04-01

As already mentioned the "basaltic" succession investigated in UK209/04-01 is not as chemically homogeneous as the basaltic successions in the other wells investigated as a part of this project. At least to the extent it can be judged from the natural gamma radiation. This is illustrated in a cross plot of gamma radiation versus seismic velocity (Figure 10.10). The spread of data points from the intrusions partly reflects the presence of xenoliths and partly the fact that boundaries of intrusions not are well defined when the side rock is metamorphosed neither on the natural gamma radiation nor on the velocity or other porosity related logs. There is apparently no distinct connection between the gamma radiation within a lava bed and magnitude of the seismic velocity (or other porosity related logs. Within the volcaniclastic sediment units, there is an overall tendency that the velocities decreases with increasing gamma radiation from the formation, as also seen in other studied wells. This may reflect variable degree of mixing of volcaniclastic material and siliciclastic material.

The neutron porosity of the basaltic rocks from this well is at any seismic velocity generally lower than in the other studied wells (Figure 10.11). Based on the range of neutron porosity measurements, these measurements appear to be a more realistic estimate of true porosity than neutron porosity measurements in the other wells. Either there is less hydrous minerals in the matrix of the basaltic rocks in this well or some kind of correction has been applied to the neutron porosity log. The first is not considered likely, as we are less than 20 km from UK209/03-01 and the volcanic rocks are found in the same depth range. No kind of correction of the neutron porosity log is indicated in the completion log. The apparent good quality of the neutron porosity log as an estimate of porosity is thus puzzling, especially as the neutron porosity at high velocities still is in excess of 10 %.

The porosity derived from the density log in this well is neither very realistic (Figure 10.12). At high velocities negative porosity estimates are occurring frequently indicating that log densities are too high or that the matrix densities of the volcanic rocks in this well are significantly higher than the reduction density used (2950 kg m^{-3}). Neither is considered realistic. Most probably both the neutron porosity and the density log from this well are influenced by some systematic error of unknown origin.

As both estimates of porosity are dubious, interpretation of resistivities is even more problematic in this well than in the other wells. However, qualitatively it appears that the relationship between resistivity and porosity is the same in the lava beds of this well as in those from two other wells investigated as part of this study (UK205/09-01 and UK209/03-01). An approximately linear trend, which can be attributed to the conductivity of the pore fluids, is observed at high porosity values ($\Phi>15\%$). At lower porosities, the resistivity is almost constant, however, not quite the same for the three different resistivity tools. We suggest that the resistivity porosity trend observed in Figure 10.13 primarily is the result of bed effects rather than a significant conduction through the matrix (e.g. as cation exchange capacity of hydrous minerals). This is among other things based on the approximate “Archie” behaviour of lava beds in UK164/07-01, UK164/07-01z, Glyvursnes-01, and Vestmanna-01.

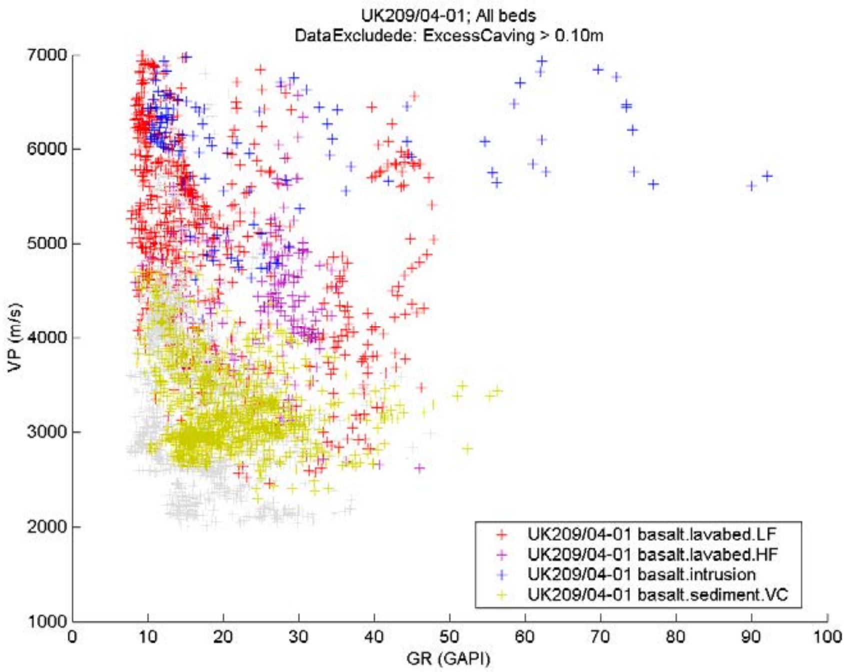

Figure 10.10. Cross plot of seismic velocity, VP, versus natural gamma radiation, GR, from basaltic volcanic units in UK209/04-01. The data points are coded according to what type they represent. Data points from intervals with caving in excess of 5 cm are shown in grey.

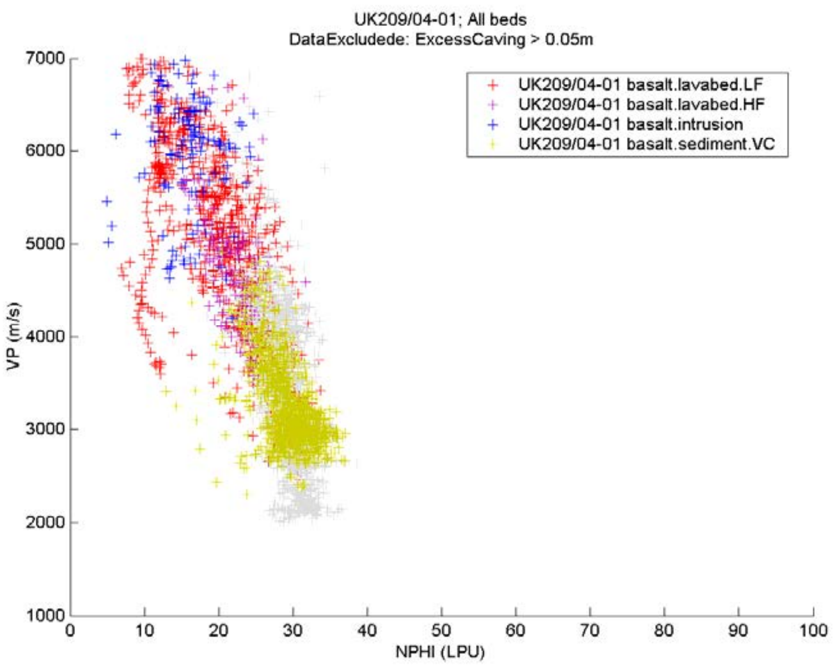

Figure 10.11. Cross plot of seismic velocity, VP, versus neutron porosity, NPHI, from basaltic volcanic units in UK209/04-01. The data points are coded according to what type they represent. Data points from intervals with caving in excess of 5 cm are shown in grey.

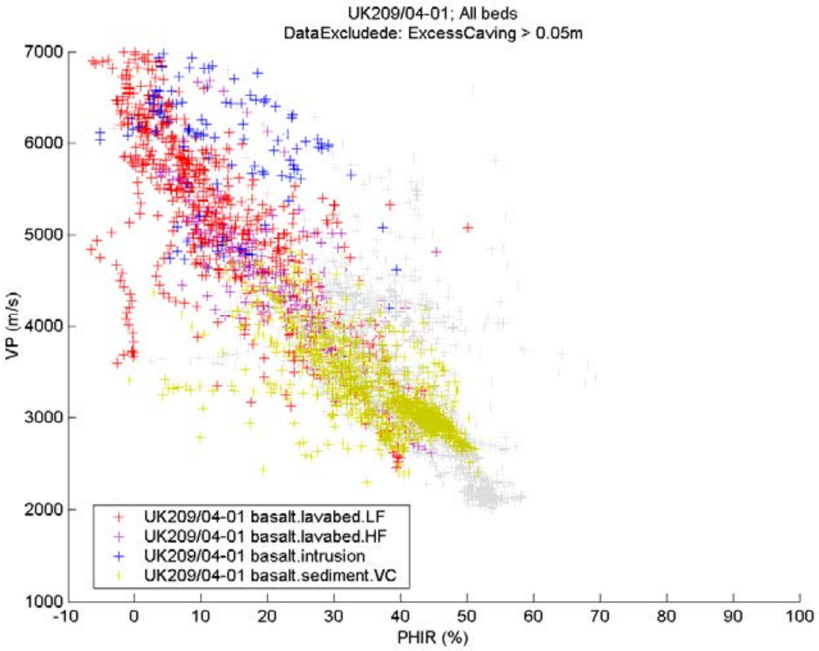

Figure 10.12. Cross plot of seismic velocity, VP, versus porosity, PHIR (calculated from the density logs assuming a matrix density of 2950 kg m^{-3}), from basaltic volcanic units in UK209/04-01. The data points are coded according to what type they represent. Data points from intervals with caving in excess of 5 cm are shown in grey.

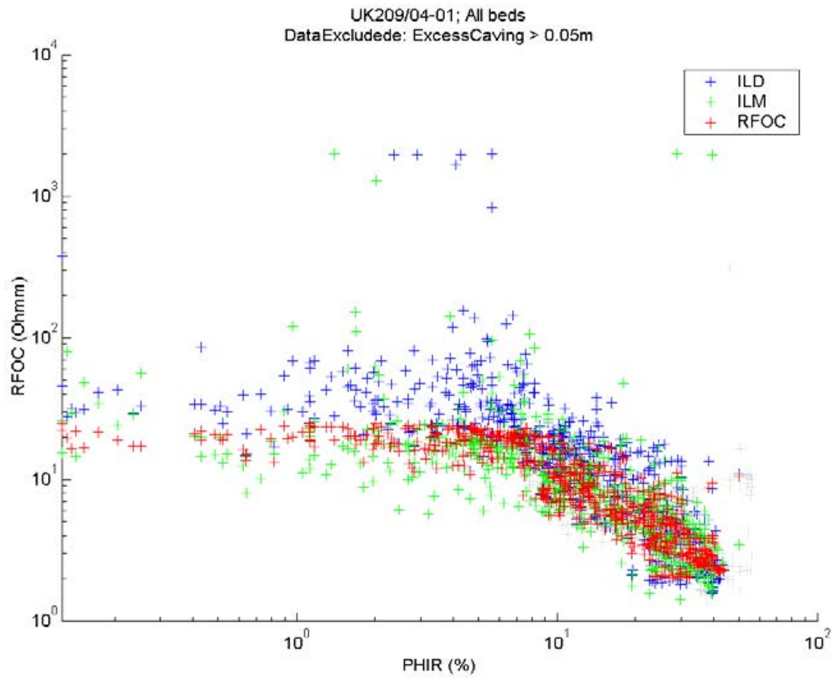

Figure 10.13. Cross plot of porosity, PHIR (calculated from the density logs assuming a matrix density of 2950 kg m^{-3}), versus resistivities measured with a deep penetration induction tool, ILD, a medium penetration induction tool, ILM, and a spherically focussed resistivity tool, RFOC, from basaltic volcanic units in UK209/04-01. The data points are coded according to what resistivity tool they represent. Data points from intervals with caving in excess of 5 cm are colored grey.

11 Well UK209/09-01

The well UK209/09-1 (61º45’44.298”N 0º20’39.193”W) in the northern part of the Faroe Shetland Channel was drilled in 1979 with BNOC as operator. The primary objective of the well was to test a postulated Mesozoic/Palaeozoic reservoir beneath Upper Cretaceous claystones. Paleocene sandstones sealed below Eocene claystones constituted a secondary objective. The well penetrated a ca 165 m thick basaltic succession in the 12.25” hole (at depth 1172.6-1337.4 m) and three intrusive basaltic intervals deeper in the well. Borehole conditions are generally good and caving is mostly less than 5 cm.
The suite of log measurements in UK209/09-01 comprises

- calliper, CAL,
- natural gamma radiation, GR,
- sonic transit time (P-wave), DT,
- density, RHOB,
- neutron porosity, NPHI,
- resistivity measured with a deep induction tool, ILD,
- resistivity measured with a spherically focussed tool SFLU.
- spontaneous potential, SP.

The data from the spontaneous potential tool is considered useless presumably reflecting potential variations originating at the surface rather than in the borehole. The resistivity logs are characterised by extremely high gradients at the base of basaltic low porosity units, and are typically not well correlated with other porosity related logs in the lowermost part of these zone. This is presumably to some extent reflecting bed effects. The other log traces appear to be of fair to good quality.

The relevant log traces from the depth interval of interest are presented as enclosure 4. However, sonic transit time is recalculated to sonic velocities and presented as the trace, VP. A part of the log from 1160-1360 m is shown as Figure 11.1.

11.1 Unit descriptions

In UK209/09-01 we have interpreted the following basaltic units 14 low frequency lava bed units 7 high frequency lava bed units and two ca. 2m thick volcaniclastic sediment units. Overall the basaltic units in this well are characterised by a natural gamma radiation in the range 15-25 GAPI in the lava beds. Higher values of natural gamma radiation are seen in thin intervals between or in the marginal zones of lava bed units. Within the volcanic succession the velocity trace are generally well correlated with the other porosity related log traces (resistivity logs, ILD, SFLU, neutron porosity, NPHI, and density, RHOB).

11.1.1 Low frequency lava beds

Maximum seismic velocity of low frequency lava beds is mostly in the range 5000-6000 ms^{-1}. Some low frequency lava beds have considerably smaller maximum seismic velocities. Overall the velocity trace is well correlated with the other porosity related log traces. However, it should be noted that extreme resistivity values at the boundary to underlying low velocity/high porosity units not is accompanied by velocity and neutron porosity extremes (see above).

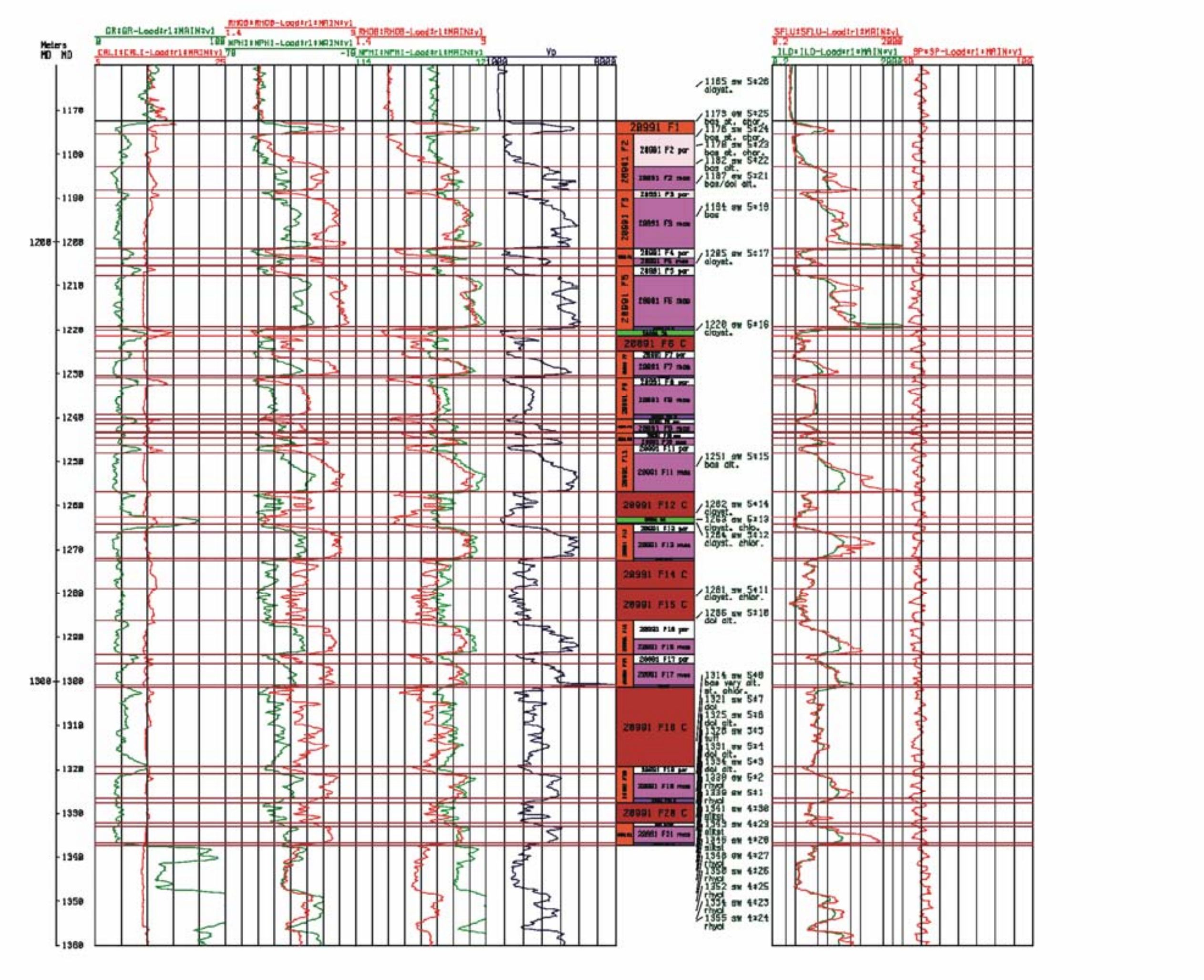

Figure 11.1. Log traces in the depth interval of interest (1160-1360m) in UK209/09-01. Showing the Paleocene volcanic succession in this well see also enclosure 4.

Unit *20991-F1* (1172.6-1175.2 m; Figure 11.2) is a thin unit with low porosity. The sonic travel time is low and density is high compared to the neutron porosity. Natural gamma radiation is low (about 15-20 GAPI). The resistivity is high. Both the top and the bottom of the unit are sharp on porosity related logs. In some aspects the log pattern of the thin unit could thus resemble that of a hypabyssal intrusive. However, the absence of a zone of gradually increasing gradients below the high basal gradients of unit 20991-F1 on porosity related log traces and the position of the unit on top of a major succession of basaltic effusive rocks indicates that unit 20991-F1 probably represents an erosional remnant of a lava bed.

Unit *20991-F2* (Figure 11.3). This, 13 m thick, unit is composed of a 7 m porous upper crust characterised by low and upwards decreasing seismic velocities (around 2000 ms^{-1} in most of the crust) and a 6 m thick massive core with seismic velocities in the range 4000-6000 ms^{-1}. Distinct separation between the spherically focussed resistivity log and the deep induction log is seen in most of the massive core of this unit except in a ca. 1 m thick more porous and conducting zone. The natural gamma radiation is slightly higher in the upper porous zone (ca. 25 GAPI) than in the core (12-20 GAPI). The ratio between density and neutron porosity changes significantly in the same interval in which the gamma radiation changes indicating that the increase in concentration of radioactive elements is coupled with a decrease in concentration of hydrous minerals or more likely a decrease in matrix density (which could be associated with higher concentration of hydrous minerals rather than lower). Volcaniclastic sediments are frequently characterised by similar values of all logs as seen in the upper crust of unit 20991-F2. However, three sidewall cores from the porous upper crust of this unit are all describes as basalt. We are thus fairly certain that the upper seven meters of this unit, despite the low seismic velocities are a lava crust rather than sediment, possibly strongly brecciated.

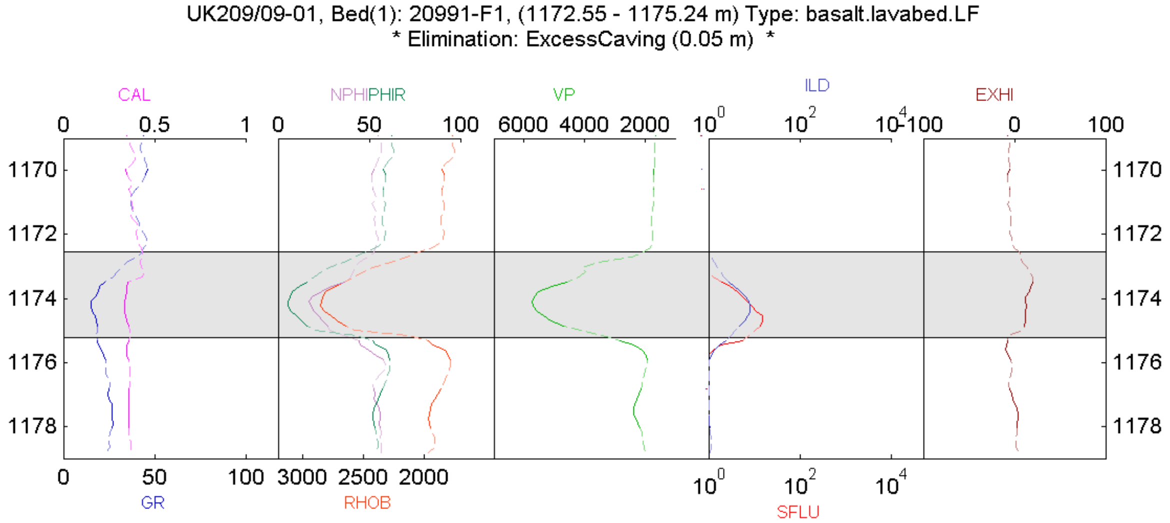

Figure 11.2. Log traces from depth interval 1179-1189 m in well UK209/09-01 showing unit 20991-F1.

Unit *20991-F3* (Figure 11.4) has a relatively thin (ca. 2 m) porous crust above a more than 10 m thick massive core. The boundary between upper crust and the massive core is most distinct on the density log and neutron porosity log. It is seen as a change in gradient on the velocity log, but is not very clear, and it can not be seen on the resistivity logs. In the uppermost 5 m of the massive core the neutron porosity and sonic travel time decrease monotonous while the density increases slightly. The resistivities increases with a fairly constant gradient to a maximum at the units porosity minimum at ca. 1198 m. Below the minimum porosity (ca. 20 LPU 5-6 m above the base of the unit) there is a thick zone, where the neutron porosity increases downwards to about 30 LPU. The lowermost meter is a very pronounced low porosity zone.

Unit *20991-F5* (Figure 11.5). This 15 m thick unit has a thin upper crust (ca. 2m) characterised by low velocity (2000 ms^{-1}) and density (1900-2000 kg m^{-3}) above a ca. 13 m thick relatively homogeneous massive core characterised by high velocities (ca. 6000 ms^{-1}). The porosity related logs are generally well correlated throughout the unit. In the upper crust the natural gamma radiation is ca. 30 GAPI compared to 15-20 GAPI in the massive core. Two ca. 2m thick zones with low velocities (ca. 4500 ms^{-1}) are found within the core. These zones are also distinct on the SFLU resistivity and the neutron porosity traces and can just be recognised on the ILD resistivity trace. Only the upper of the porosity zones are distinct on the density trace. A resistivity spike seen on the ILD resistivity trace is presumably an uncorrected bed effect.

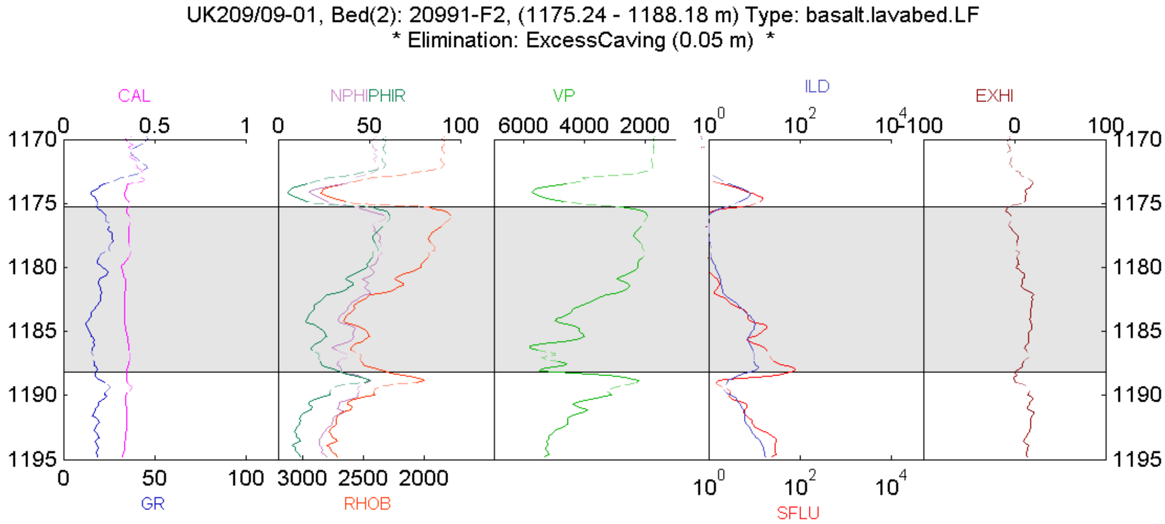

Figure 11.3. Log traces from depth interval 1170-1195 m in well UK209/09-01 showing unit 20991-F2.

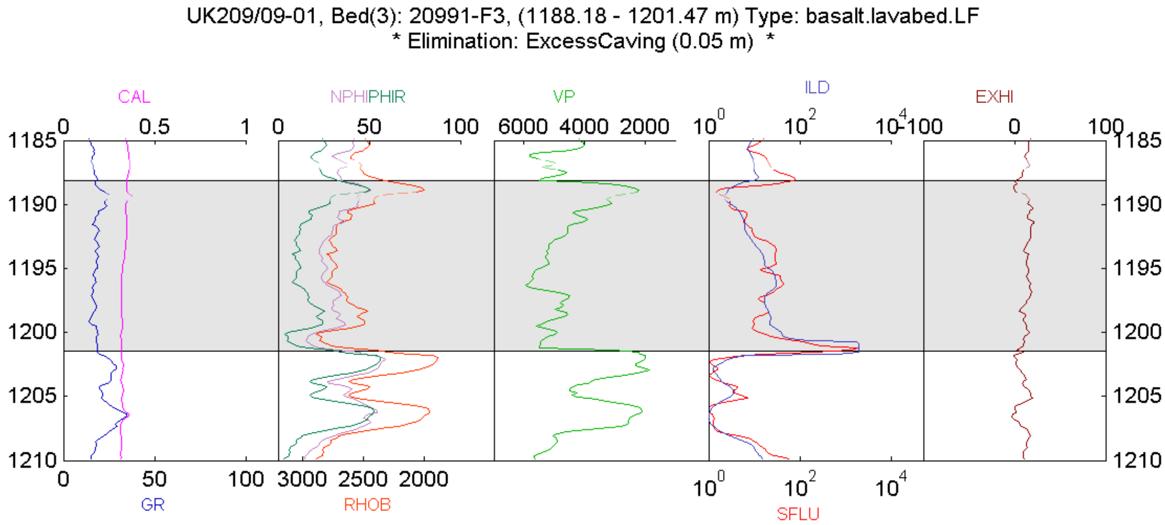

Figure 11.4. Log traces from depth interval 1185-1210 m in well UK209/09-01 showing unit 20991-F3.

Unit *20991-F8* (Figure 11.6). Overall this unit is characterised by velocities that are significantly lower than in other units of low frequency basalts (<3600 ms^{-1}). The other porosity related logs varies similarly. However, the overall log response of the unit is similar to other low frequency lava bed units. A 2 m thick distinct porous upper crust with a minimum velocity of 2000 ms^{-1} is situated on top of a core, which is unusually porous for low frequency lava beds (maximum neutron porosity is ca. 50-55 LPU, velocity ca. 3000-3600 ms^{-1}, density 2200-2450 kg m^{-3}). As in most other low frequency lava beds in this well the natural gamma radiation is significantly higher in the upper crust than in the core. Apparently unit 20991-F8 represents a lava bed with a highly porous core compared to other low frequency lava beds. The reason for the unusual porosity observed in the core of unit 20991-F8 is not known.

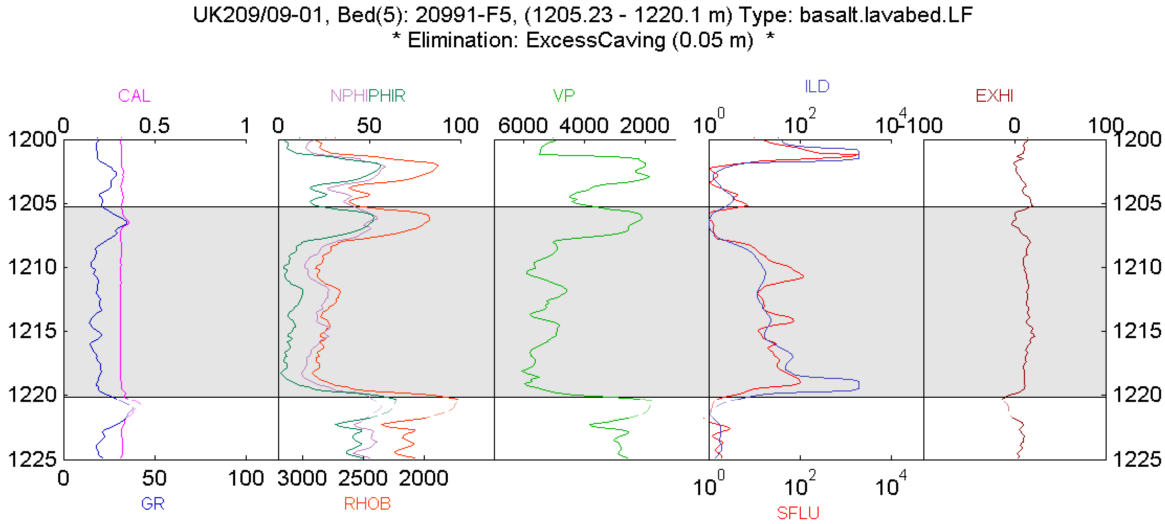

Figure 11.5. Log traces from depth interval 1200-1225 m in well UK209/09-01 showing unit 20991-F5.

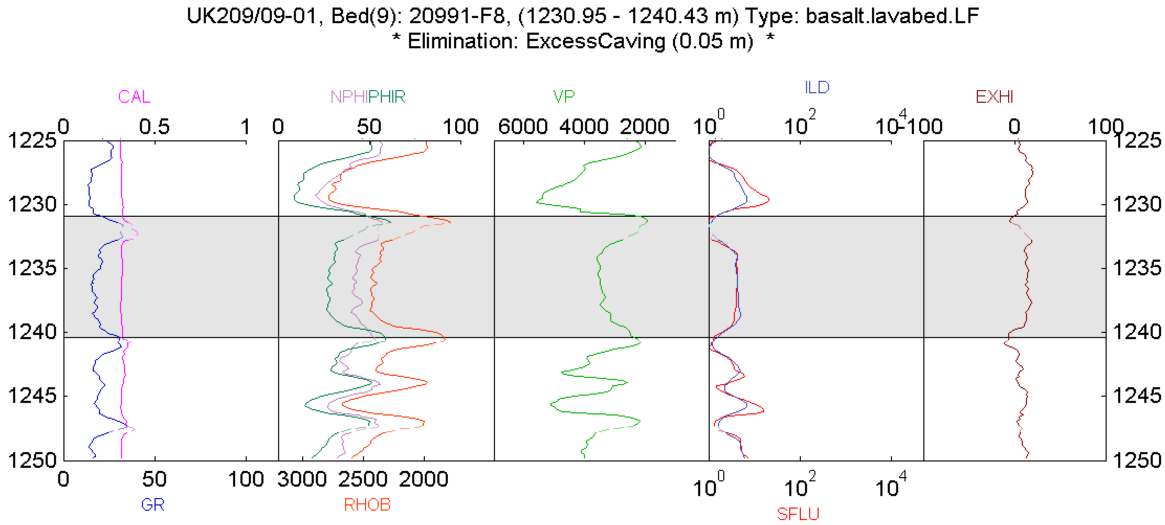

Figure 11.6. Log traces from depth interval 1225-1250 m in well UK209/09-01 showing unit 20991-F8.

11.1.2 High frequency lava beds

The high frequency lava bed units constitute ca. 42 m of the ca. 190 m thick basaltic volcanic succession in UK209/09-01. Overall, the high frequency lava bed units are characterised by lower seismic velocities and more restricted velocity ranges (3000-5000 ms^{-1}), when compared to the low frequency lava beds. Similar relationships are also observed for the other porosity related logs.

Unit *20991-F18* (Figure 11.7). This ca. 18 m thick unit is typical for high frequency lava beds in UK209/09-01. The seismic velocity is in the range 2750-4500 ms^{-1}. Five fairly distinct velocity maxima are seen in the central part of the unit. Within the unit the velocity is well correlated with both neutron porosity and density. Resistivity is fairly constant (2-10 Ωm). Both in the upper and the lower 2-3 m of the unit the natural gamma radiation is distinctly higher than in the central part, and as both density and velocity is fairly low, it could be argued that the upper and lower part of the unit are volcaniclastic sediments enriched in radioactive elements. However, as in many other high frequency lava bed units interpreted as a part of this study, it has not been considered convenient to separate possible sediment intercalations within the units.

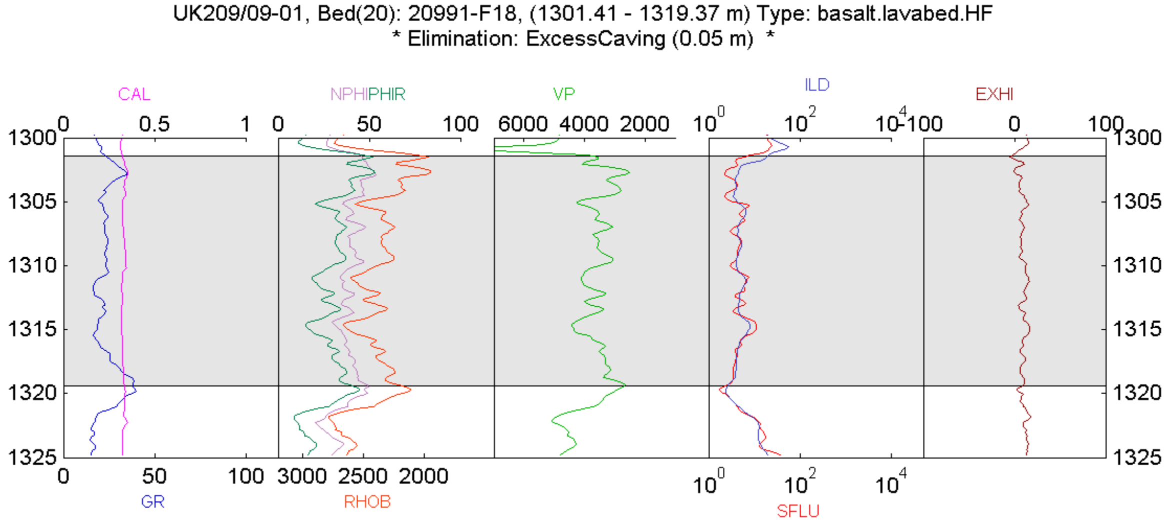

Figure 11.7. Log traces from depth interval 1300-1325 m in well UK209/09-01 showing unit 20991-F18.

11.1.3 Volcaniclastic sediments

Intervals of 1-3 m thickness characterised by natural gamma radiation up to about 40 GAPI, well above the typical level of gamma radiation from lava beds, are frequent within the volcanic succession of UK209/09-01. Generally we have interpreted these zones as part of the porous upper crust of low frequency lava beds assuming that alteration of the lava beds may lead to an increase of radioactive isotopes in the porous crust. However, two thin layers are interpreted as separate sediment units

Unit *20991-VS2* (Figure 11.8) is a 3.5 thick unit characterised by low velocity (ca. 2000 ms^{-1}), density (1950 kg m^{-3}) and resistivity (ca. 1 Ωm). The neutron porosity is ca 50 LPU. In the lower part of the unit natural gamma radiation is very high compared to the rest of the volcanic succession (maximum ca. 80 GAPI). The response is in accordance with that of sediment units in other wells investigated in this study (e.g. Glyvursnes-01). However, as indicated earlier, it is in no way simple to distinguish between thin sediment intercalations and altered flow tops in a volcanic succession, and it should not be ruled out completely that unit 20991-VS2 actually constitutes the upper part of an extremely altered flow top of the underlying unit (20991-F13).

11.1.4 Intrusives

Below the volcanic succession in 209/09-01 three units of basaltic intrusives have been identified within a succession of cretaceous claystones. The intrusives are recognised based on a low natural gamma radiation, high density, seismic velocity and resistivity. The neutron porosity is low (ca. 20-25 LPU).

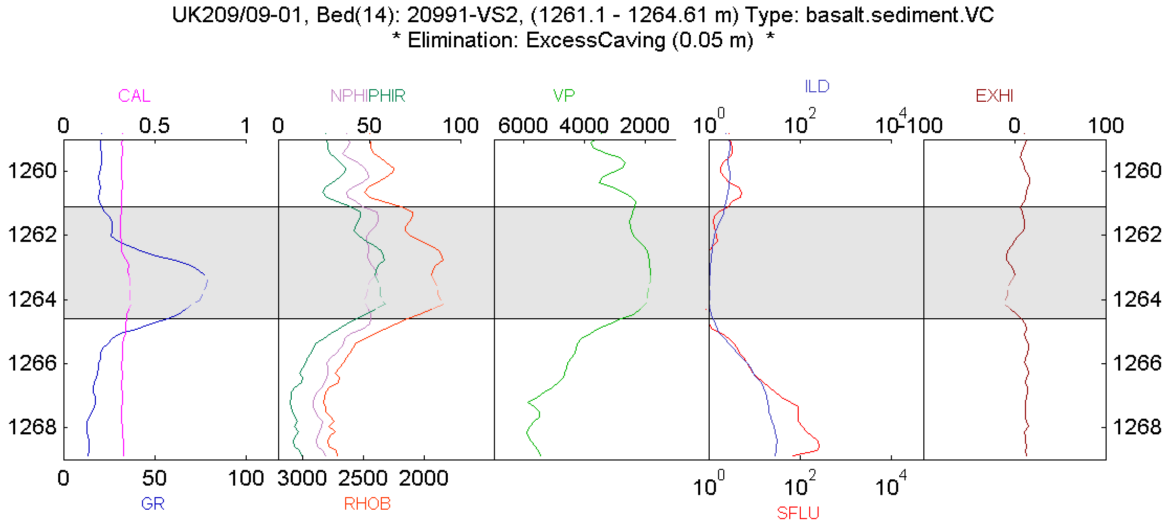

Figure 11.8. Log traces from depth interval 1259-1269 m in well UK209/09-01 showing unit 20991-VS2.

Unit *20991-I1* (Figure 11.9). The boundaries of this unit are fairly sharp on all log traces. Within the unit the values on the log traces are fairly constant and distinctly different from the bounding claystone. However, both above and below the intrusives a gradual increase towards the boundary is seen on the velocity, density, and resistivity traces. This is most likely a result of contact metamorphism.

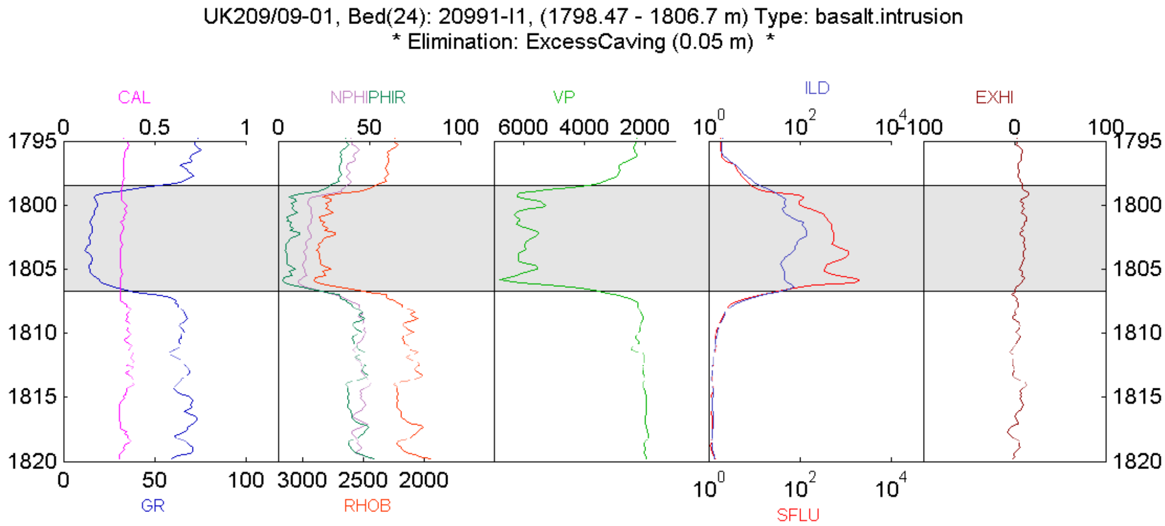

Figure 11.9. Log traces from depth interval 1795-1820 m in well UK209/09-01 showing unit 20991-I1.

Unit *20991-I2* (Figure 11.10). This 15 m thick unit is distinct on the natural gamma ray, seismic velocity and the resistivity trace. Although the values of both the velocity and the resistivities within the unit are distinctly different from those in the bounding claystone they are characterised by larger fluctuations than in unit 20991-I1. To some extent this may be a result of hole conditions (large and fluctuation calliper). The density is low compared to the seismic velocity, especially in the upper part of the unit. This is most likely a result of the hole conditions. As around unit 20991-I2 a gradual change in resistivity and velocity values towards the boundaries is seen in the bounding claystone above and below the intrusive unit. In addition a distinct decrease in natural gamma radiation is seen towards both boundaries of unit 20991-I2. The maximum level of gamma radiation is apparently first reached well within the unit boundaries of both unit 20991-I1 and –I2 suggesting that some elements with radioactive isotopes were mobilised during contact metamorphism or at some later time after emplacement of the intrusive units.

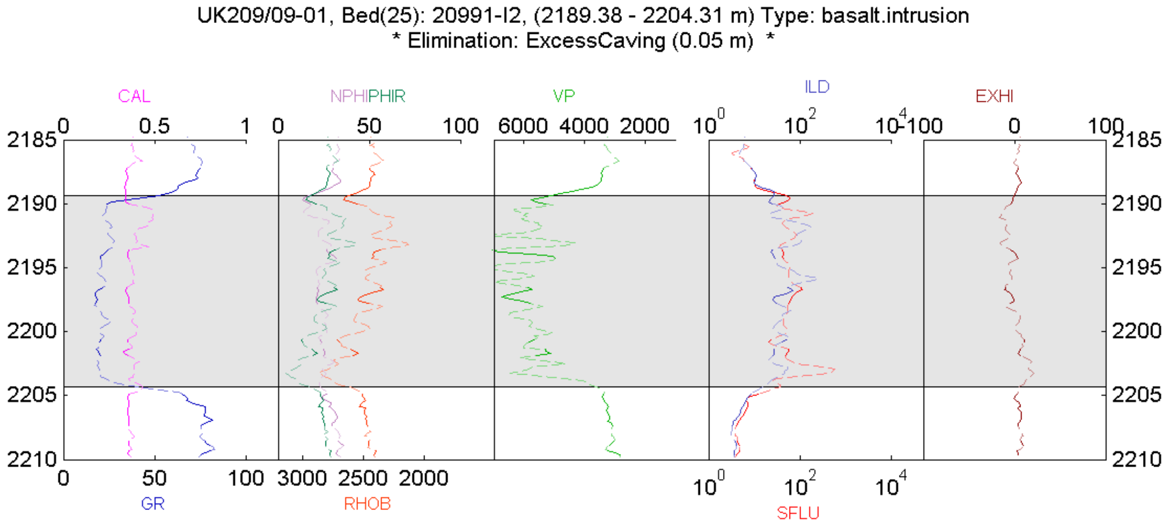

Figure 11.10. Log traces from depth interval 2185-2210 m in well UK209/09-01 showing unit 20991-I2.

11.2 Properties of basaltic rocks in UK209/09-01

As in several of the other wells, there is a tendency that natural gamma radiation is lower (ca. 18 GAPI) in sample points from lava bed units with high seismic velocity than in sample points with low seismic velocity (ca. 25 GAPI; Figure 11.11). At velocities lower than ca. 4000ms-1, there is a larger spread in natural gamma radiation from sample points within lava bed units than at higher velocities. This may either reflect variable degree of mobilization of elements with radioactive isotopes during alteration or thin beds of sediments not recognised during the interpretation. Some of the data points from the intrusives lie along a crude trend from high velocities and low natural gamma radiation towards low velocities and high gamma radiation. This is data points from the margins of the units reflecting contact metamorphism and possible mobilisation of elements with radioactive isotopes.

The lowest neutron porosity observed in basaltic rocks from UK209/09-01 is ca. 11 LPU (Figure 11.12). This is considered to high to represent the true porosity of massive cores of lava beds. An alternative estimate, PHIR, can be obtained using the density log assuming a fixed matrix density (Figure 11.13). In the most massive parts of the lava beds and in the intrusives PHIR is presumably the most reliable estimate of the porosity. However, both the porosities obtained from densities and those obtained from the neutron porosity tool appear to be too high in the porous parts of lava beds and in volcaniclastic sediments (predicting up to ca. 60 % porosity).

Taking into consideration that the porosity estimates may not be quite representative a crude correlation is still seen between porosity and resistivity (Figure 11.14). At low porosities, there is a tendency that resistivities measured with the spherically focussed resistivity tool are higher than those from the induction tool. This is most likely reflecting induction tools generally not perform well at the low resistivities found in basalts (e.g. Goldberg 1997).

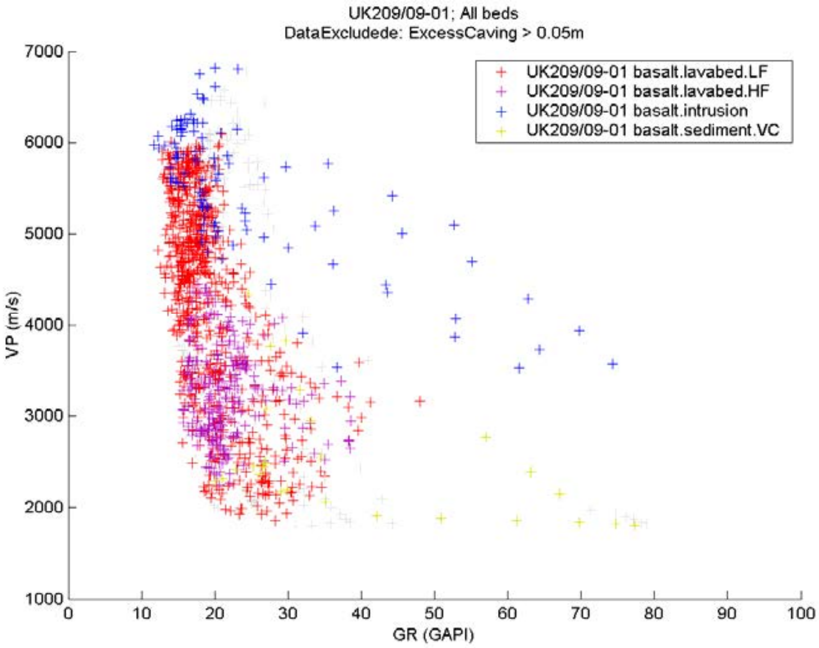

Figure 11.11. Cross plot of seismic velocity, VP, versus gamma radiation, GR, from basaltic volcanic units in UK209/09-1. The data point are colour coded according to what type of unit they belong to. Points in grey represent data points from those parts of the well where caving exceeds 5 cm.

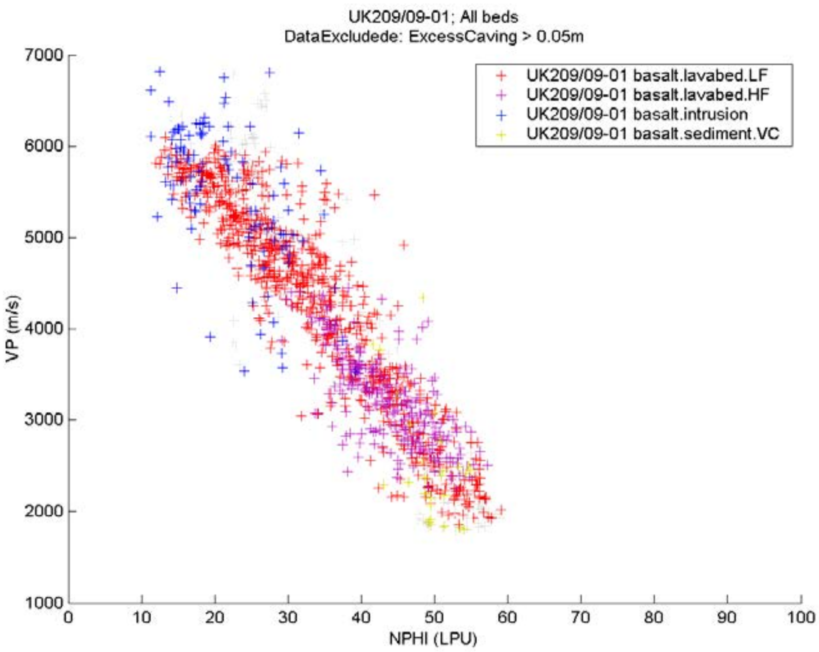

Figure 11.12 Cross plot of seismic velocity, VP, versus neutron porosity, NPHI, from basaltic volcanic units in UK209/01-01. The data point are colour coded according to what type of unit they belong to. Points in grey represent data points from those parts of the well where caving exceeds 5 cm.

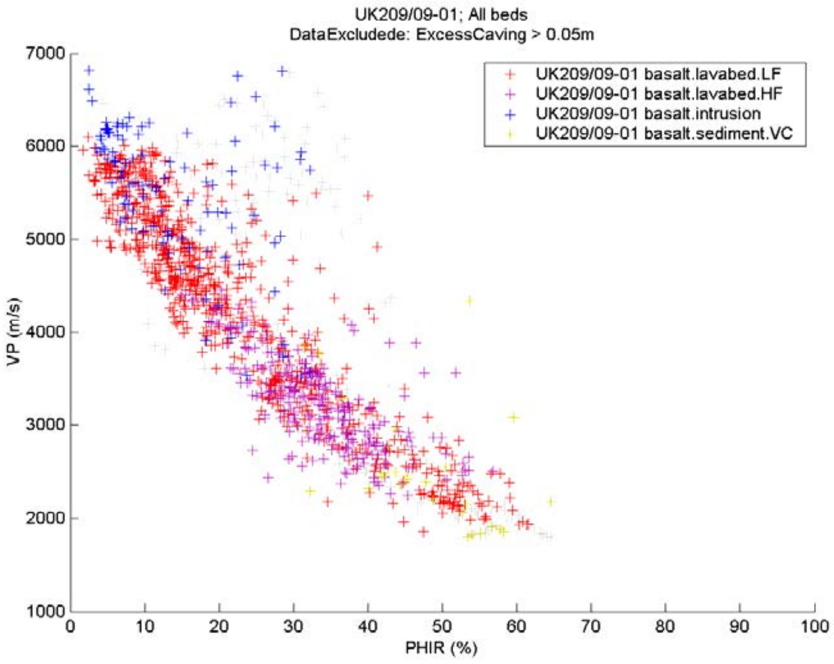

Figure 11.13 Cross plot of seismic velocity, VP, versus porosity calculated from the density log, PHIR, from basaltic volcanic units in UK209/03-01. The data point are colour coded according to what type of unit they belong to. Points in grey represent data points from those parts of the well where caving exceeds 5 cm.

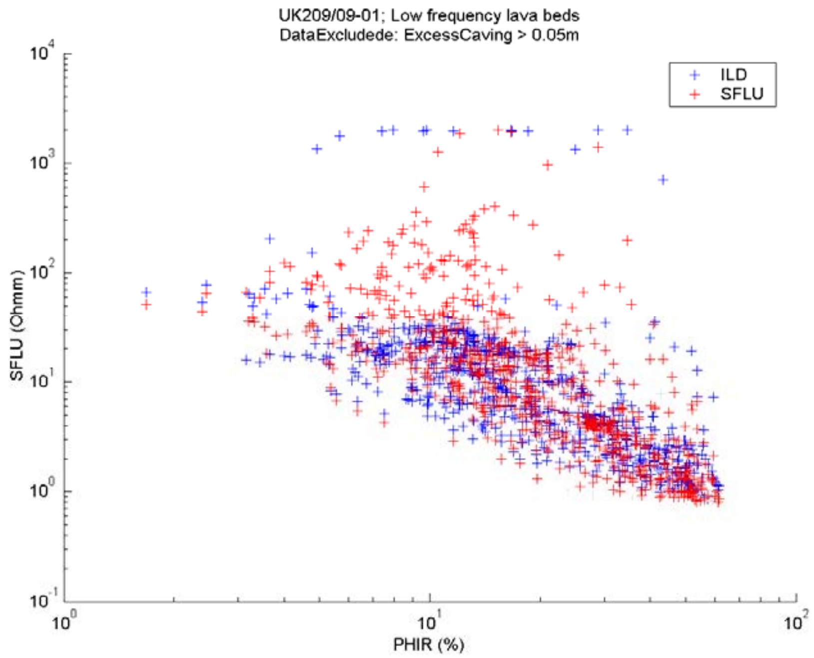

Figure 11.14. Resitivity (both SFLU and ILD) versus gamma radiation, GR, from basaltic low frequency lava bed units in UK209/09-01. The data point are colour coded according to the log tool. Points in grey represent data points from those parts of the well where caving exceeds 5 cm.

12 Well Vestmanna-1

The well Vestmanna-1 (62º09.079757’ N 7º08’786178’W) was drilled as a research well in 1980 by Landsverkfrøðingurin, Jardfrøðisavnið and Danmarks Geologiske Undersøgelse (Waagstein & Hald 1984). The main objective was the A-horizon between the Faroes Middle and Lower basalt formations. The A-horizon was found at 553 m depth (MD). The well was fully cored with a recovery rate more than 99.9% (Waagstein & Hald). The drilled succession was almost entirely basaltic lava beds (N/GLavabed≈ 0.94). Based on detailed petrological and geochemical analysis the penetrated succession was divided into individual lava beds, each of which either represents an individual volcanic event or one of several flow units forming a compound lava flow (Waagstein & Hald). The individual lava beds are grouped into 8 major mineralogical/geochemical units (Figure 12.1). The upper seven units constitute the lower part of the Middle Basalt Formation while the lowest unit is the uppermost flows of the Lower Basalt formation.

Formation	Chemical unit		Lithology
Faroes Middle Basalt Formation			
	g		Coarse-plagioclase phyric basalt
	f		Olivine-phyric basalt
	e		Olivine-phyric basalt
	d		Olivine-phyric basalt
	c		Olivine-phyric basalt; platy olivine
	b		Olivine-phyric basalt
	a		Olivine-phyric basalt
		A-horizon	
Faroes Lower Basalt Formation			Sparsely plagioclas-phyric

Figure 12.1. Stratigraphic subdivision of the Vestmanna-1 well (simplified from Waagstein 1984; Waagstein & Andersen 2004).

The Vestmanna-1 well was reamed in 2002 and subsequently the following wireline-logs were run:

- calliper, CAL,
- natural gamma radiation, GR,
- full wave form sonic VP (P-wave velocity) and VS (S-wave velocity),
- density, RHOB,
- neutron porosity, NPHI,
- resistivity measured with a deep induction tool, ILD,
- resistivity measured with a pad mounted spherically focussed tool, MSFL,
- Temperature,
- Electric conductivity.

In addition an optical televiewer were run through the full length of well.

The wireline-logs and processing of the optical televiewer and full wave form sonic log is described in Waagstein & Andersen (1984).

Hole conditions in the Vestmanna-1 well is excellent for logging. Caving is generally very small less than 0.1 cm. A number of processing have been carried out and in this study VS Guided pick finding have been used.

12.1 Unit descriptions

Based on core analysis Waagstein & Andersen (2004) identified four main lithologies,

1. lava core,
2. lava crust,
3. top lava breccia,
4. sediment.

Although these lithologies are seen distinctly on the core, they are - due to thin layering and overlapping physical properties - difficult to identify on the classical wireline-logs. The top and base of thicker lava beds (> 4 m) may be identified using the neutron porosity log trace (NPHI). It is more difficult to identify the top of the lava core of these lava beds. However, they can generally be picked with an accuracy of ca. 20-30 cm using the maximum (negative) gradient of the neutron porosity log. Basal crusts and breccias are generally so thin they not can be identified using wireline-logs.

There is a tendency that lava breccia have higher neutron porosity values than lava crust (other porosity related logs varies correspondingly). However, there is a large overlap of lava breccias and lava crusts properties (in all measured logs), and using classical well logs, it is generally not possible to distinguish between lava breccias and lava crusts (a problem we also have observed in the exploration wells from the UK sector of the Faroe Shetland Channel).

The logged sediment intercalations in Vestmanna-1 are characterised by very high neutron porosity, and corresponding extreme values on other porosity related logs. However, there is an overlap between the properties of the (basaltic) sediments in Vestmanna-1 and the most porous parts of lava beds.

As the main lithologies in the Vestmanna-1 well is not easily identified on classical logs and appear to reflect the same type of petrophysical variations as observed in the wells from the UK sector of the Faroe Shetland Channel, the same unit types as used in the wells from UK sector will also be used in analysis of the log response in Vestmanna-1. However, unit boundaries are generally forced to coincide with petrological/geochemical boundaries identified by Waagstein & Hald (1984). This will allow an investigation of possible variations of physical properties due to primary geochemical properties, which not were possible in the exploration wells from the UK sector.

Twenty low frequency lava beds (varying in thickness from 3.8 to 15.7m) and twenty six units of high frequency lava beds and four sediment layers were picked based on the original interpretation of the core (Waagstein & Hald 1984).

12.1.1 Low frequency lava beds

The log responses of low frequency lava beds are generally similar to log responses from low frequency lava beds in the exploration wells in the UK sector of the Faroe-Shetland Channel. However, the absolute values of the neutron porosity (NPHI) are low compared to the wells from the UK sector. Correspondingly the bulk density (RHOB) and sonic velocities, VP (and VS) are high (compared to the wells from the UK sector (chapters 5-11). The resistivities measured in the Vestmanna-1 well are very high compared to the wells from the UK sector. This is because

Vestmanna-1 is filled with fresh water while the drilling fluid and brine in the offshore wells are saline. The log response of a few low frequency lava beds are described below.

Unit *VM-b-c* (Figure 12.2). This 14.1 m thick olivine-phyric lava bed from the Middle Basalt Formation is comprised of a ca. 7 m thick upper high porosity zone (ca. 20-45%). On the core, it can be seen that this zone consist of a ca. 5 m thick lava crust overlain by a 2 m thick breccia. In this unit and several other low frequency basalt beds from the Vestmanna-1 well the boundary between the lava crust and the top breccia is recognised on the log traces due to a change in porosity and related parameters at the boundary. While the lava crust is characterised by a fairly constant porosity (ca. 20-25%), the top breccia is characterised by upwards increasing porosity in the range (ca. 25-45%). The Poisson's ration is averaging to ca. 0.28 with the maximum (0.35) in the top breccia.

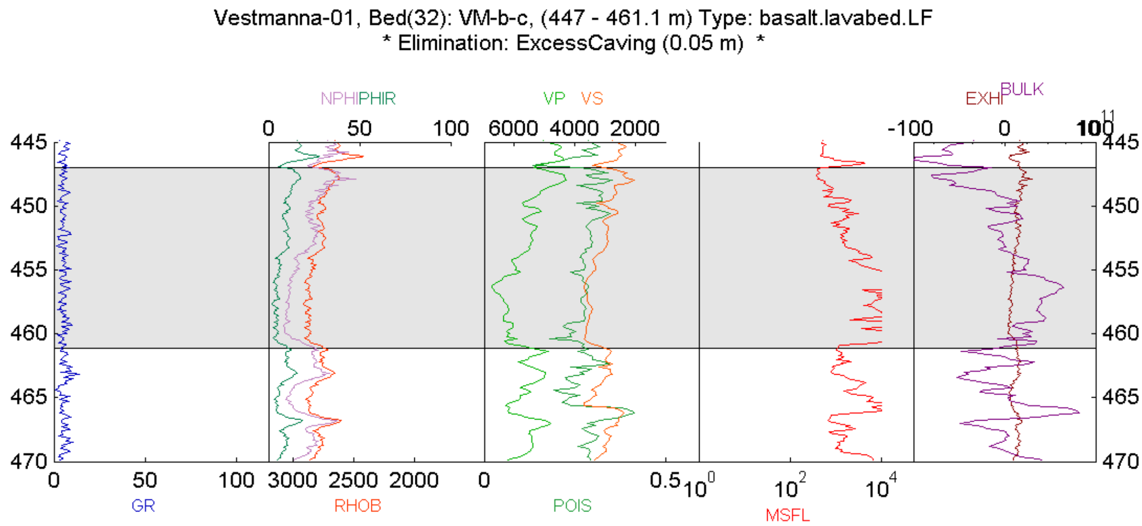

Figure 12.2. Log traces from depth interval 445-470 m in well Vestmanna-01 showing unit VM-b-c.

Unit *VM-e-b* (Figure 12.3). This is a 12.5 m thick olivine-phyric lava bed from the Middle Basalt Formation. It has a ca. 8 m thick core and 4 m thick upper crust with a distinct boundary in between, which also is recognised on the logs. A thin lower crust (ca. 0.5 m) is seen on the core. The top of the lower crust can be seen as a large gradient on all the porosity related traces, and the base can be seen as a sharp deflection on the GR trace. The lower ca. 3 m of the core has higher neutron porosity and - surprisingly - also significantly higher resistivity. A similar observation between neutron porosity and resistivity is seen in a few other lava beds in the Vestmanna-1 well but is rare. It is therefore not likely that the relation can be attributed to bed effects. Reduced connectivity between pores in the lower part of these few flows is a possible explanation. Natural gamma radiation increases upwards in this lava bed from ca. 5 GAPI in the bottom of the unit to ca 15 GAPI about 2 m below the top of the unit. It is possible this reflects alteration/soil formation prior to emplacement of the next unit. However, the sharp decrease in natural gamma radiation about 2 m below the top of the flow is difficult to explain in this context.

Unit *VM-LBF1c* (Figure 12.4). This is an 8 m thick plagioclase-phyric lava bed from the Lower Basalt formation. The lava bed has a thin upper crust (1 m) and top breccia (0.5 m), which can be identified collectively on the log traces. The seismic velocities in this lava bed is low (compared to the two above mentioned olivine-phyric lava beds), also if neutron porosity are taken into consideration. This may indicate that primary lava mineralogy/composition may influence the seismic velocities of basalts (see also: chapter 13).

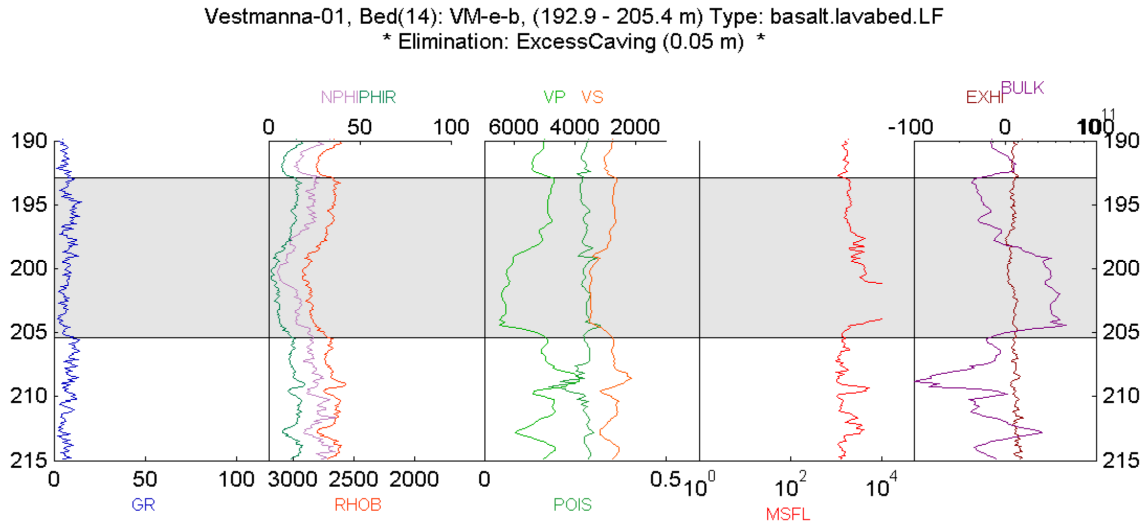

Figure 12.3. Log traces from depth interval 190-215 m in well Vestmanna-01 showing unit VM-e-b.

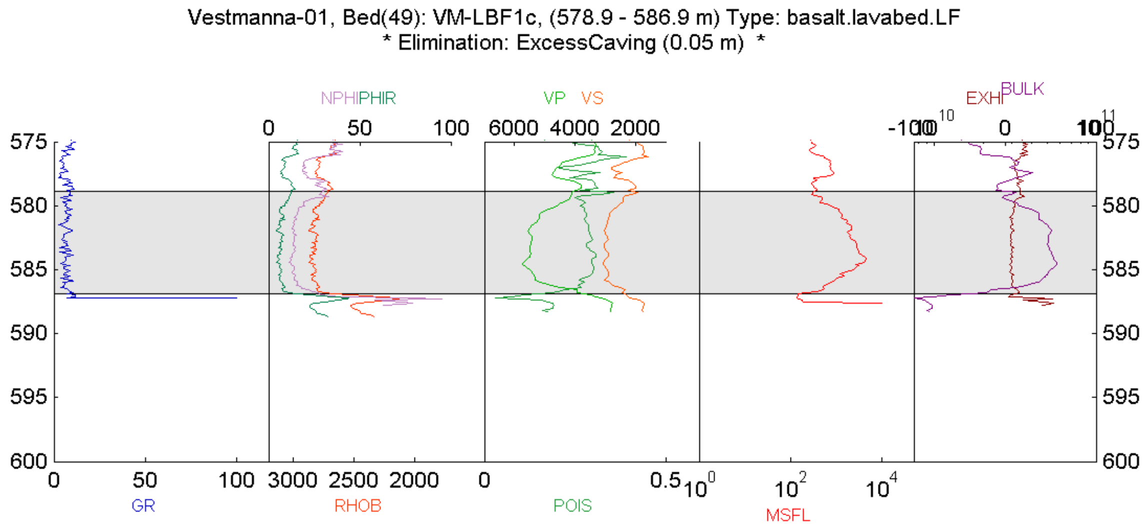

Figure 12.4. Log traces from depth interval 575-600 m in well Vestmanna-01 showing unit VM-LBF1c.

12.1.2 High frequency lava beds

Most log-units in the Vestmanna-1 well are interpreted as high frequency lava bed units. As in the wells from the UK sector the high frequency lava beds are characterised by oscillations of neutron porosity, bulk density and seismic velocity of a short period (1-5 m). The P-wave velocity range in the high frequency lava bed units (4000-6000 m/s) is generally somewhat smaller than in the low frequency lava beds (4000-6500 m/s). However, the difference is not as clear as in the wells from the UK sector. Below the log response of two high frequency lava bed units are described.

Unit *VM-g2* (Figure 12.5). Based on the description of the core this ca. 67 m thick unit consist of 25 individual lava beds of plagioclase-phyric basalt (Waagstein & Hald 1984; Waagstein & Andersen 2004). Several of the lava beds in the unit can be recognised on the log traces. Both natural gamma radiation and resistivity is fairly constant and the resistivity does not exceed 10^4 Ωm as it usually is seen in the thicker low frequency lava beds. Both the unit above VM-g3c and that below VM-g1 is high frequency lava bed units, and without the information from the core descriptions these units would probably have been joined into one unit.

Unit *VM-e-c* (Figure 12.6). This unit consist of 12 individual lava beds of olivine-phyric basalt (Waagstein & Hald 1984; Waagstein & Andersen 2004) and is ca. 24 m thick. Several of the lava beds that constitute this unit may be recognised on the logs, but as for the unit described above identification of all flow boundaries based on the log pattern would be very difficult if not impossible. Electric resistivity is fairly constant ca. 1500 Ωm. Natural gamma radiation within the lower twenty meters of this unit is fairly constant around (8 GAPI) but in the upper 4-5 m the gamma radiation is somewhat higher (ca. 15 GAPI) indicating possible early alteration of this unit prior to emplacement of the overlying unit VM-e-b.

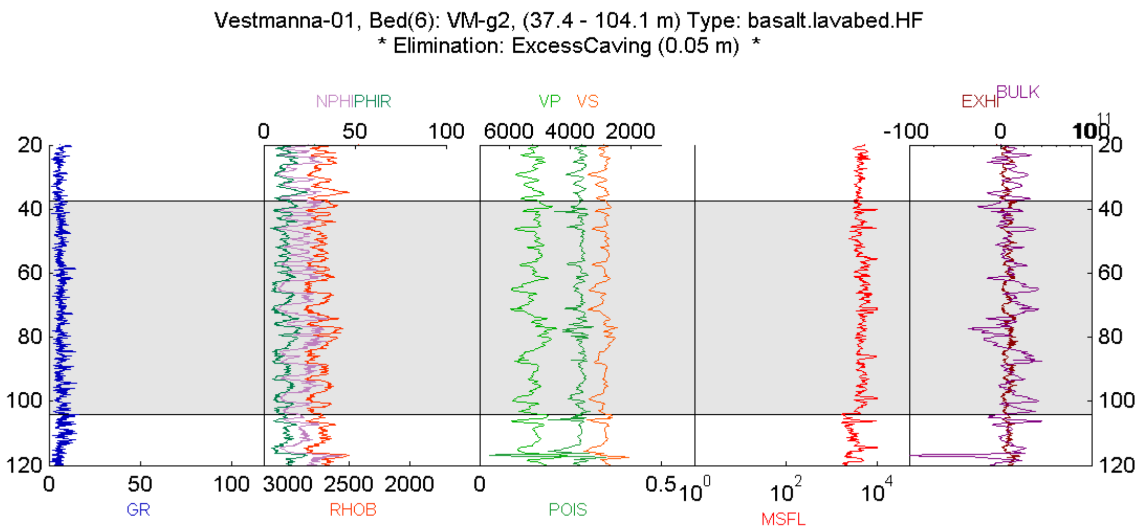

Figure 12.5. Log traces from depth interval 20-120 m in well Vestmanna-01 showing unit VM-g2.

12.1.3 Volcaniclastic sediments

Only few volcaniclastic sediments layers are penetrated in the Vestmanna-1 well. The most pronounced logged sediment unit in the well is the 2.8 m thick A-horizon which is equivalent of the coal bearing series on Suðuroy and Vágar (Figure 12.7). It is characterised by low seismic velocities and very high neutron porosities (above 50 LPU in the central part of the unit). The natural gamma radiation is slightly higher (ca. 3 GAPI) than the unit below indicating that potassium not have been up-concentrated in the sediment.

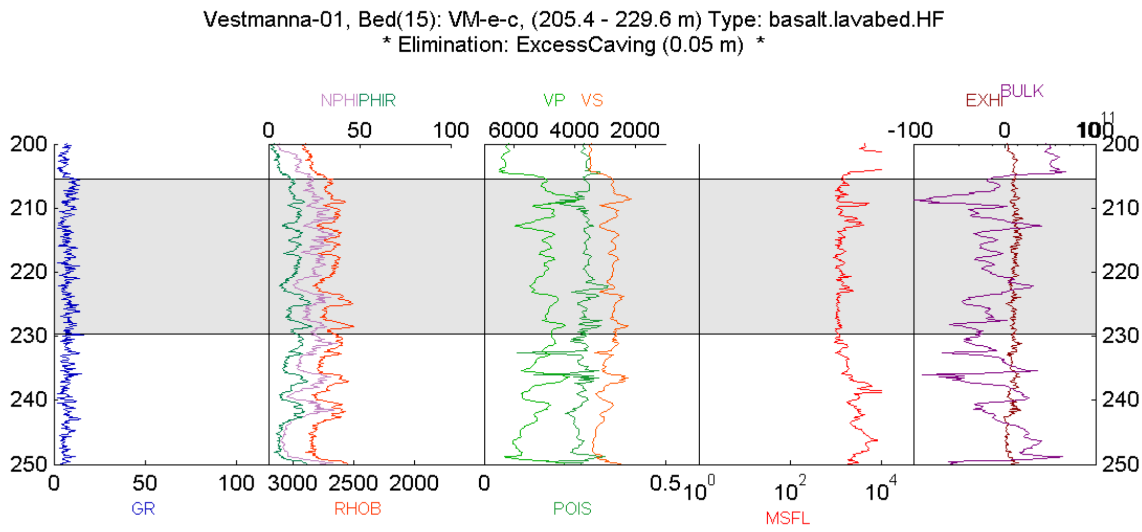

Figure 12.6. Log traces from depth interval 200-250 m in well Vestmanna-01 showing unit VM-e-c.

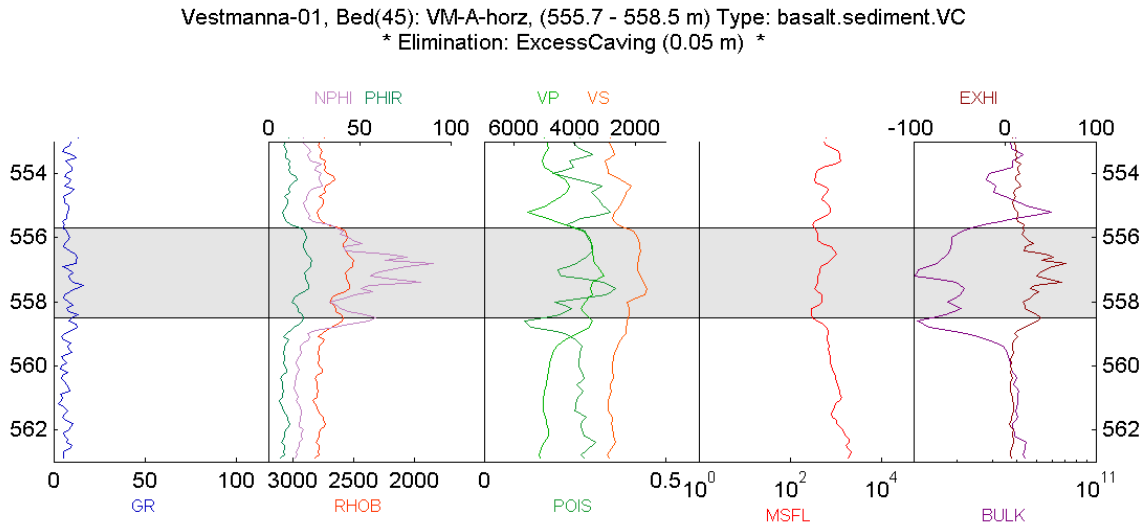

Figure 12.7. Log traces from depth interval 553-563 m in well Vestmanna-01 showing unit VM-A-horz.

12.2 Properties of basaltic rocks in Vestmanna-1

In most aspects the basaltic rocks in Vestmanna-1 resemble the basaltic rocks in the wells from the UK sector of the Faroe-Shetland Channel investigated as a part of this project, but the P-wave velocity range is narrower. The maximum seismic velocity in basaltic lava beds from Vestmanna-01 is comparable to the maximum velocities in similar rock types from wells in the UK sector. However, the minimum velocity in lava beds from Vestmanna-01 is generally higher than that in lava beds from the wells in the UK sector. This is true both for low frequency lava beds and units of high frequency lava beds. Several factors may contribute to the different velocity ranges:

- Lava bed units in the exploration wells from the UK sector may contain sediments that not were recognised during the interpretation.
- Lava beds in different wells may be of different composition and texture.

- Alteration may contribute to reduced seismic velocities and burial may contribute to increased velocities.
- Tools might be different calibrated in different wells.
- Hole condition may affect the logs.

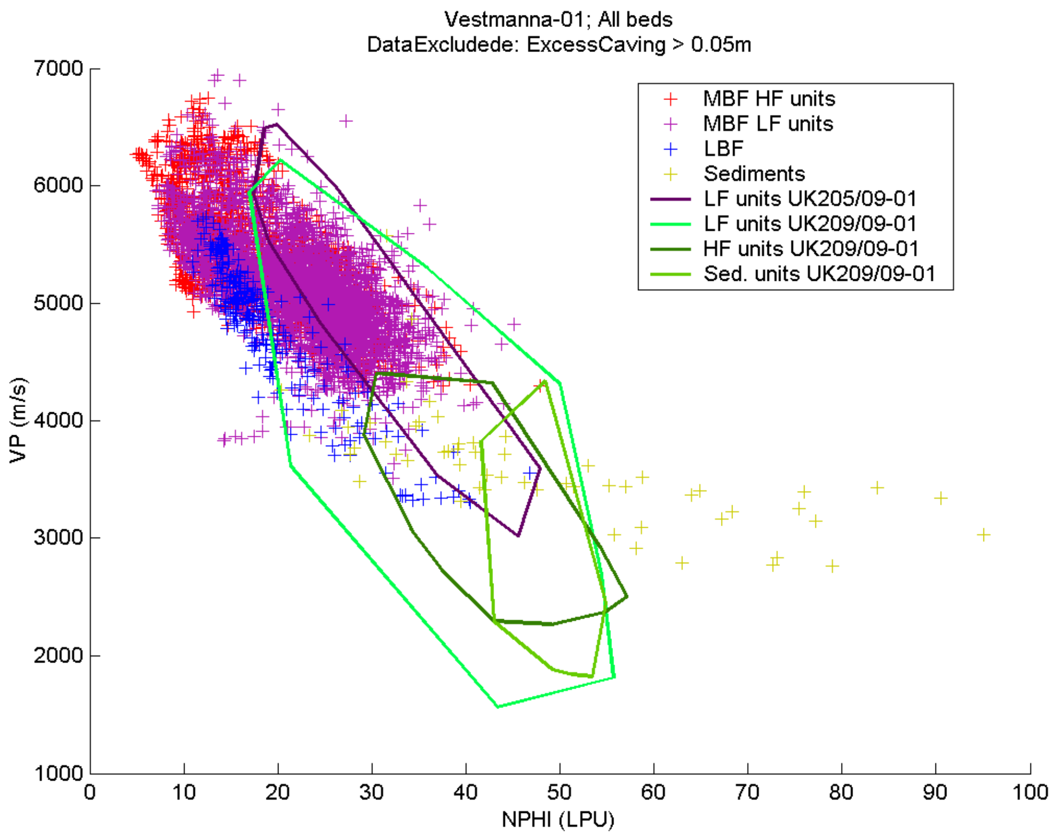

Figure 12.8. Cross plot of seismic velocity, VP, versus neutron porosity, NPHI, from basaltic volcanic units in Vestmanna-01. Data hulls of basaltic rocks in UK205/09-01 and UK209/09-01 are shown for comparison. Data points from intervals with caving in excess of 5 cm is not used to define the data hulls.

12.2.1.1 Sediments

As mentioned above (e.g. chapter 7, 11) it is likely that units of high frequency lava beds contain a significant amount of sediments. The overlap between the field of sediments from UK209/09-01 and the low velocity/high porosity part of the field of high frequency lava bed units from the same well (Figure 12.8) indicates that part of the explanation for higher minimum velocities in the high frequency lava bed units from Vestmanna-01 than in the wells from the UK sector could be that almost none sediments are present in the high frequency lava bed units from Vestmanna-01. It is tempting to use a similar explanation for the overlap between the sediment field and the low velocity/high porosity part of the field of low frequency lava bed from UK209/09-01, and as mentioned above, it is not straight forward to pick the top of low frequency lava beds, and these units may therefore contain some sediments in the top. However, an interpretation of the logs from UK209/09-01, where the velocities of low frequency lava bed units from UK209/09-01 is assumed to fall within the range of velocities observed in lava beds in the Middle Basalt Formation (MBF) from Vestmanna-01, is not easy to reconcile with the descriptions of sidewall cores from the well. As an example this would require that two side wall cores described as basalt are explained as representing boulders/breccia fragments in order to re-interpret the upper 7 m of unit 20991-F2 (see chapter 11) as a sediment or breccia.

Sediments may thus cause a significant part of the lowest velocities in high frequency lava bed units in the wells from the UK sector. Similarly, some of the lowest velocities in low frequency lava bed units may be caused by sediments and breccias in the upper part of lava beds.

12.2.1.2 Composition and texture

As mentioned above (chapter 8) the boundaries of the four basaltic units in UK205/09-01 are determined with an accuracy of ca. 25 cm. The field for the basaltic lava beds in UK205/09-01 is thus representing true measurements of seismic velocity and neutron porosity. Although, the lowest velocities in the basalts from UK205/09-01 are considerably lower than the velocities in lava beds in the Middle Basalt Formation from Vestmanna-01, the velocity range is comparable to the velocity range in lava beds in the Lower Basalt Formation from Vestmanna-01. The generally constant natural gamma radiation through lava beds in both UK205/09-01 and Vestmanna-01 indicates that pre-burial alteration of the basalts in these two wells not has been extensive.

Different composition and texture is thus an obvious explanation for the different data fields for the basaltic lava beds in UK205/09-01 and the Lower Basalt Formation and the Middle Basalt Formation in Vestmanna-01 (Figure 12.8). A more detailed comparison of the geochemical units in Vestmanna-01 substantiates this conclusion (see below).

12.2.1.3 Alteration

In contrast to the lava beds from Vestmanna-01 and UK205/09-01, the lava beds from UK209/09-01 is characterised by significantly higher natural gamma radiation in the top of most lava beds (e.g. unit 20991-F2). In chapter 11 it was indicated that the higher gamma radiation in the top of lava bed units could be related to alteration prior to burial (formation of red boles). It is possible that extensive re-crystallisation during formation of red boles could be causing a reduced seismic velocity. This effect is expected to be most severe in the upper (and most porous) part of lava beds.

Based on the variation of natural gamma radiation through basalt beds pre-burial alteration appears to be important in many lava beds in some of the investigated wells from the UK sector. However, a low correlation between seismic velocity and natural gamma radiation in almost all lava beds indicates that pre-burial alteration not is contributing significantly to the seismic velocity distribution in the investigated wells. However, a proper study of the relation between pre-burial alteration and seismic velocity should involve detailed comparison of mineralogical, geochemical and petrophysical data.

12.2.1.4 Burial (compaction, diagenis and metamorphism)

It is well known that the seismic velocity in basalt increase as the pressure increases and that the velocity increase generally is largest in porous basalts (e.g. Richter & Kern 1979). Re-crystallisation during burial may fill the pore spaces, stabilize the structure of sediments and act as a mechanism for stress release thus giving rise to an irreversible increase in seismic velocity.
In Figure 12.9 velocity is plotted against depth for six wells with basalt successions in excess of 500 m. A general z-VP trend is not defined by these wells. However, comparing velocities in Vestmanna-01 with seismic velocities in UK164/07-01 indicates that the basalts in Vestmanna-01 some time during their history were buried and partially re-crystallised under a pressure comparable to that in the lower part of the volcanic succession in UK164/07-01 (more than ca. 2.5 km).

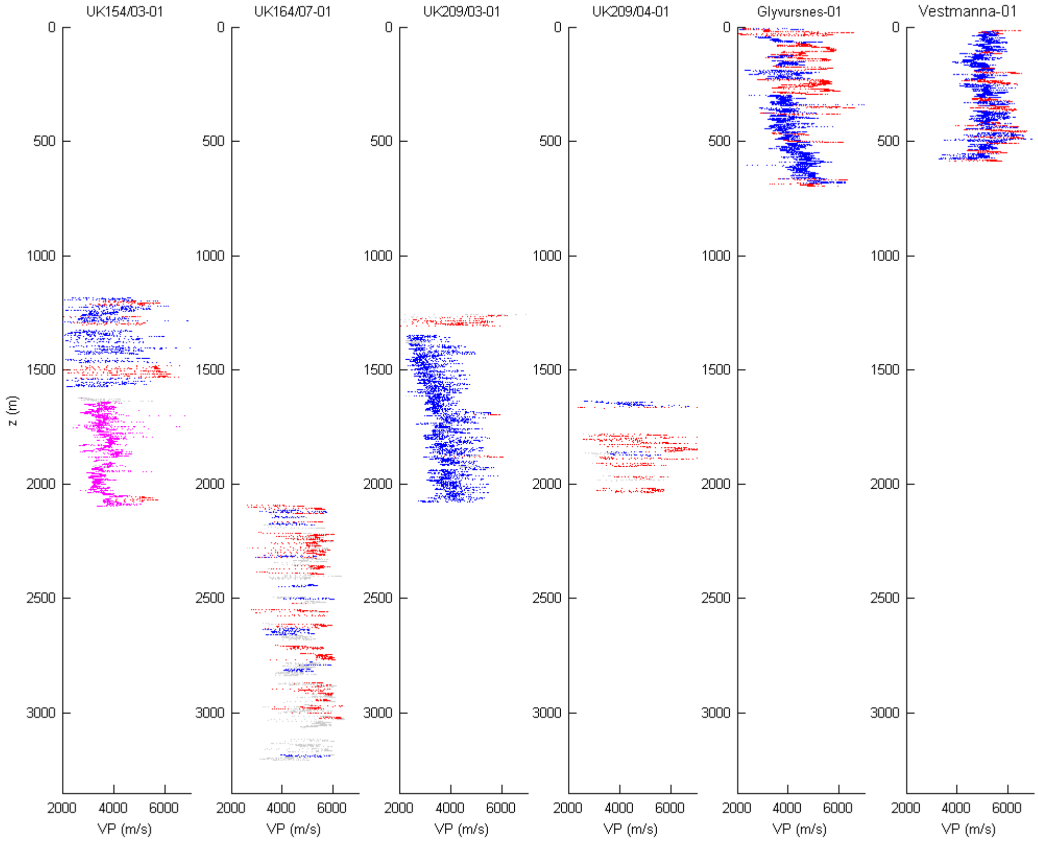

Figure 12.9. Condensed plots illustrating the relation between depth (z (MD)) and seismic velocity in basaltic rocks (VP) from four wells in the Faroe-Shetland Channel and two wells on the Faroes. Red are low frequency lava beds, blue are high frequency lava bed units and magenta is a forset breccia in UK154/03-01. Distinct trends are seen in UK209/03-1. and the lower part of Glyvursnes-01. In UK164/07-01 there is a tendency that bed minimum velocity increases with depth.

12.2.1.5 Instrument calibration and hole condition

In addition to sediment intercalations, composition and texture, burial effects and pre-burial alteration, different calibration of instruments may also involved in the different velocity ranges observed in different wells (e.g. UK209/04-01; chapter 10), but is difficult to quantify without core measurements.

Overall, all of the five possible explanations listed earlier in this section appear to contribute to inter-well variation of seismic velocity distribution. Different sediment/lava bed ratio and instrument calibration and hole condition is probably the two most important. However, core descriptions (or more realistic: descriptions of image logs) is probably needed to improve the interpretation of basaltic successions in future exploration wells. Instrument calibrations including documentation of gap corrections should be considered during data acquisition.

12.2.2 Properties of geochemical units

The natural gamma radiation from the geochemical units in Vestmanna-1 is low and falls mostly in the range 2.5-12.5 GAPI (Figure 12.10 and Figure 12.11). If natural gamma radiation or seismic velocities are plotted against depth distinct changes in the range of natural gamma radiation are seen at most unit boundaries (Figure 12.10). The difference between the individual chemical units are small compared to the variation within the units, and it is unlikely that the seven units (a-g) defined by Waagstein (1984) would have been identified only using wire-line logs.

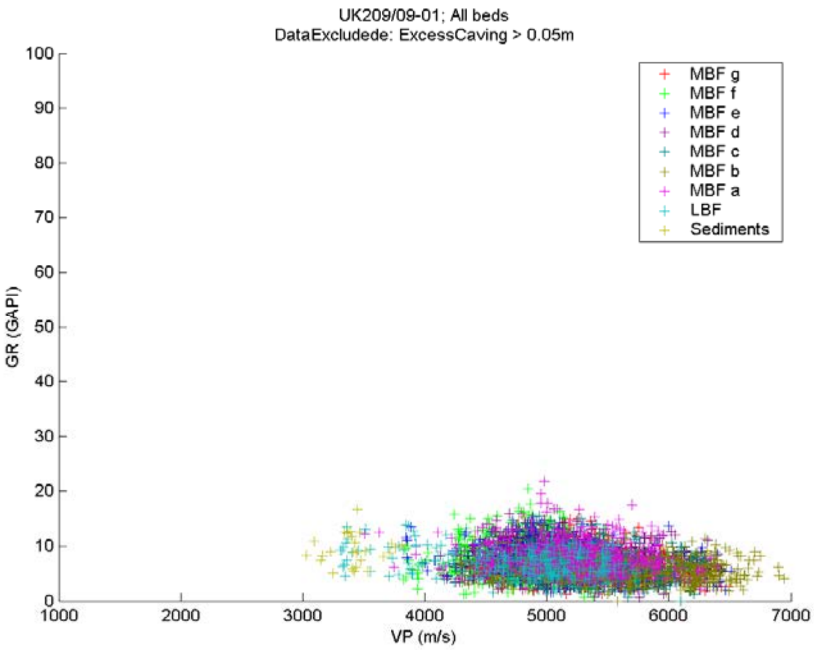

Figure 12.10. Cross plot of seismic velocity, VP, versus gamma radiation, GR, from basaltic volcanic units in Vestmanna-01. The data point are colour coded according geochecal unit (Waagstein 1984).

Sample points from the few basalt beds from the Lower Basalt Formation present in the Vestmanna-01 fall on a trend offset towards low velocities (compared to the Middle Basalt formation in Vestmanna-01) if plotted against neutron porosity (Figure 12.13 and Figure 12.14) or bulk density.

The uppermost chemical unit of the Middle Basalt Formation found in the Vestmanna-01 well (unit-g) is characterised by low negative gradients ($dV_P/d\Phi_N$ and $dV_P/d\rho$) compared to the units found deeper in the well. The other chemical units in Vestmanna-01 have trends with gradients in between those of unit g and those of the Lower Basalt Formation. Units with low gradients have lower intercept velocities (Figure 12.13 and Figure 12.14), and the units intercept velocities appear to increase with depth. The trends of the different units (Figure 12.13, Figure 12.14 and Figure 12.15) may thus reflect compaction/burial as well as different chemistry, mineralogy or texture of the unit in the Middle Basalt Formation.

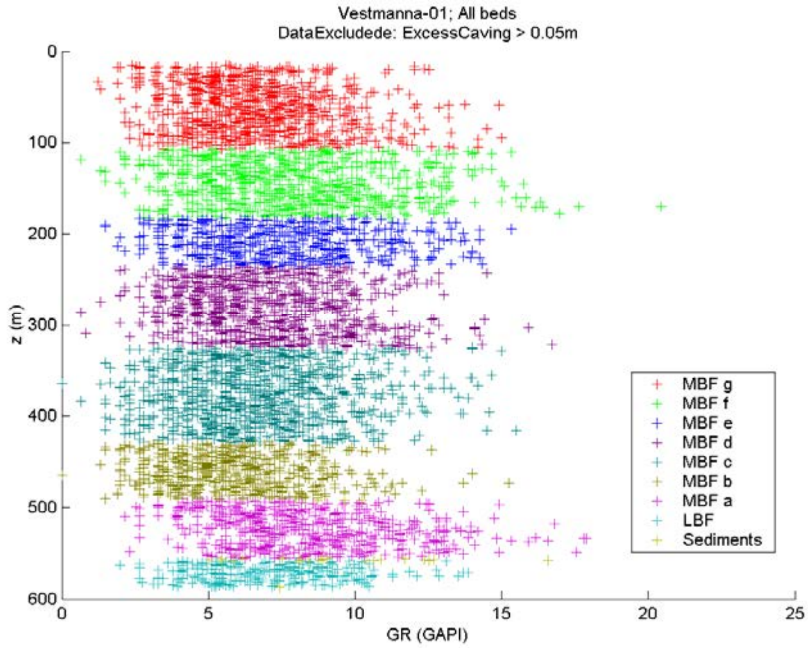

Figure 12.11. Plot of gamma radiation, GR, versus depth (z) from basaltic volcanic units in Vestmanna-01. The data point are colour coded according geochecal unit (Waagstein 1984).

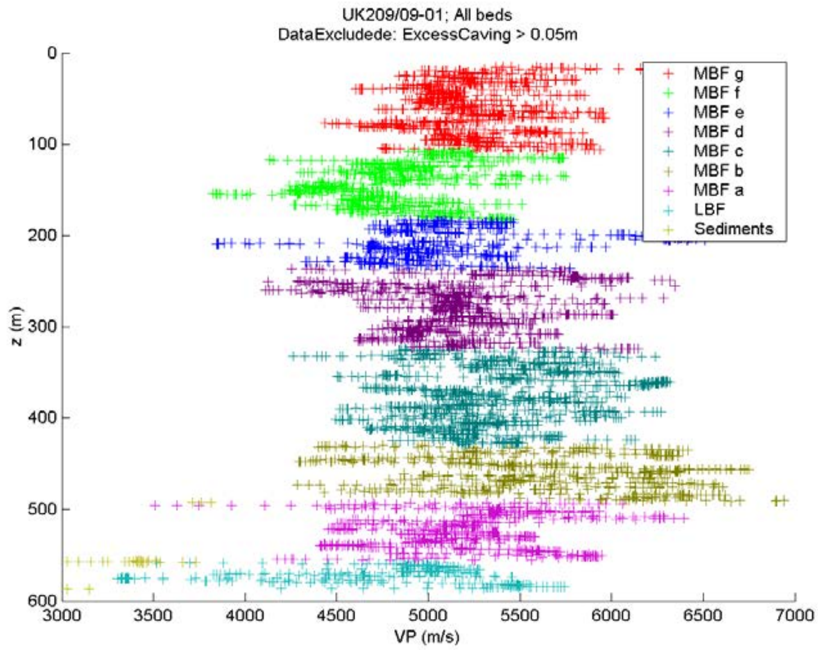

Figure 12.12. Plot of seismic velocity, VP, versus depth (z) from basaltic volcanic units in Vestmanna-01. The data point are colour coded according geochecal unit (Waagstein 1984).

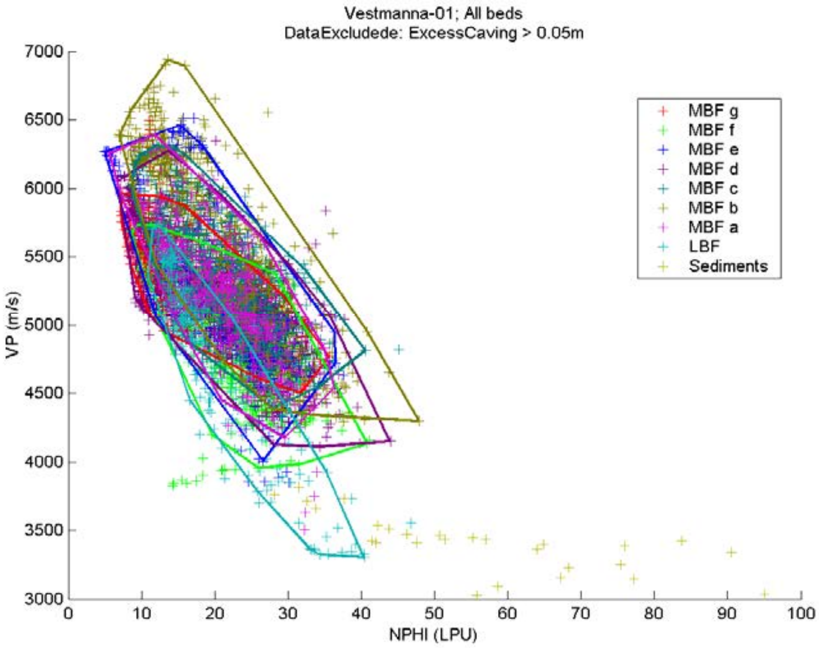

Figure 12.13. Cross plot of seismic P-wave velocity, VP, versus neutron porosity, NPHI, from basaltic volcanic units in Vestmanna-01. The data point are colour coded according geochecal unit (Waagstein 1984).

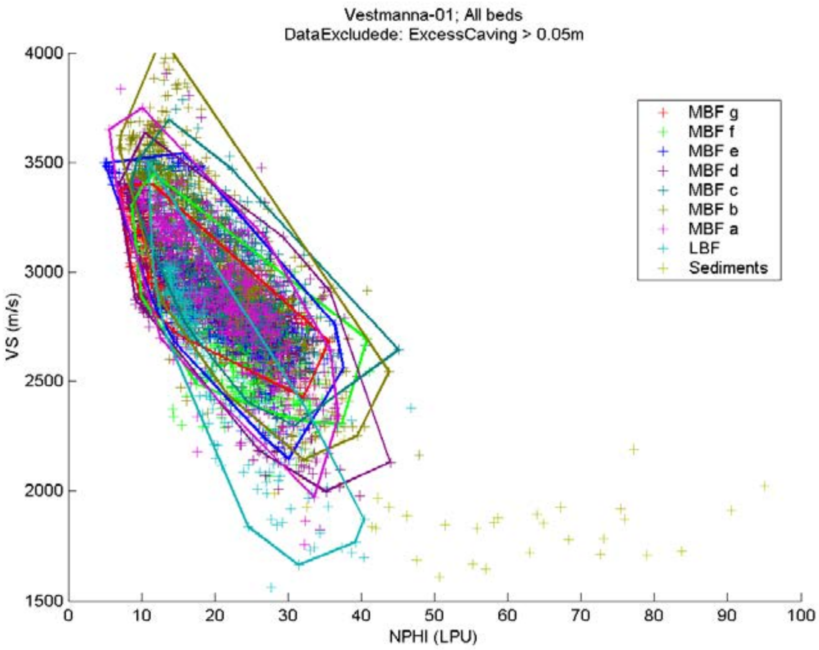

Figure 12.14. . Cross plot of seismic S-wave velocity, VS, versus neutron porosity, NPHI, from basaltic volcanic units in Vestmanna-01. The data point are colour coded according geochecal unit (Waagstein 1984).

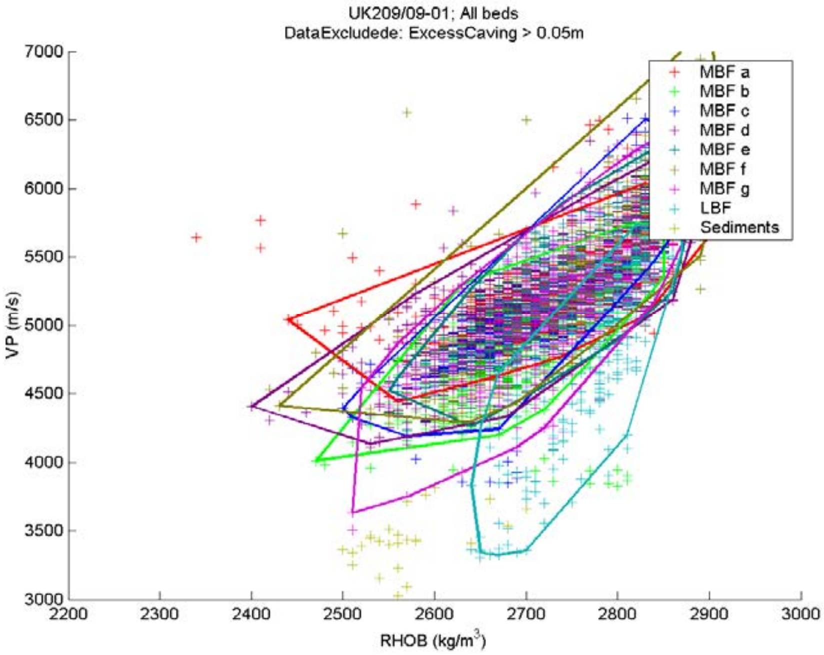

Figure 12.15. Cross plot of seismic velocity, VP, versus neutron porosity, NPHI, from basaltic volcanic units in Vestmanna-01. The data point are colour coded according geochecal unit (Waagstein 1984).

13 Well Glyvursnes-01

The well Glyvursnes-01 (61º58965493’ N 6º44592609’W) was drilled in 2002 as task 1 of the SeiFaBa project with the Geological Survey of Denmark and Greenland as operator (Waagstein & Andersen 2004). The main objective was to penetrate the C-horizon (or equivalent horizon) in the base of Faroes Upper Basalt Formation and penetrate ca. 300 m into the Faroes Middle Basalt Formation. The C-horizon was found at 346 m depth (MD). The well was fully cored with a recovery rate of ca. 99 %. The drilled succession was almost entirely basaltic lava beds ($N/G_{Lavabed} \approx 0.97$). Based on visual core inspection the penetrated succession was divided into individual lava beds, each of which either represents an individual volcanic event or a compound lava flow unit. Based on the size and general concentration of phenocrysts the individual flow units are grouped into 37 flow groups, F1-F37 (Waagstein & Andersen 2004).

For the purpose of this study the flow groups are tentatively grouped into ten major intervals (Figure 13.1). Eight of these intervals each represent a cycle characterised by general upward decreasing phenocryst abundance and upward increasing phenocryst size and two represents two low potassium lava beds. The upper five intervals constitute the lower part of the Upper Basalt Formation, while the lower five intervals constitute the upper part of the Middle Basalt formation.

Formation	Tentatively combined intervals	Flow groups	Depth
Faroes Upper Basalt Formation		F1	7
	UBF d	F2-F3	30
	UBF c	F4-F6	148
	UBF b	F7	213
	UBF a	F8-F14	346
	C-Horizon	F15	355
Faroes Middle Basalt Formation	MBF z	F16-F26	523
	MBF y	F27-F32	617
	MBF x	F33-F34	664
	MBF w	F35	682
	MBF v	F36-F37	700

Figure 13.1. Stratigraphic subdivision of the Glyvursnes-01 well (simplified from Waagstein & Andersen 2004).

The following wireline-logs were run in the Glyvursnes-01 well:

- calliper, CAL,
- natural gamma radiation, GR,
- full wave form sonic VP (P-wave velocity) and VS (S-wave velocity),
- density, RHOB,
- neutron porosity, NPHI,
- resistivity measured with a deep induction tool, ILD,
- resistivity measured with a pad mounted spherically focussed tool, MSFL,
- Temperature,
- Electric conductivity.

In addition an optical televiewer was run through the full length of well.

The wireline-logs and processing of the optical televiewer and full wave form sonic log is described in Waagstein & Andersen (2004). The VP and VS traces used for this study is the guided pick finding with pseudo borehole compensation processed by LogTek in October 2003.

Hole conditions in the Glyvursnes-01 well is excellent for logging. Caving is generally very low (<0.01 m).

13.1 Unit descriptions

Based on core analysis Waagstein & Andersen (2004) identified four main lithologies in the Glyvursnes-01 well,

- lava core,
- lava crust,
- top lava breccia,
- sediment.

Although these lithologies are seen distinctly on the core, they are - due to thin layering and overlapping physical properties - difficult to identify precisely on the classical wireline-logs. Log units have thus be picked using the same criteria as for the wells in the UK sector. In total 50 log units were picked, thus giving a less detailed description of the well than the core description. In the Upper Basalt Formation the log units are generally well defined by the available log traces and equivalent to the units described from the core. However, beds below about ca. 6 m thickness are generally grouped into units of high frequency basalts. In the Middle basalt formation a few low frequency lava beds and sediment intercalation are good marker horizons otherwise the middle basalt formation is very homogeneous and the boundaries of the flow groups described by Waagstein and Andersen (1984) are generally not recognised on the log traces. A few additional unit boundaries has thus been introduced which coincide with flow group boundaries.

13.1.1 Low frequency lava beds

Twenty low frequency lava beds (varying in thickness from 3.8 to 15.7m) and twenty six units of high frequency lava beds and four sediment layers were picked based on the original interpretation of the core (Waagstein & Hald 1984). The log responses of low frequency lava beds are generally similar to log responses from low frequency lava beds in the exploration wells in the UK sector of the Faroe-Shetland Channel. However, the absolute values of the neutron porosity (NPHI) are low compared to the wells from the UK sector. Correspondingly the bulk density (RHOB) and sonic velocities (VP and VS) are high (compared to the wells from the UK sector (chapters 5-11). The resistivities measured in the Glyvursnes-01 well are very high compared to the wells from the UK sector. This is because Glyvursnes-01 as Vestmanna-01 is filled with fresh water, while the drilling fluid and brine in the offshore wells are saline. The log response of a few low frequency lava beds are described below.

Unit *GL-F6f* (Figure 13.2): This ca. 14 m thick flow, which is one of five low frequency and two high frequency lava bed units constituting flow group F6 of Waagstein & Andersen (2004), has a ca. 13 m thick core, which can be identified clearly on the neutron porosity, NPHI, and density log, RHOB. The core is characterised by downwards decrease of the porosity from ca. 15 LPU in the top of the core to ca. 7 LPU about one meter above the base of the unit. The upper crust is ca. 1.5 m thick and characterised by porosities greater than 20 LPU. The upper crust is also identified on the traces of seismic velocities, VP and VS (P-wave velocity is less than 4000 ms^{-1}), but not on the resistivity trace, MSFL. Both on the resistivity and velocity traces a sharp deflection is seen 6 m below the top of the lava bed at a depth of 139 m indicating that a property influencing the seismic velocities and resistivity but not neutron porosity and density is changing at this depth. This could be either pore configuration or matrix texture. Significant compositional changes are considered unlikely. No significant changes were noted during the macroscopic description of the core.

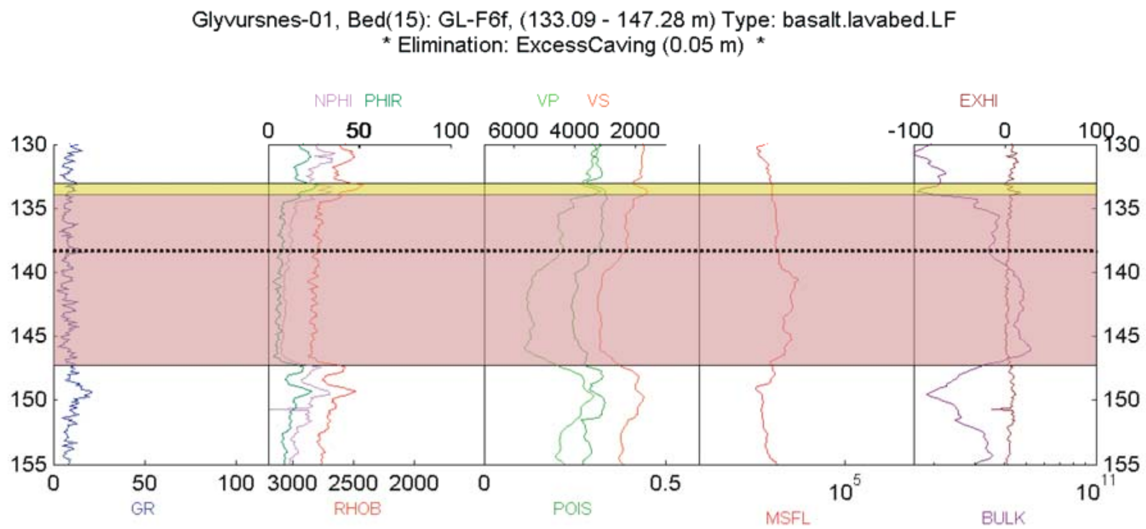

Figure 13.2. Log traces from depth interval 130-155 m in well Glyvursnes-01 showing unit GL-F6b. The core description (Waagstein & Andersen 1984) is indicated by color coding. Yellow is brecciated lava crust. Pink is massive core (<5% vesicles). Stippled line indicate the base of the soft top (see text)

Unit *GL*-F6*f* (Figure 13.3): This almost 20 m thick lava bed has a ca. 11 m thick upper crust characterised by low seismic velocities (VP is ca. 4000 ms^{-1}) in the upper part of the crust and increases gradually to ca. 5500 in the lower 4 m of the crust. The other porosity related parameters varies correspondingly. The boundary between the crust and the core is seen as a sudden drop in the Poisson's ratio and an increase of the resistivity. The core of the lava bed is characterised by constant low porosity (ca. 5 LPU) and high density (ca. 2850 kg m^{-3}). Both resistivity and seismic velocities is highest in the top of the crust and decreases gradually towards the base of the lava bed. According to the macroscopic description of the core this lava bed consists of a ca. 7 m thick top breccia and a 13 m thick core (Waagstein & Andersen 2004). The discrepancy between the log pattern and the macroscopic description is a reminder that the relation between geological and physical properties frequently not is simple. However, it is worthwhile noting that the top breccia actually is well constrained by the bulk modulus. Both in this unit and the previously described unit an upper soft zone of the lava bed can be distinguished by fairly sharp changes of the Poisson's ratio, POIS. The base of the soft top is indicated by a stippled line (Figure 13.2 & Figure 13.3). In unit GL-F7b a lower soft zone can also be distinguished.

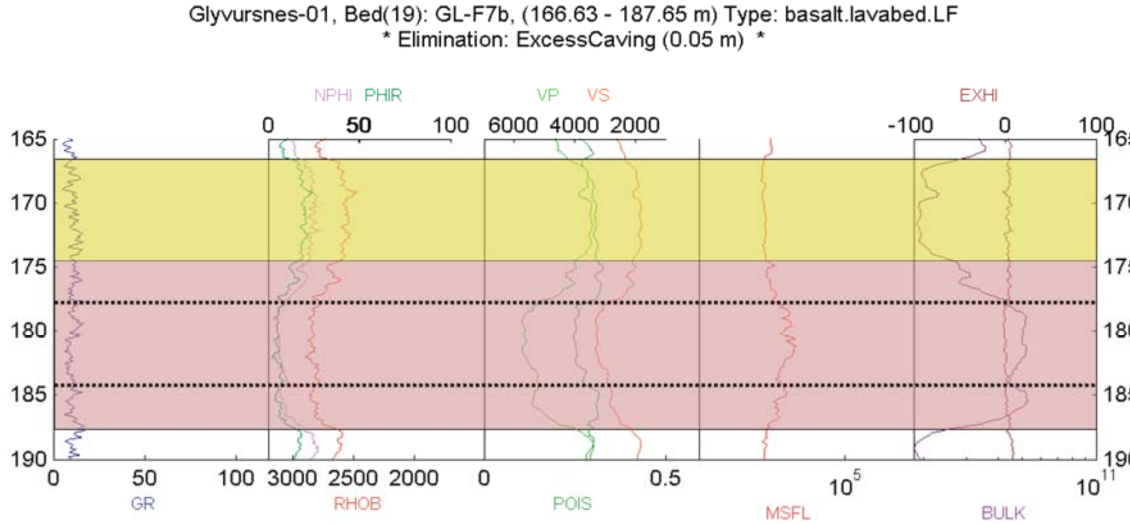

Figure 13.3. Log traces from depth interval 165-190 m in well Glyvursnes-01 showing unit GL-F7b. The core description (Waagstein & Andersen 1984) is indicated by same color coding as Figure 13.2. Stippled line indicate the base of the soft top and top of soft bottom (see text)

Unit *GL-F11a* (Figure 13.4): This ca. 26 m thick lava bed is the second thickest lava bed encountered in Glyvursnes-01. The core of this bed is ca. 23 m thick, and the lower 21 m is characterised by almost constant porosity (ca. 6 LPU) and density (ca. 2900 kg m^{-3}). A thin low porosity zone is found below the upper ca. 1 m of the core (M in Figure 13.4), which is slightly less massive than the lower 23 m. The seismic velocity traces are well correlated with the neutron porosity trace. However, thin low velocity zones in the core may represent porous zones in the core indicating episodic inflation of the lava bed. A ca. 4 m thick upper soft zone can be defined by the Poisson's ratio. This zone includes the upper part of the core and the porous zone just below. It could thus be argued that the thin massive layer M actually should be interpreted as a large massive block in a brecciated upper crust. The log description is in agreement with the macroscopic core description (Waagstein & Andersen 2004). However, the low velocity zones in the core are not mentioned in the core description.

Unit *GL-F15* (Figure 13.5): This 9 m thick lava bed is interpreted as the C-horizon. Compared with most other lava beds in the Glyvursnes-01 it is characterised by a low natural gamma radiation. A ca. 1 m thick upper crust may be distinguished on the neutron porosity and density traces. The ca. 8 m thick core are characterised by an overall decrease of the neutron porosity and increase of the density. A porosity high in the middle of the core is probably due to a fracture observed during the macroscopic description. The thin upper crust is not recognised on the resistivity and seismic velocity traces, which all are characterised by gradually increasing values in the upper 3 m. The fracture mentioned above is seen as a distinct low on these traces. According to the macroscopic description the top crust of this lava bed is ca. 3 m thick and is thus approximately equivalent to the upper zone of high resistivity and velocity gradients. Although the Poisson's ration is higher in the top of this flow than in the core, a distinct upper zone is not present. However a fairly distinct lower soft zone is present.

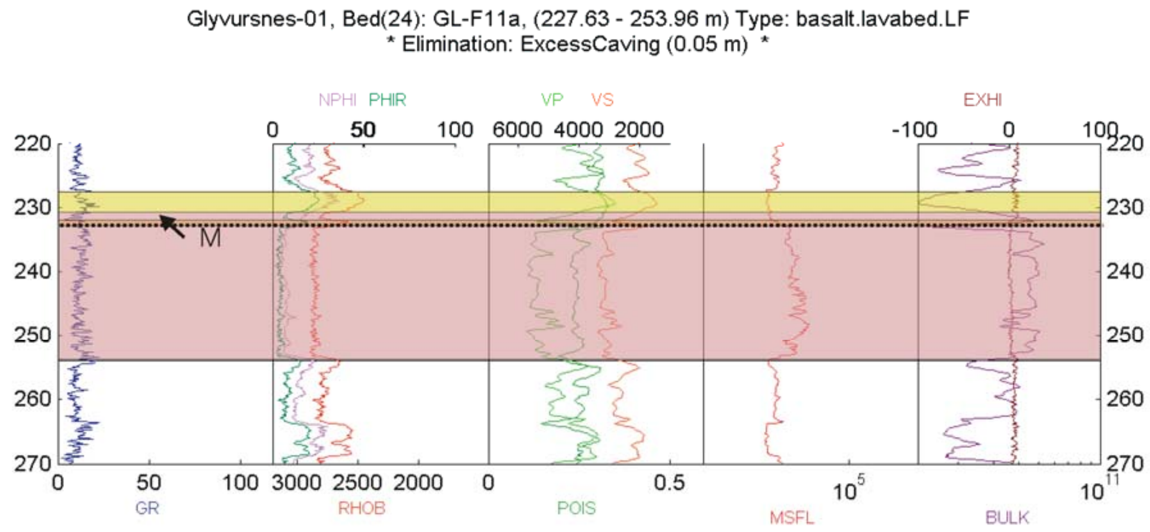

Figure 13.4. Log traces from depth interval 220-270 m in well Glyvursnes-01 showing unit GL-F11a. The core description (Waagstein & Andersen 1984) is indicated by color coding. Brown is vesicular lava crust (>5% vesicles), otherwise the same as Figure 13.2. Stippled line indicate the base of the soft top (see text).

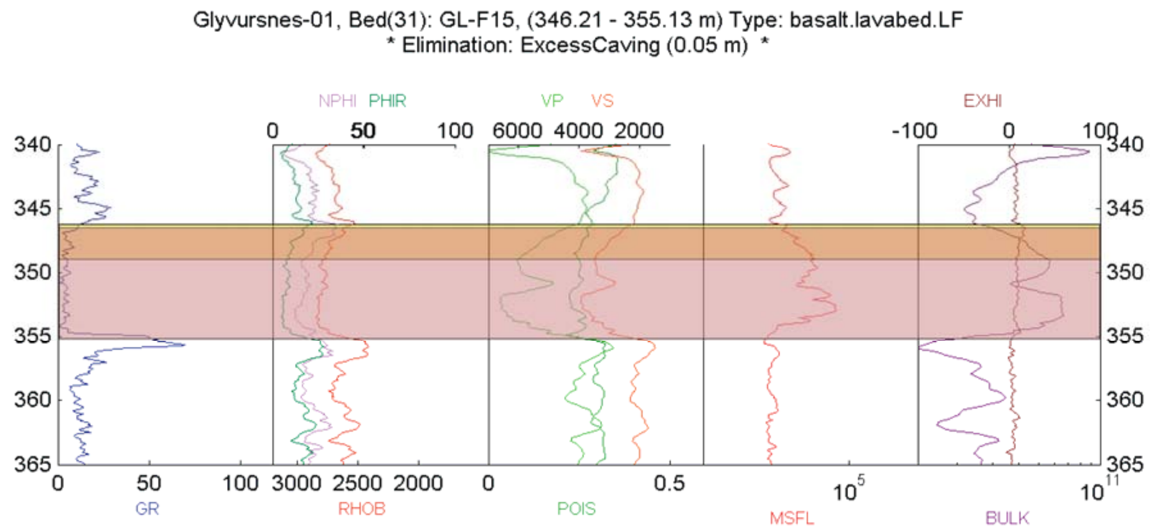

Figure 13.5. Log traces from depth interval 340-365 m in well Glyvursnes-01 showing unit GL-F15.

Tops and bases of low frequency lava beds picked from wire-line logs is in fair agreement with tops and bases picked from core descriptions. However, picking of surfaces related to the internal configuration of the lava beds from wire-line logs is generally not in agreement with the macroscopic description of the lava morphology. It is possible that an improved consistency between core description and wire-line logs could be obtained by a revised core description. However, most of the discrepancies are probably related to details of the pore configuration and matrix texture and detailed petrographic and petrophysical work is required understand these relations.

13.1.2 High frequency lava beds

Most log-units in the Middle Basalt Formation from Glyvursnes-01 well are interpreted as high frequency lava bed units. As in the wells from the UK sector the high frequency lava beds are characterised by oscillations of neutron porosity, bulk density and seismic velocity of a short period (1-5 m). The P-wave velocity range in the high frequency lava bed units (3500-5000 m/s) is generally somewhat smaller than in the low frequency lava beds (3500-6500 m/s). However, the difference is not as clear as in the wells from the UK sector. Below the log response of two high frequency lava bed units are described.

Unit *GL-F27-F29* (Figure 13.6): The top of this nearly 50 m thick log unit is defined by slightly elevated natural gamma radiation (15-20 GAPI) compared to the general level of radiation (5-12 GAPI). This may represent pre-burial alteration and thus a temporal break in volcanism. At the base a thin sediment layer with maximum gamma radiation above 50 GAPI is found. The base of the log unit is picked just above the sediment layer. The unit is equivalent to the three flow groups F27, F28 and F 29 (Waagstein & Andersen 2004). The boundaries between the flow groups may be recognised on displays on the logs, and the boundary between flow groups F27 and F28 coincides with an increase of the level of seismic velocities. However, the flow group boundaries within this log unit are not obvious log picks. For consistency with the interpretation of the exploration wells from the UK sector these three flow groups are considered as one log unit. For detailed petrophysical work it may be relevant to treat flow group F27 separately.

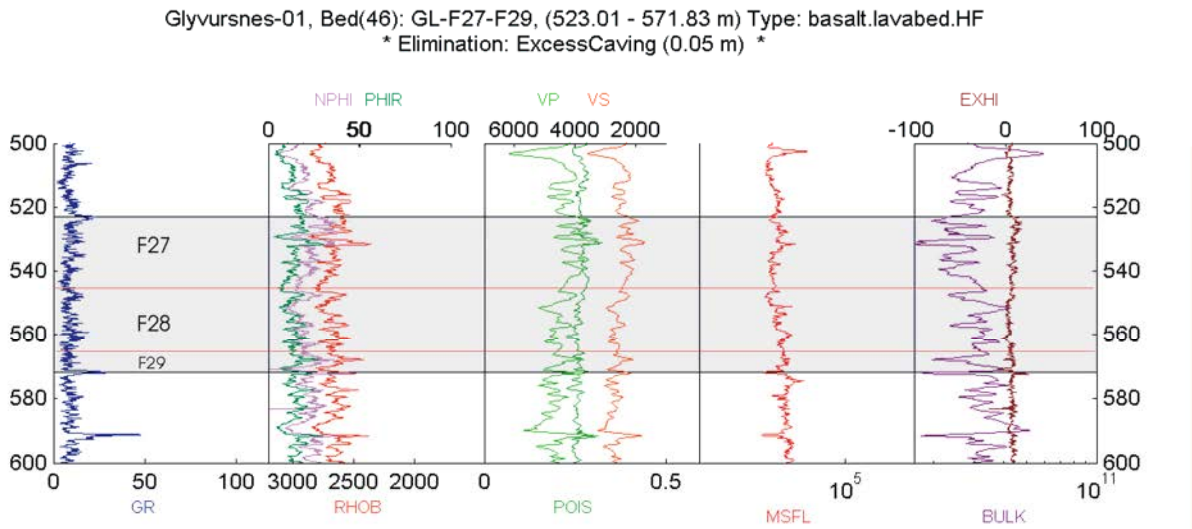

Figure 13.6. Log traces from depth interval 500-600 m in well Glyvursnes-01 showing unit GL-F27-F29. The boundaries between flow groups F27, F28 and F29 (Waagstein & Andersen 2004) are indicated by red lines.

Unit *GL-F18m* (Figure 13.7): This log unit comprises flow group F18 and the lower 2.5 m of flow group F17. The upper part of the log unit is characterised by upwards increasing gamma radiation, a signature that probably indicate pre-burial alteration during a break in volcanism. According to the core description GL-F18m consists of three individual units. The upper and lower are identified as distinct velocity peaks. The middle may be identified by a slight increase in density. However, the individual lava beds are not distinct on the wire-line logs as is usual for high frequency lava bed units in Glyvursnes-01.

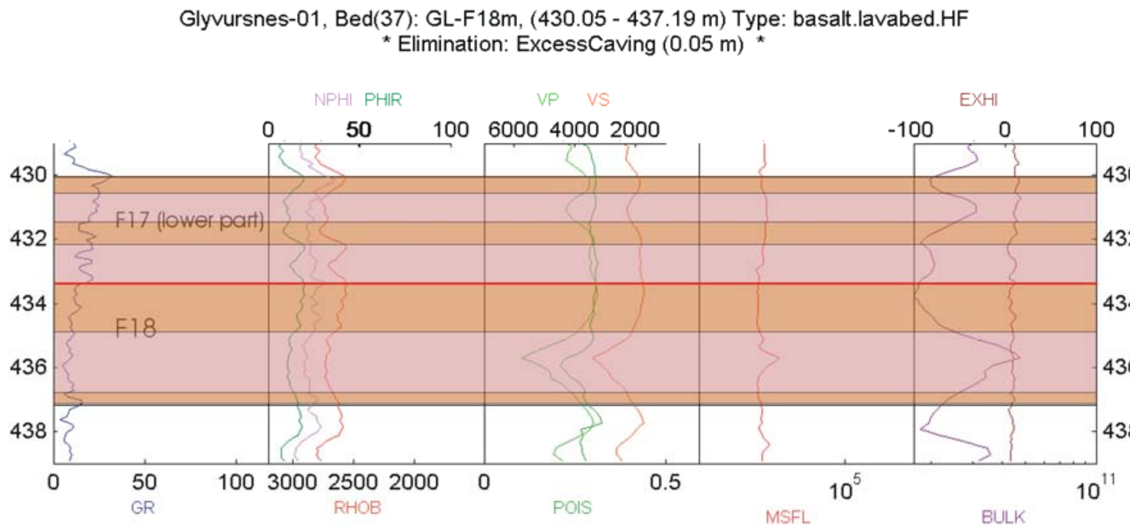

Figure 13.7. Log traces from depth interval 429-439 m in well Glyvursnes-01 showing unit GL-F18m. The core description (Waagstein & Andersen 1984) is indicated by same color coding as Figure 13.2. The boundary between flow groups F17 and F18 is highlited by a red line.

13.1.3 Volcaniclastic sediments

Sediments are very scarce in the Glyvursnes-01. Twenty three beds with an average thickness of ca. 0.60 m are identified by inspection of the cores. The thickest bed are ca. 5 m thick and only a few beds are thicker than 0.25 cm, which is the approximate limit below which sediment layers not are recognised on the wire-line logs. The sediment intercalations in Glyvursnes-01, which are recognised on the wire-line logs, are characterised by high neutron porosity, and correspondingly extreme values on other porosity related logs. In addition the sediment layers are characterised by high natural gamma radiation (20-40 GAPI; sometimes even higher).

Unit *GL-S32* (Figure 13.8): This 2.3 m thick unit is representative of the thicker sediment intercalations in the Glyvursnes-01 well. The almost symmetrical peak on the GR trace (>60 GAPI) combined with a high neutron porosity (max ≈ 60 LPU) and fairly high correlation between natural gamma radiation and neutron porosity is characteristic for the thicker sediment beds in Glyvursnes-01 well.

Note an apparent mismatch between the log traces. The GR, VP, VS and MSFL trace is apparently offset by ca. -0.25 m relatively to NPHI and RHOB trace. A mismatch of the same magnitude is also observed at a depth of 472 (GL-S30) and 491 m (GL-S31). As the mismatch is small and occurring over a short span in the well, the data have not been resampled.

13.2 Properties of basaltic rocks in Glyvursnes-01

The gamma radiation from the lava beds in Glyvursnes-01 falls within a narrow range (3-20 GAPI). The C horizon and one flow group from the Middle Basalt Formation (F-35 equivalent to stratigraphic interval MFB w) are characterised by low gamma radiation combined with high seismic velocities (Figure 13.9, Figure 13.10 & Figure 13.14). However, upward concentration of radioactive elements in lava beds is the most important contribution to variation in natural gamma radiation (Figure 13.7 & Figure 13.11). Gamma radiation is thus not suitable to distinguish between individual lava beds.

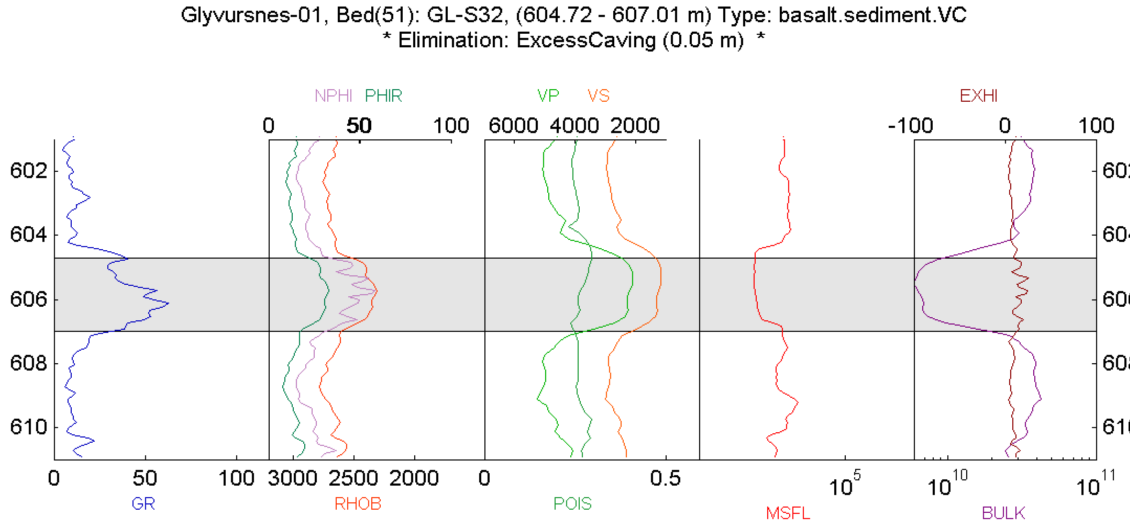

Figure 13.8. Log traces from depth interval 601-611 m in well Glyvursnes-01 showing unit GL-S32.

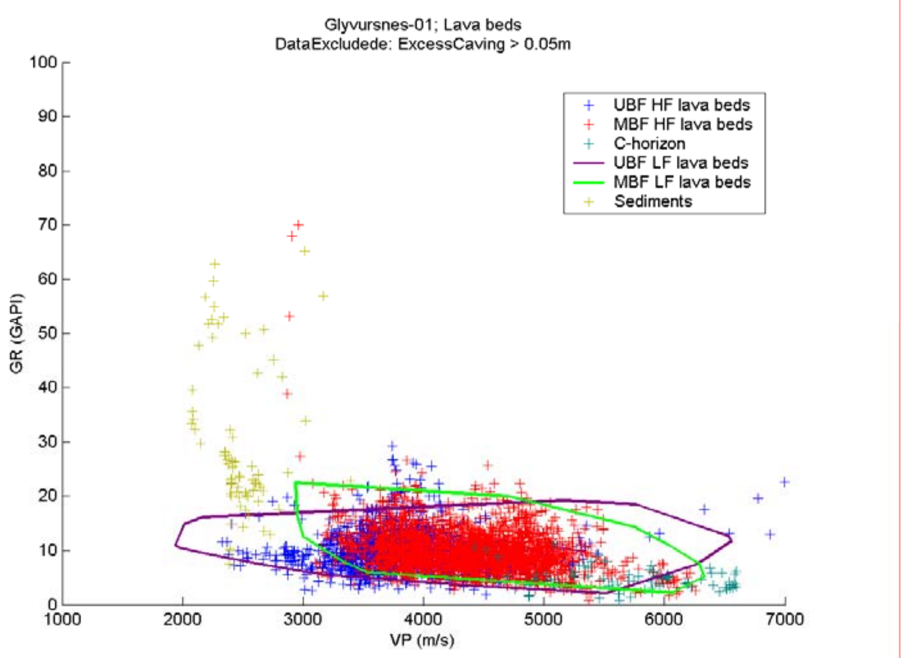

Figure 13.9. Cross plot of seismic velocity, VP, versus gamma radiation, GR, from basaltic volcanic units in Glyvursnes-01. Data point from high frequency lava beds in both Upper Basalt Formation (UBF) and Lower Basalt Formation (MBF) and the The C-horizon (actually the lowest bed in UBF) are shown as crosses. For clarity, only the data fields are shown for low frequency lava beds from UBF and MBF Subdivision according to (Waagstein & Andersen 2004). Note larger overall velocity range for the low frequency lava beds.

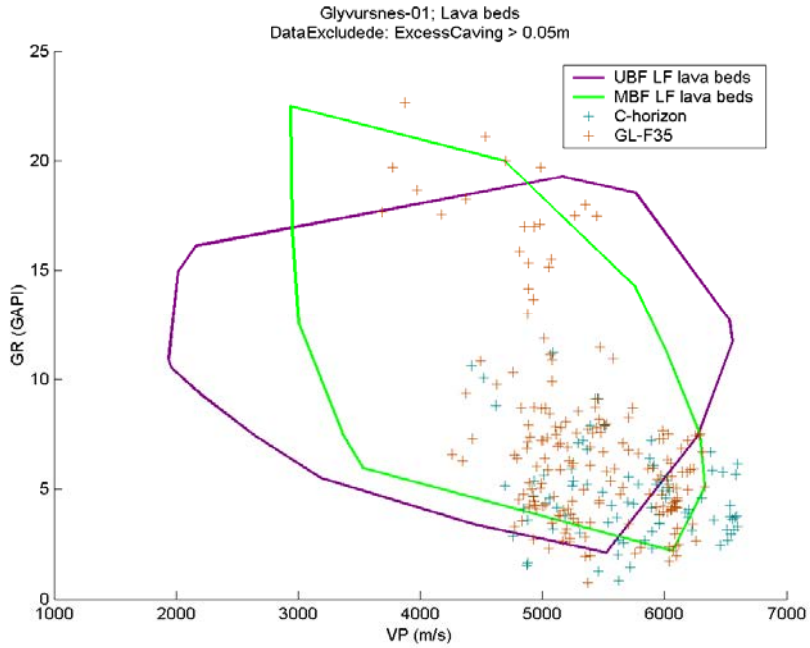

Figure 13.10. Cross plot of seismic velocity, VP, versus gamma radiation, GR, from basaltic volcanic units in Glyvursnes-01. Detail of Figure 13.10. The data fields of low frequency lava beds and data points from two "low potassium basalts" are shown. Note that most data points in the low potassium basalts clusters at low gamma radiation and high seismic velocities. Higher gamma radiation for some data points in GL-F35 is presumably associated with alteration in the top of this flow group prior to burial (see Figure 13.11).

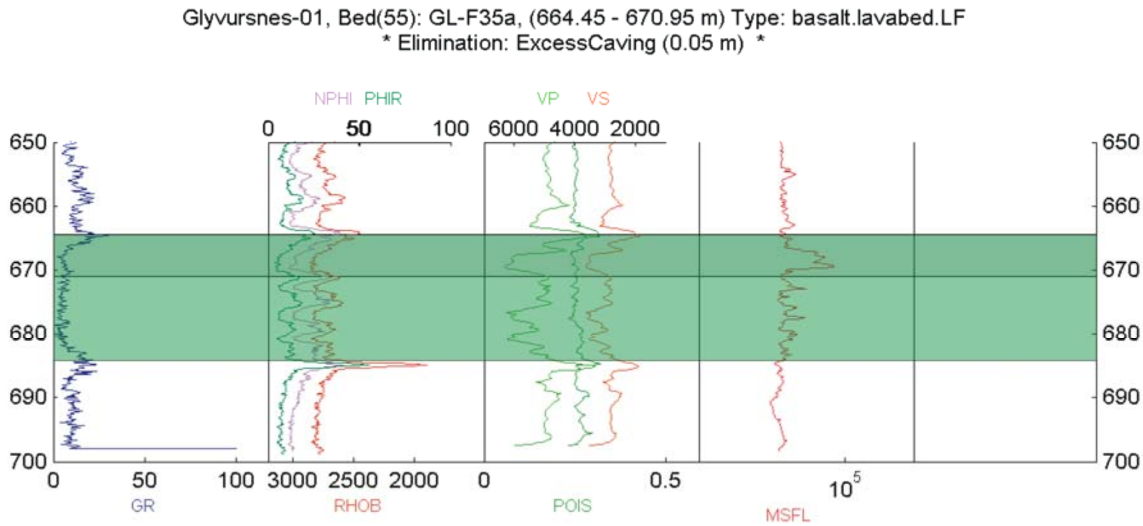

Figure 13.11. Log traces from depth interval 601-611 m in well Glyvursnes-01 showing flowgroup F35 (unit GL-F35a, dark green, and GL-F35b, light green). Note distinct increase of gamma radiation, GR, close to the top and base of the flow group.

Seismic velocities and the neutron porosity are well correlated both within Upper Basalt Formation from the Glyvursnes-01 well (excluding the C-horizon). The trends for low frequency lava beds and units of high frequency lava beds are coincident (Figure 13.12), but most data points from units of high frequency lava beds fall within a more restricted range than data points from low frequency lava beds. The data field for the Middle Basalt Formation is partially overlapping the field of the Upper Basalt Formation, and extends towards higher velocities and neutron porosities. Overall seismic velocity and neutron porosity is less well correlated within the Middle Basalt Formation. However, each of the individual stratigraphic intervals defined in Figure 13.11 falls within their own data field (Figure 13.13). If we plot seismic velocity versus depth it is clear that each of the three upper stratigraphic intervals in the Middle Basalt formation (MBF z, MBF y and MBF z) is characterised by seismic velocities increasing with depth. However, data points from each of these three intervals fall along a trend, which is specific for that interval. As the intervals are characterised by a systematic change in phenocryst abundance and size, it is suggested that these trends reflects changes of the seismic velocity of the matrix due to fractionation and or abundance and size of phenocrysts. The spread around the general trend would mainly be due to porosity variations.

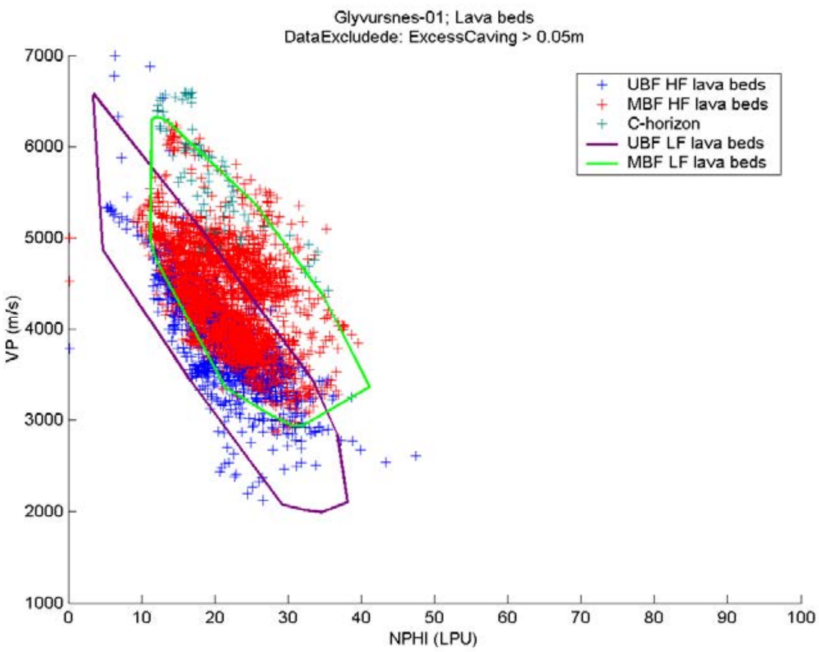

Figure 13.12. Cross plot of neutron porosity, NPHI, versus seismic velocity, VP, from basaltic volcanic units in Glyvursnes-01. Symbols as Figure 13.9.

The Poisson's ratio is uncorrelated with the density and neutron porosity. However, except in the uppermost 50 m the Poisson's ratio is relatively well correlated to the resistivity (enclosure 4; Figure 13.16). The reason for this correlation is not well understood. However, as mentioned above the Poisson's ratio may be used to define soft zones in the upper part of low frequency lava flows (Figure 13.2, Figure 13.3 & Figure 13.4). These zones may penetrate into the massive core of the lava beds, and they are therefore not a simple consequence of high porosity. In addition to high Poisson's ratio these soft zones are also characterised by low resistivity. Both clay content (contributing to cation exchange conductivity) and pore configuration may vary independently of the porosity. At the same time these parameters are expected to influence the resistivity and the Poisson's ratio. Detailed petrophysical work is needed to identify whether it is the clay content, the core configuration or some other parameter that causes the correlated variation of Poisson's ratio and resistivity.

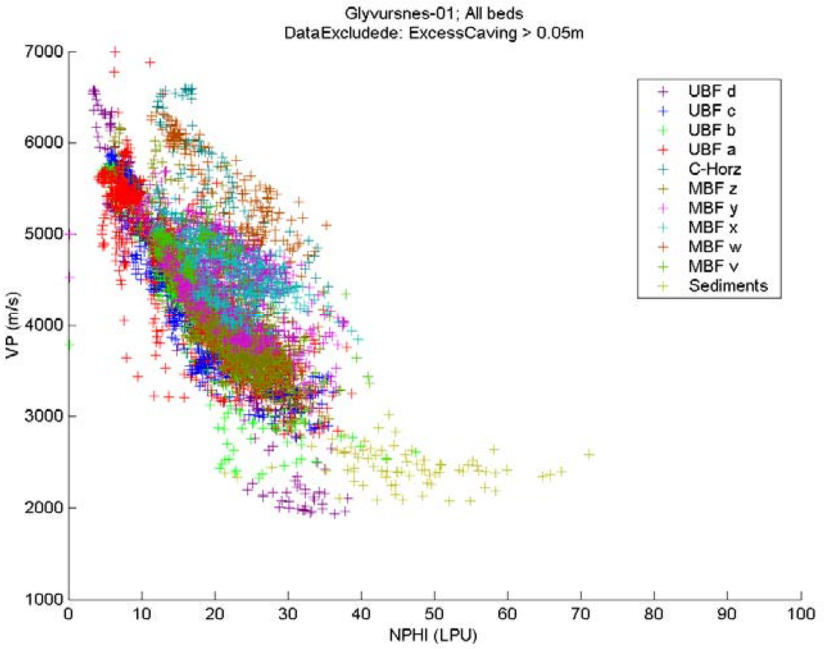

Figure 13.13. Cross plot of neutron porosity, NPHI, versus seismic velocity, VP, from basaltic volcanic units in Glyvursnes-01. In this figure color coding is according to stratigraphic intervals in Figure 13.1. Note that each interval falls within a restricted part of the hole data field and that intervals MBF w and the C-Horizon define a trend characterised by higher velocities separate from the main trend.

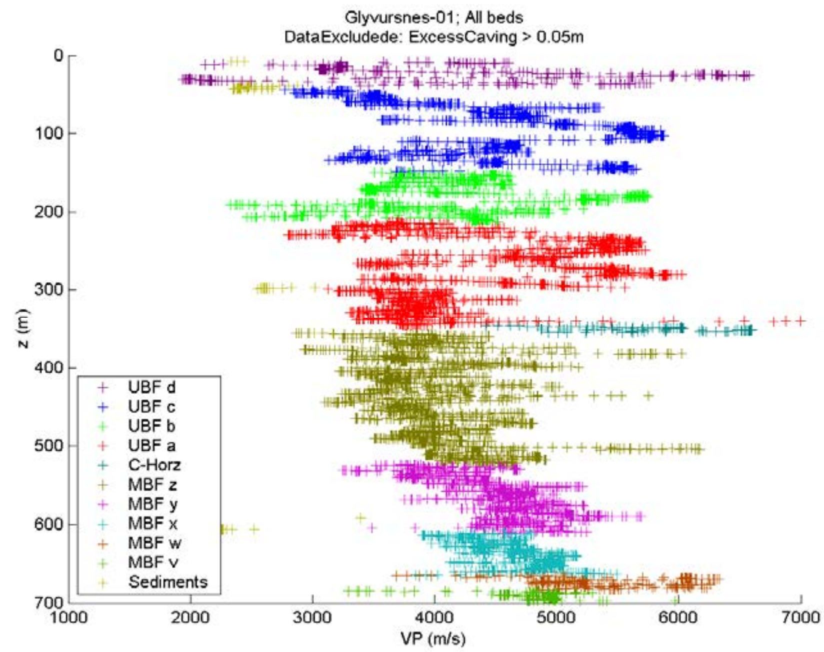

Figure 13.14. Seismic velocity, VP, plotted against measured depth, z. Note crude separate trends for units MBF x, MBF y and MBF z. See text for discussion.

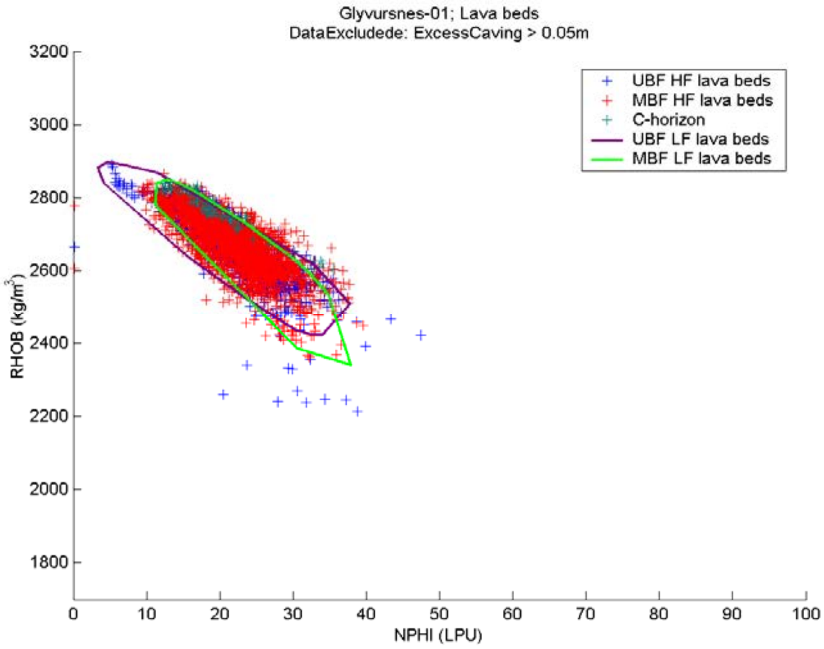

Figure 13.15. Cross plot of neutron porosity, NPHI, versus bulk density, RHOB, from basaltic volcanic units in Glyvursnes-01. Symbols as Figure 13.9.

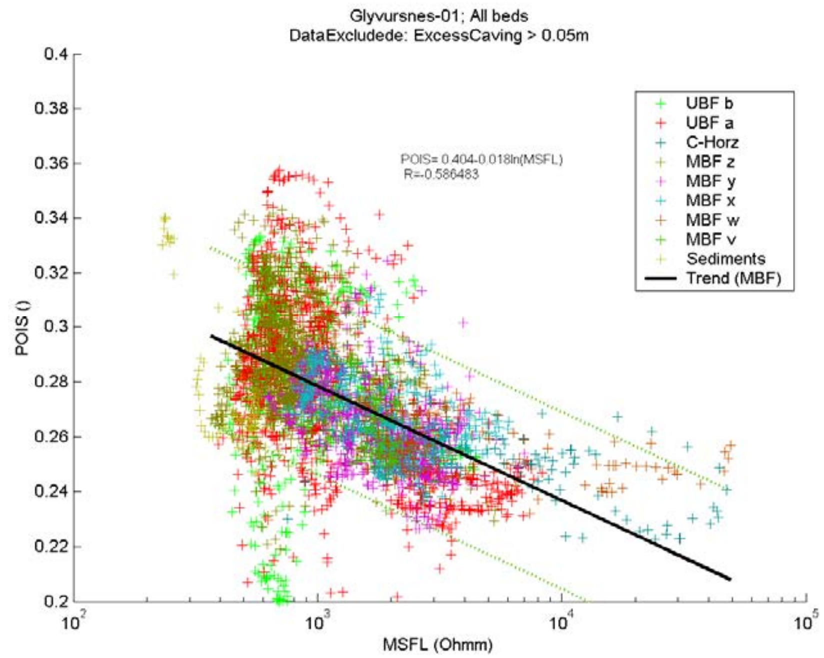

Figure 13.16. Cross plot of neutron porosity, NPHI, versus seismic velocity, VP, from basaltic volcanic units in Glyvursnes-01. Color coding is according to stratigraphic intervals in Figure 13.1. The two uppermost intervals are excuded for clarity. See text for discussion.

Neutron porosity and formation factor are fairly well correlated within the Upper Basalt formation (Figure 13.17). In the Middle Basalt Formation the correlation is poor. However, within the individual stratigraphic intervals of the Middle Basalt Formation correlation is comparable with the correlation of the Upper Basalt Formation (Figure 13.18). The cementation exponent varies from ca. 0.6 (stratigraphic interval MFB z) to ca. 2.5 (the C-horizon).

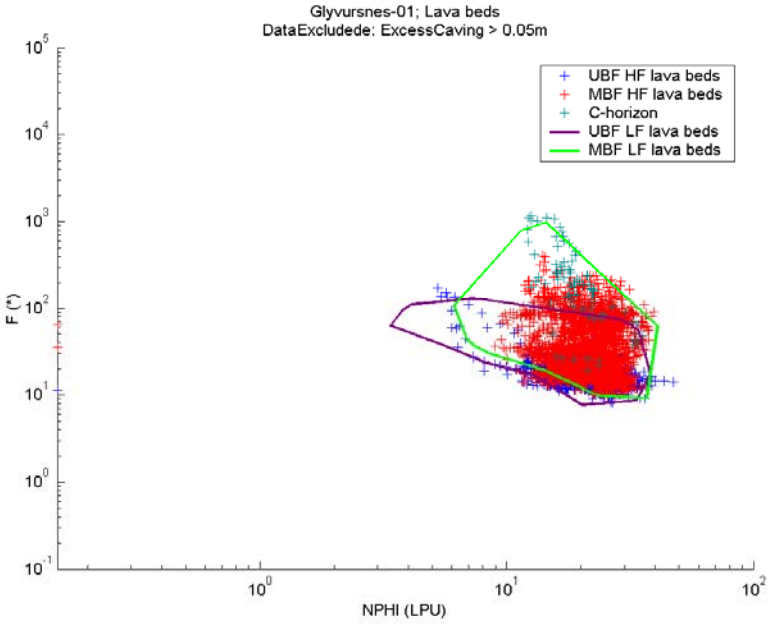

Figure 13.17. Cross plot of neutron porosity, NPHI, versus formation factor, F, from basaltic volcanic units in Glyvursnes-01. Symbols as Figure 13.9. Formation factor is calculated using data from the conduction log, assuming pore fluid has equilibrated with water in well.

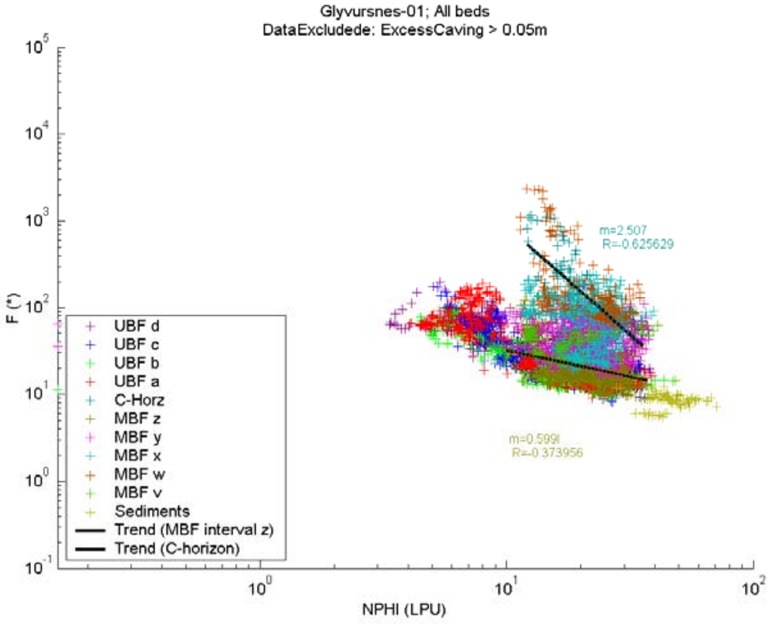

Figure 13.18 Cross plot of neutron porosity, NPHI, versus formation factor, F, from basaltic volcanic units in Glyvursnes-01. Symbols as Figure 13.13. Formation factor is calculated using data from the conduction log, assuming pore fluid has equilibrated with water in well. Note that each interval falls within a restricted part of the hole data field and that intervals MBF w and the C-Horizon define a trend separate from the main trend. This trend is characterised by higher formation factors and higher cementation exponent, m≈ 2.5, than the main trend, exemplified by interval MBF z, m≈ 0.6.

14 Comparison of physical properties

As seen in the preceding sections, the properties of basaltic rocks are quite variable. Within individual units and within a well most properties logged during conventional well logging are fairly well correlated to the neutron porosity (NPHI). However, if we look at the full population of 10 wells, the data are quite scattered (Figure 14.1; Table 14.1), and it is obvious that the variations not can be described by a simple model.

In order to describe the difference between the wells we have calculated linear RMS fits between the various variables (e.g. NPHI-RHOB; NPHI-VP) for all basaltic samples in each well. The well UK164/25-01 has been omitted from tables presenting the variations between wells. This is because the log traces from this well are assumed to be of inferior quality compared to the log traces from UK164/25-01z, as explained in chapter 7.

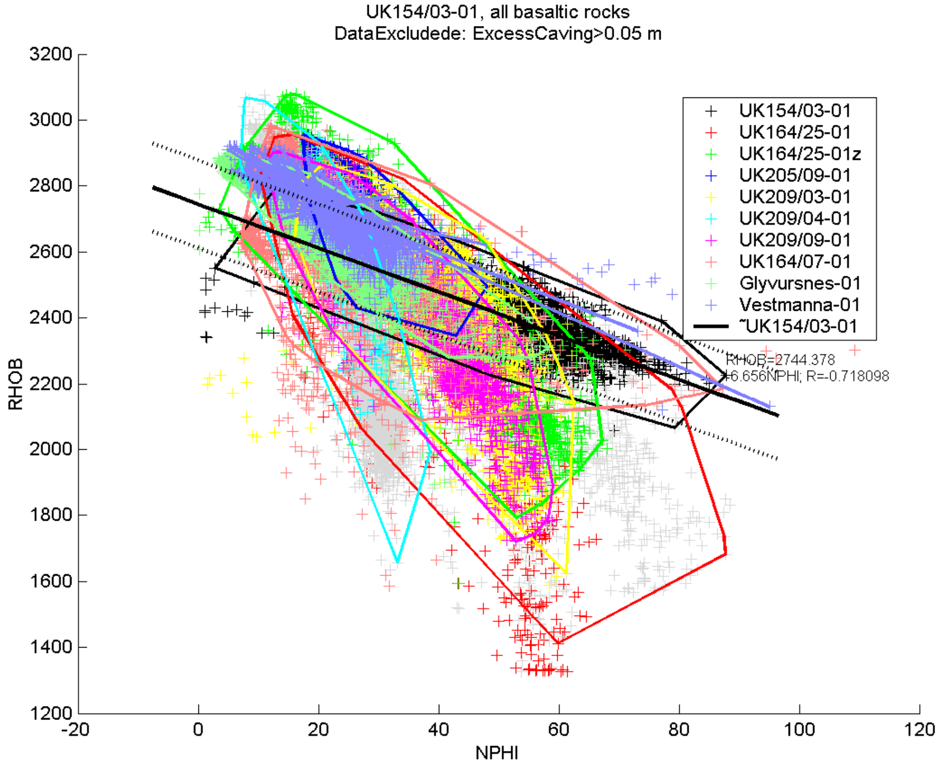

Figure 14.1. Logged values of Neutron porosity versus bulk density of basaltic rocks from 10 wells in the Faroe-Shetland area. We have highlighted the distribution of data points from each well by drawing the convex hull around ca. 99% of the data points (outliers are ignored). Grey crosses represent data points that are considered of dubious quality (due to excessive caving). These are not used in calculations of trends etc.

14.1 Porosity

As seen from Table 14.2 there is a fairly high correlation between NPHI and RHOB in most of the wells. It is seen that the value of the zero crossing are found in the range 2750 to 3200 kg m^{-3}. In five of the exploration wells (UK164/25-01z, UK205/09-01, UK209/03-01, UK209/04-01 and UK209/09-01) the zero crossing are high (3145-3200 kg m^{-3}) compared to typical matrix densities of basaltic rocks (e.g. Rasmussen & Noe-Nygaard, 1969; Høier 1997), while it is ca 2950 kg m^{-3} in both of the two wells from the Faroe Islands. The zero crossings in the Faroes wells are fairly close to typical matrix densities of Faroes basalts.

Low Freq. Flows; High Freq. Flows; Intrusive

Well	154/3-1	164/25-1	164/25-1Z	164/7-1	205/9-1	209/3-1	209/4-1A	209/9-1	Glyvursnes	Vestmanna
NPHI % LPU	29.53 55.06	39.47 53.51 31.31	27.87 42.61 21.10	24.53 33.80 16.88	27.88	33.37 38.80 30.44	19.91 24.21 20.29	34.20 43.94 22.21	10.52 21.34	15.20
RHOB g/ccm	2.62 2.38	2.49 2.30 2.60	2.68 2.44 2.78	2.62 2.48 2.75	2.77	2.56 2.48 2.57	2.67 2.48 2.55	2.51 2.30 2.61	2.82 2.68	2.80
Vp m/sec	4729 3695	4064 3303	4989 3705 5719	5188 4540 5612	5089	4567 3967 4565	5110 4286 5718	4250 3198 5769	5356 4162	5645
Res	188 61	85 14	49 5 359	358 282 985	11	76 7 18	11 6 7	39 4 20	3990 1281	4423
GR	5.89 8.35	8.12 9.29 12.76	10.30 12.56 13.21	28.03 30.42 25.96	26.97	22.66 21.24 31.97	19.61 23.71 15.71	19.80 21.83 22.26	9.90 10.28	6.35
K		0.29 0.32 0.00	0.36 0.43 0.38	2.22 2.30 2.09	0.81		0.5 0.64 0.4			

Table 14.1. Average values of selected logged properties of different unit classes from the investigated wells. Low frequence lava beds shown in black; High frequence lava beds shown in red; Intrusives shown in blue.

Table 14.2: Parameters for linear trends between NPHI and RHOB (RHOB = a + NPHI * b).

Well	a	b	R
UK154/03-01	2742.3	-6.6	-0.72
UK164/25-01z	3163.8	-18.5	-0.93
UK205/09-01	3146.9	-14.8	-0.73
UK209/03-01	3197.6	-19.1	-0.72
UK209/04-01	3182.8	-27.4	-0.81
UK209/09-01	3196.7	-21.3	-0.89
UK164/07-01	2877.8	-11.0	-0.62
Glyvursnes-01	2949.0	-12.8	-0.89
Vestmanna-01	2934.6	-9.4	-0.83

The gradient of the linear trends from the five exploration wells with high zero crossings vary from -14.8 kg m^{-3} LPU^{-1} to -27.4 kg m^{-3} LPU^{-1}. This is larger negative gradients than in the two Faroes wells (-12.8 kg m^{-3} LPU^{-1} to -9.4 kg m^{-3} LPU^{-1}. in Vestmanna-01).

As the neutron porosity tools actually measures the hydrogen index, the measured neutron porosity represents the combined concentration of hydrogen in the pore water and hydrogen in the hydrous minerals in the formation. If the concentration of hydrous minerals in the formation is constant, the effect is to give a steeper gradient than expected in the ideal case and a zero crossing above the true matrix density (Figure 14.2). In this case it is in principle simple to calculate the true porosity (if no other complications have to be taken into consideration.

It commonly occurs that vesicles in basalts are partly filled with hydrous minerals. Both the density and hydrogen concentration are likely to be distinctly different from the density and hydrogen concentration in the matrix. In Figure 14.2 we have illustrated possible effects of partially filled vesicles. Comparing Figure 14.1 and Figure 14.2 it seems likely that the scattering of data points in NPHI-RHOB diagrams to a large extent could be attributed to various hydration of the matrix and variable concentration of secondary minerals filling the vesicles. If we know the matrix density and the hydrogen content as well as the fraction of vesicle filling minerals, we can establish a correction function and calculate the true porosity. Gaining access to this information will generally require detailed analysis of a large number of samples from each well. As an alternative it has been suggested to use the “slowing down length” of thermal neutrons to account for alteration minerals in basalts (Broglia & Ellis 1990). This approach has been used during the ODP project. But it is the experience that neutron porosity data not correlate directly to interconnected porosity. In any case this approach is not realistic within this study as “slowing down length” data not are available.

14.1.1 Estimating porosity from measured bulk density

Matrix densities of basalts from the Faroe Islands generally lie within a narrow range (2900-3000 kg m^{-3}). We may thus use the measured bulk density to calculate an estimate of the porosity of basaltic rocks using a fixed matrix density. If the matrix density not varies too much within the dataset, a fairly accurate estimate of the porosity is obtained. As seen in Table 14.3 the maximum densities measured in seven out of nine wells lie in the range 2878-2954 kg m^{-3}. The high maximum density in UK164/25-01 is higher (3077 kg m^{-3}). However, the maximum density of basaltic rocks in this well is caused by a few intrusives which are heavier than other basaltic rocks in this well (Chapter 7). The maximum density observed in UK154/03-01 is ca. 2800 kg m-3. However, in this well the dominating basaltic lithology (in the interval of the well logged for density) is interpreted as hyaloclastic rocks (presumably a foreset breccia/progradational lava delta). This lithology is possibly never quite as massive as the core of lava beds. Porosity and density are measured for 17 samples from the Vestmanna-01 well (Abrahamsen & Argir 2004). Based on these data the common average density of basalt matrix in Vestmanna-01 is calculated to be 2924 kg cm^{-3}, (Abrahamsen and Argir 2004). A matrix density of 2950 kg cm^{-3} is used to estimate the porosity from the density measurements in all nine well. With the lack of core data from most wells this is considered most appropriate to use the same density in all wells.

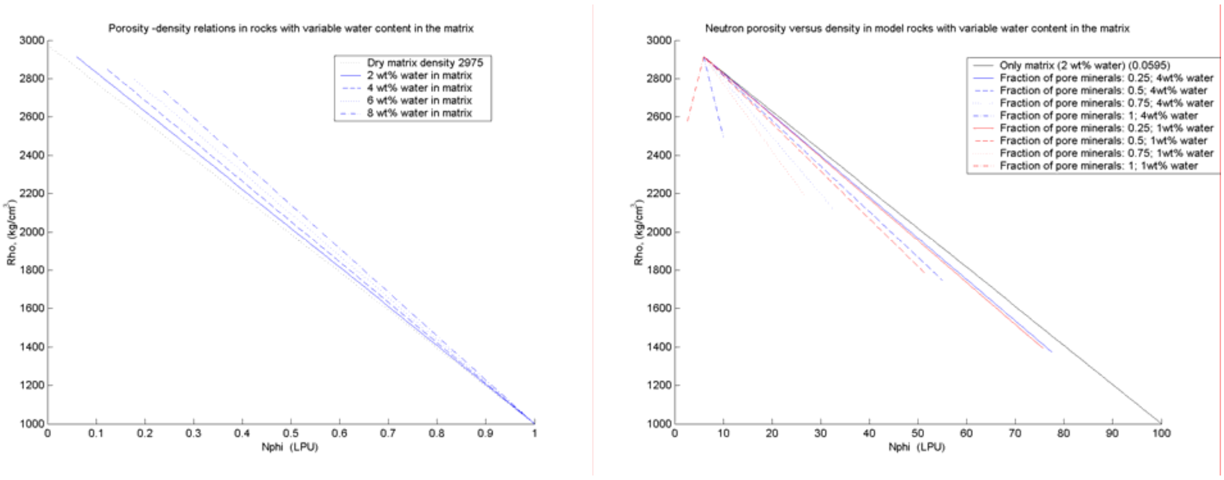

Figure 14.2. Left: Model calculations showing the influence of water bound in the matrix on the data trend in a neutron porosity versus density diagram. Each line represents the complete theoretical trend. Right: Model showing the influence of vesicle fillings on the data trend in a neutron porosity versus density program. Each line represents the complete theoretical trend.

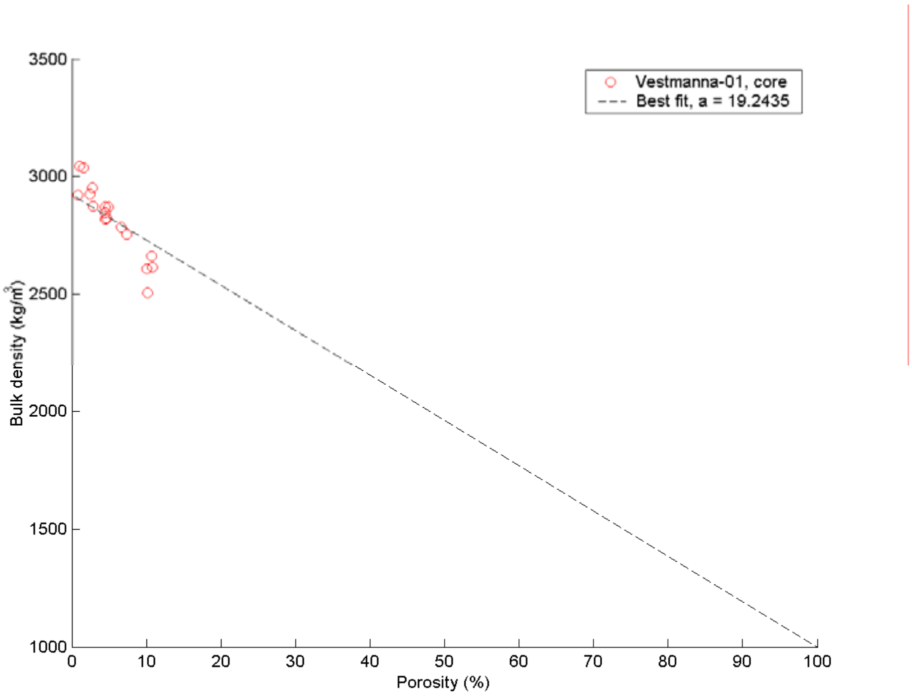

Figure 14.3. Bulk density of plugs from the Vestmanna-01 well plotted against porosity.

As seen in Figure 14.4 the porosity of basaltic rocks estimated from the density log using this matrix density, PHIR, is generally considerably lower than the porosity obtained from the neutron porosity log, NPHI.

Table 14.3. Mean, median, standard deviation minimum and maximum of measured density (RHOB) in basaltic rocks from the 9 wells included in the study.

Well	Mean	Median	Std.dev.	Minimum	Maximum
UK154/03-01	2388.9	2377.9	99.1	2058.0	2792.1
UK164/25-01z	2623.1	2736.4	290.2	1593.2	3077.5
UK205/09-01	2738.4	2783.0	150.2	2238.7	2954.0
UK209/03-01	2413.0	2433.9	200.9	1589.0	2878.4
UK209/04-01	2569.9	2526.1	230.4	2106.9	2945.5
UK209/09-01	2406.5	2384.3	269.4	1720.6	2918.0
UK164/07-01	2575.6	2622.8	230.9	1314.7	2932.6
Glyvursnes-01	2689.5	2696.4	111.8	2060.6	2901.0
Vestmanna-01	2731.8	2730.0	83.6	2400.0	2920.0

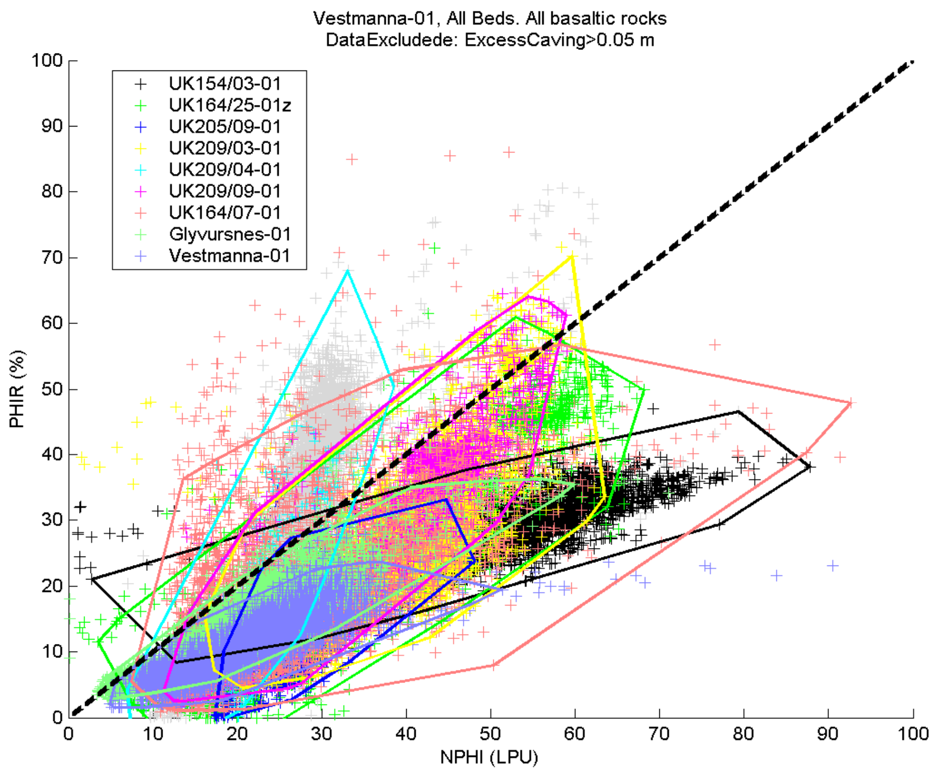

Figure 14.4. Crossplot of NPHI, neutron porosity, versus PHIR, porosity estimated from the density log, in nine wells from the Faroe-Shetland Area (see text for further discussion).

In Figure 14.5 the difference between the two porosity estimates, EXHI, is plotted against the P-wave velocity, VP. In most of the wells EXHI is virtually independent of VP. As both the porosity and the density of porous rocks is strongly correlated with the seismic velocity, while hydration not is expected to be directly correlated to the seismic velocity, this indicates that the porosity estimated from the density log, PHIR, is a realistic measure of porosity, which is better than NPHI. EXHI, the difference between NPHI and PHIR can be considered a measure of hydration (see below#).

As the matrix density not is well determined an unspecified (and possibly systematic) error is associated with PHIR. This error may vary not only from well to well but also within the wells. Systematic determinations of density and porosity in plugs will provide more realistic data to use for calculation of the porosity from density data and thus constrain the error and possibly improve the calculation of porosity. The data from Vestmanna-01 and Glyvursnes-01 will be reviewed when all data from the core analysis is available.

Although, the porosity estimated from the density log, PHIR, generally is lower than the neutron porosity there is some important exceptions from this general tendency.

1. In UK209/04-01 the volcaniclastic units the porosity estimated from the density log is considerably higher than neutron porosities. As mentioned in chapter 10 these rocks are possibly not basaltic but rather volcaniclastics of an intermediary composition or with a high concentration of basaltic alteration minerals or siliciclastic sediments (with low potassium concentration).
2. In basaltic rocks with high apparent porosity from most of the wells, the difference between porosity estimated from the density log and the neutron porosity is less than for rocks with lower porosity. This indicates that the matrix densities of these high porosity rocks are less than that of the more massive basaltic rocks. We believe this to a large degree reflects larger alteration of volcaniclastic sediments and the most porous parts of lava beds. However, as mentioned above contamination with siliciclastic material in volcaniclastic sediments could also reduce the density and thus lead to a too high estimate of the porosity.
3. In UK154/03-01 the porosity estimates derived from the density log, PHIR, are much lower than the neutron porosity. The values of PHIR also fall in a more realistic range (10-40 %) than those of NPHI (10-80 LPU). The basaltic rocks in UK154/03-01 are mostly foreset breccias. It is possible this type of basaltic rocks is more evenly hydrated/altered than lava beds and volcaniclastic sediments, thus providing a better correlation between NPHI and PHIR. If the basalts are more evenly hydrated, PHIR is also a more realistic measure of the porosity.

Due to these observations the porosity estimated from the density log, PHIR, are considered fairly reliable for porosities less than ca 25 %, assuming the formation in question is correctly interpreted as basaltic rocks.

14.1.2 Hydration/alteration

As mentioned above, EXHI, the difference between the neutron porosity and the porosity estimated from the measured density may be considered an estimate of chemically bound, hydrogen, and thus be considered an estimate of hydration/alteration of the basaltic rocks. EXHI are poorly correlated with all parameters measured in the wells. However, a slight depth /burial dependence are possible. In Vestmanna-01 and Glyvursnes-01, where the basaltic rocks are most shallow, EXHI increases slightly with depth (Table 14.4; Figure 14.6). At intermediate depths (1000-2000 m) in UK154/03-01, UK209/03-01, UK209/04-01 and UK209/09-01 there is no preferred trend of EXHI as a function of depth. In the two wells, where basaltic rocks are found at greatest depth (2000-3500 m), EXHI decreases with depth.

These observations is in fair agreement with field observations from Iceland that the water content of basaltic rocks due to hydrothermal alteration increases with depth for at least the first 1000 m below the surface (Walker 1989). When the hydrothermal activity has stopped re-crystallisation due to diagensis and incipient metamorphism may lead to decreasing water content. It is thus possible that EXHI has a potential for investigation of alteration effects in basalts. However, due to the large variation, a considerably larger database than available for this study is needed to evaluate this potential.

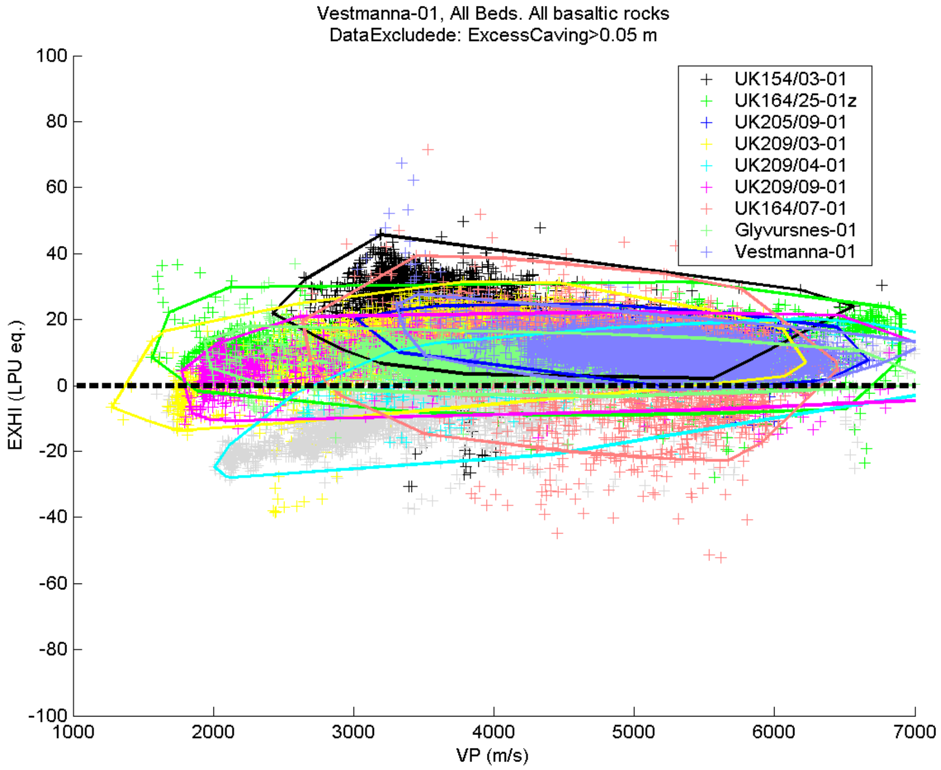

Figure 14.5. Crossplot of P-wave velocity, VP, versus excess hydrogen index, EXHI (See text for discussion).

Table 14.4. EXHI as a function of depth (EXHI = a + z * b) in nine wells from the Faroe-Shetland Area.

Well	Top	Bottom	a	b	R
UK154/03-01	1184.3	2073.7	32.92918	-0.00466	-0.07
UK164/25-01z	1830.9	3432.2	16.98381	-0.00200	-0.17
UK205/09-01	2619.5	2764.7	24.98963	-0.00322	-0.03
UK209/03-01	1244.0	2283.1	-3.13360	0.00935	0.34
UK209/04-01	1637.4	2125.1	-45.39792	0.02537	0.19
UK209/09-01	1172.4	2280.8	20.05357	-0.00800	-0.38
UK164/07-01	2092.9	3208.5	27.55647	-0.00742	-0.24
Glyvursnes-01	7.0	684.5	4.44452	0.00580	0.31
Vestmanna-01	37.6	586.8	8.01204	0.00631	0.23

14.2 Resistivity

As mentioned earlier (e.g. chapters 5, 8 and 10) “shoulder bed effects” are important when logging in basaltic rocks. Only the resistivities measured by the MSFL tool are expected to be virtually unaffected by this and other bedding effects. Although laterologs and induction logs have other benefits these have only been used qualitatively in this study to estimate whether intrusives are perpendicular to or inclined relatively to the wellbore. Also normal spherically focused tools, SFLU, are marred by bed effects. The extremely high resistivities at the base of lava beds, which frequently is used as a diagnostic criterion (e.g. Planke 1994; Delius 1995), is actually a bed effect, but still very a relevant feature when the task is to identify individual lava units.

MSFL data from basaltic rocks is available from three wells UK164/25-01, Glyvursnes-01 and Vestmanna-01 (Figure 14.7, Figure 14.8 and Figure 14.9). For lava beds in UK164/25-01 we find a fairly well constrained cementation exponent, m ≈ 1.95. Unfortunately, no data is available about the conductivity of the drilling fluids and formation waters in this well, so Archie's intercept constant, a, has not been determined. However, the cementation exponent is comparable to cementation exponent found in the basalts from ODP well 642E which penetrated the seaward dipping reflector sequence off mid-Norway (Planke 1994).

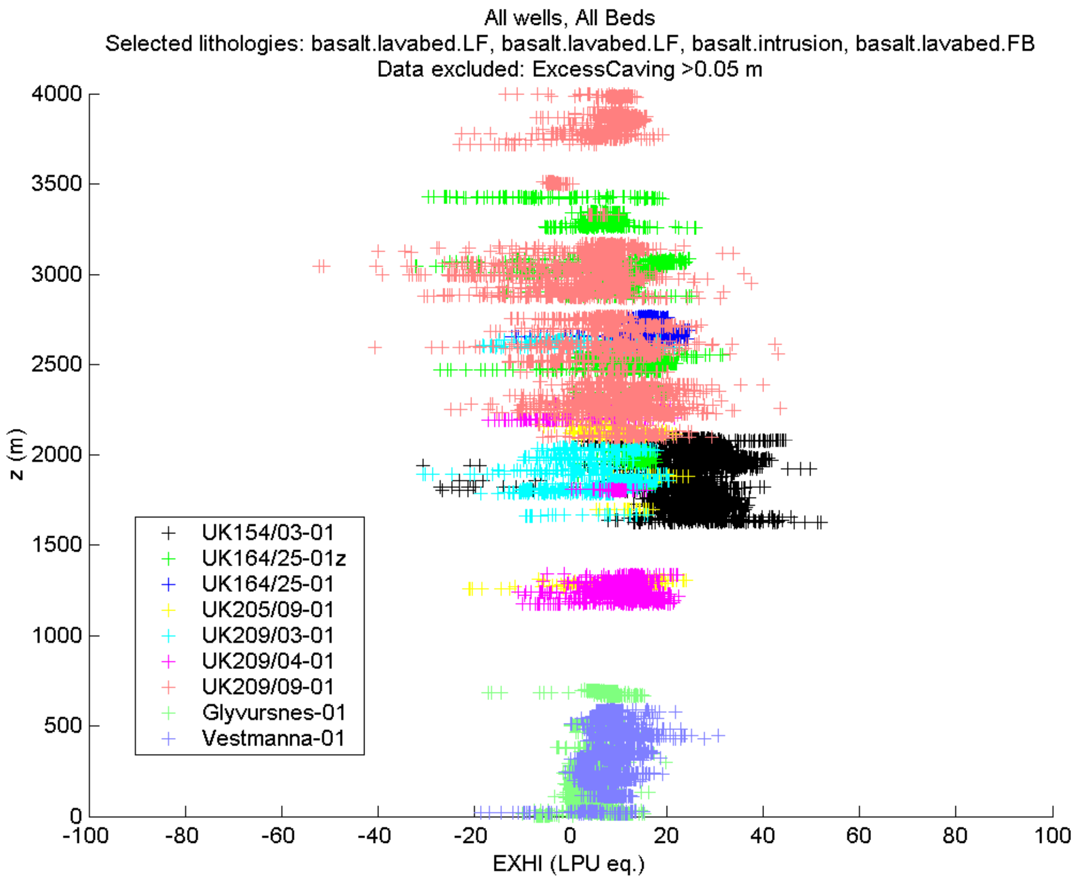

Figure 14.6. Crossplot of depth, z. versus excess hydrogen index, EXHI (See text for discussion).

Dual salinity cementation exponents calculated from resistivity measurements in plugs from the Vestmanna-01 core are in the range 2.15 to 2.81 (Abrahamsen & Argir 2004). There is apparently fair agreement between the plug data from Vestmanna-01 and the log data from UK164/25-01z. However, if the core data from Vestmanna-01 are compared with the log data from Vestmanna-01 and Glyvursnes-01, we see distinct discrepancies (Figure 14.8 and Figure 14.9). The thick lava beds from the Lower Basalt Formation in Vestmanna-01 and few thick lava beds from the Upper Basalt Formation in Vestmanna-01 lie within the range of dual salinity factors calculated from the core data. But the majority of the Upper Formation Basalts fall on a distinct trend with considerably lower slope. Log measurements from the thin lava flows in the Middle Basalt Formation fall in large cluster, which extends both above and below the trends defined by the core measurements. However, distinct petrophysical groups are not identified in the lava beds from the Middle Basalt Formation.

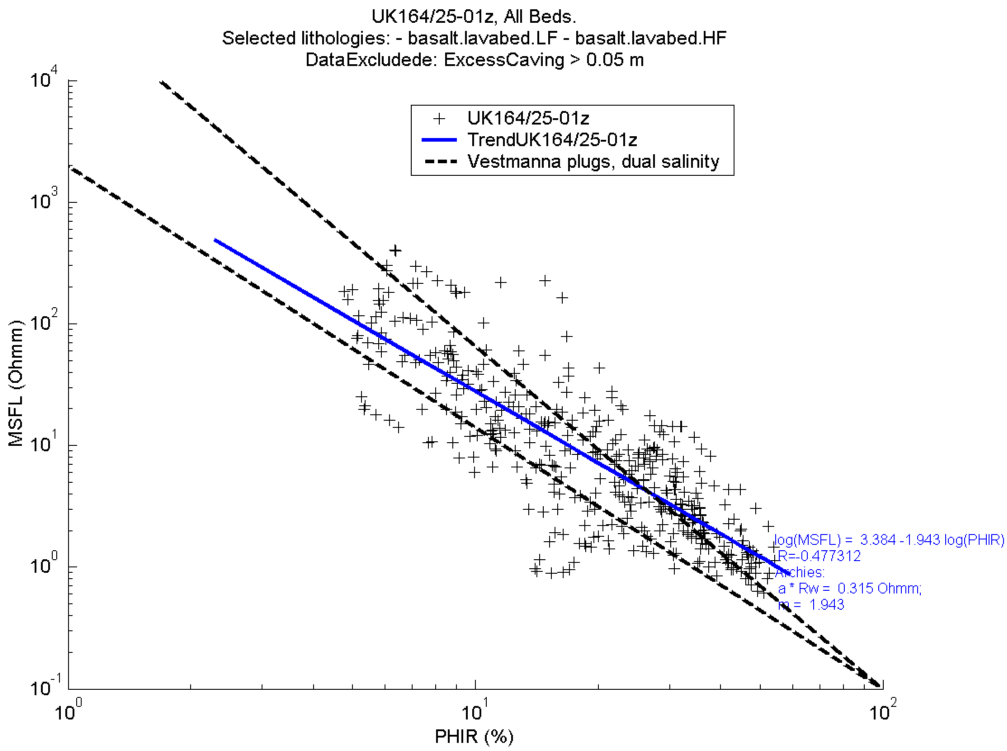

Figure 14.7. Porosity, PHIR, versus resistivity, MSFL, from log measurements in UK164/25-01. Only thick bedded basalts of Upper and Lower basalt formations included. Range predicted by dual salinity resistivity measurements (Vestmanna-01 core) is indicated by stippled line.

The complex relation between resistivity and porosity in basaltic lava beds indicated by the data Glyvursnes-01 and Vestmanna-01 is related to the mineralogy of basalts and the low conductivities of the pore fluid in the formations of these two wells. Altered basaltic rocks contain clay minerals and zeolites. Therefore small but finite matrix conductivities due these minerals cation exchange capacity are expected. Conduction due to the cation exchange capacity is independent of the conductivity of the pore water and is thus constant within any homogenous petrophysical group. In addition conducting minerals like oxides and sulphides may also be present in basalts and will contribute with a constant term to the conductivity. Due to the contributions from oxides and minerals with cation exchange capacity, basalts should be treated as a proper two phase system and will not obey Archie's equation unless the conductivity of pore water is sufficiently high. The data from the lava beds in 164/25-01z indicates that the conductivity of the pore fluid is sufficiently high that we can use Archie's equation on data from this well. Unfortunately no fluid conductivity data have been made available from this well.

If the conductivity is measured at two salinities, it is possible to obtain a characterisation of the pore space, the dual salinity cementation exponent, m_{Δ}, of rocks with a finite conductivity outside the pore space (e.g. Worthington 2003). An equivalent to Archie's intercept constant, a, is not obtained by the Worthington's approach to the dual salinity method. However, a complete two phase solution of mixing rules (e.g. Korvin 1982; Bussian 1983) does not provide feasible results with the data from the Vestmanna-01 cores. Worthington's (2003) dual salinity approach is therefore presently considered the most realistic to characterisation of the pore space in basaltic rocks. A more complete description will presumably require measurements and modelling of the full complex admittance not only the conductivity (Abrahamsen & Argir 2003).

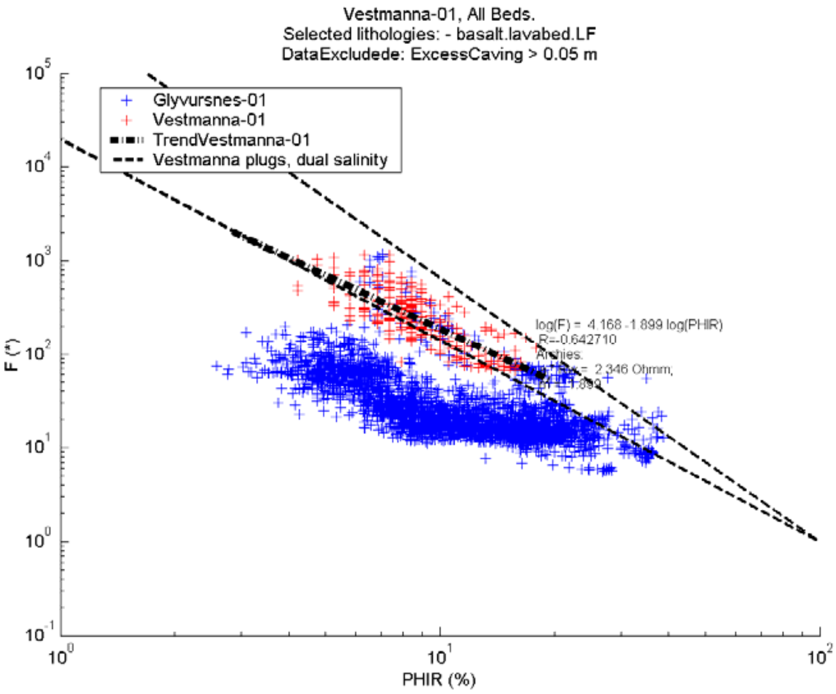

Figure 14.8 Porosity versus formation factor from log measurements in Vestmanna-01 and Glyvursnes-01. Only thick bedded basalts of Upper and Lower basalt formations included. Range predicted by dual salinity resistivity measurements (Vestmanna-01 core) is indicated by stippled line.

14.3 Seismic velocities

The seismic velocities in the basaltic rocks in the nine investigated wells vary considerably. In the most porous rock types, volcaniclastic basaltic sediments the measured P-wave velocities is less than 2000 m s^{-1} while it exceeds 6000 m s^{-1} in intrusions and in the most massive parts of the lava beds (Figure 14.10). An apparently curved trend in Figure 14.10, where all data are plotted may indicate that V_P's dependence on porosity (as estimated from the density log) is a harmonic function (V_P=k Φ^{-1}). However, if we look at the individual wells and only analyse the trend of one type of basaltic rocks at the time, good fits are obtained assuming a linear dependence between V_P and Φ. Basaltic intrusives and lava beds are characterised by the highest seismic velocities and by a large negative gradient in a Φ-V_P diagram (Table 14.5; Figure 14.11, Figure 14.12, Figure 14.13 and Figure 14.14). In general the zero crossing for intrusives and thick bedded basalts are higher than zero crossings for thin bedded basalts. In the exploration wells from the Faroe-Shetland Channel the seismic velocities observed in thin bedded basalts are mostly lower than in thick bedded basalts with the same porosity (e.g. Figure 14.11; compare Table 14.5 and Table 14.6). This may reflect that units of thin bedded basalts may include various amounts of sediments, which not was identified during the unit definition.

In Vestmanna-1 the rocks from the thin bedded Middle Basalt Formation have almost the same zero crossing as the thick bedded basalts from the Lower Basalt Formation. At the same porosity both in Glyvursnes-01 and Vestmanna-01, the seismic velocities in thin bedded basalts of the Middle Basalt

Formation are generally slightly higher than the velocities of thick bedded Lower and Upper basalt formations.

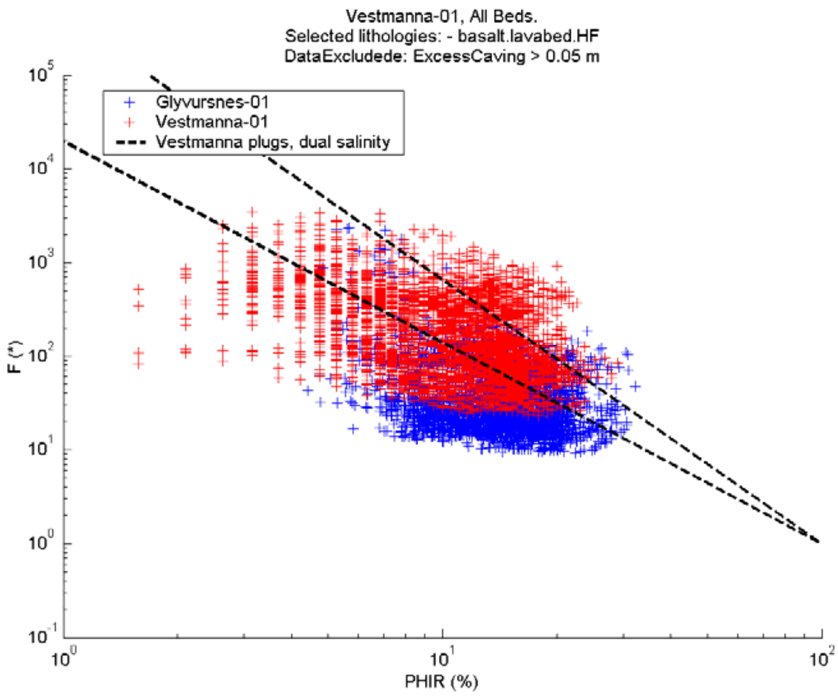

Figure 14.9. Porosity versus formation factor from log measurements in Vestmanna-01 and Glyvursnes-01. Only thin bedded basalts of Middle Basalt Formation are included. The range predicted by dual salinity resistivity measurements (Vestmanna-01 core) is indicated by stippled line.

Table 14.5. Parameters for linear trends between V_P and Φ, (V_P = a + Φ * b) in thick basaltic lava beds.

Well	Top	Bottom	a	b	R
UK154/03-01	1198.6	2073.7	6409.4	-81.7	-0.92
UK164/25-01z	1836.1	1979.4	6005.8	-69.3	-0.87
UK205/09-01	2619.5	2764.7	5862.2	-63.1	-0.65
UK209/03-01	1255.8	1883.4	5851.1	-70.8	-0.76
UK209/04-01	1661.8	2037.1	6559.9	-81.6	-0.76
UK209/09-01	1175.2	1337.5	5907.6	-70.8	-0.90
UK164/07-01	2092.9	3169.3	5768.9	-31.8	-0.55
Glyvursnes-01	8.1	354.9	5807.6	-118.4	-0.84
Vestmanna-01	559.0	586.8	6375.1	-175.3	-0.83

Table 14.6. Parameters for linear trends between V_P and Φ, (V_P = a + Φ * b) in thin basaltic lava beds.

Well	Top (m)	Bottom (m)	a	b	R
UK164/25-01z	1830.9	1905.8	5571.7	-70.8	-0.94
UK209/09-01	1172.4	1332.4	5237.2	-59.3	-0.85
UK164/07-01	2113.0	3208.5	5134.5	-24.0	-0.48
Glyvursnes-01	354.8	684.5	5550.1	-84.5	-0.64
Vestmanna-01	37.6	555.3	6249.7	-89.8	-0.80

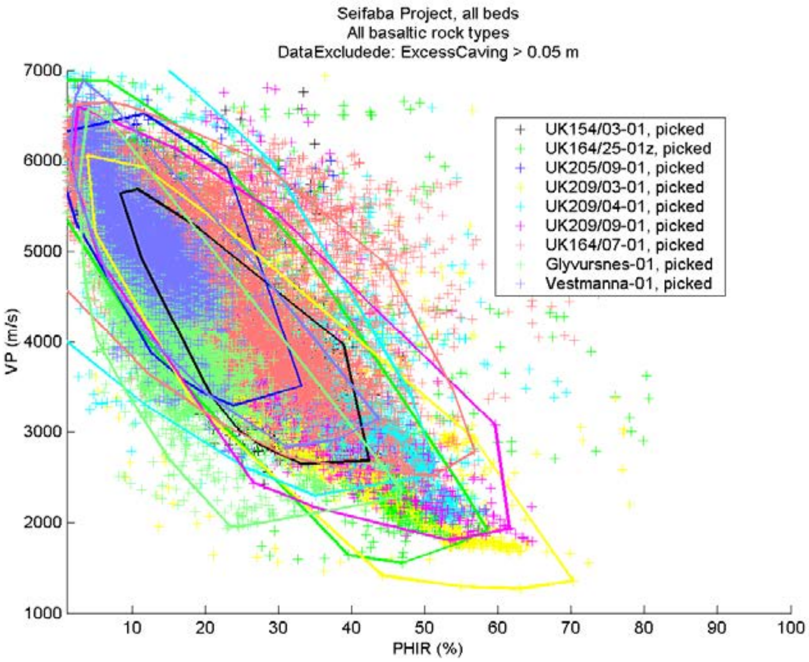

Figure 14.10. P-wave velocity versus porosity (estimated from the density log) for all nine wells.

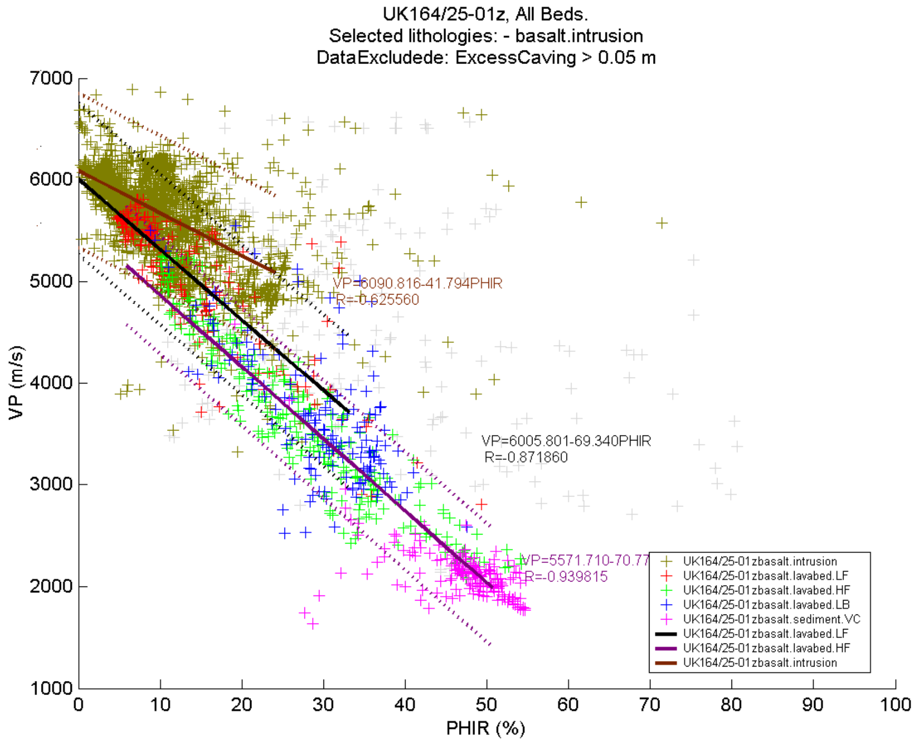

Figure 14.11. P-wave velocity versus porosity (estimated from the density log) in UK164/25-01z. Linear trends for lava beds and intrusions are inserted.

Volcaniclastic basaltic rocks are mostly characterised by low velocities and low negative gradients (Table 14.8). In Glyvursnes-01 and Vestmanna-01 porosities of volcaniclastic sediments may be quite small and the velocity trend of the sediments is offset towards lower velocities compared to the trend of the lava beds (Table 14.5 and Table 14.6). However, in the exploration wells, identified volcaniclastic sediments are generally considerably more porous than lava beds (Figure 3.1Figure 14.11). We believe this is an artefact introduced during definition of the log-units in the exploration wells. As it is very difficult to identify all volcaniclastic basaltic sediments without a core description, it is likely that some volcaniclastic sediments actually are included within what has been interpreted as units of thin bedded basalts and in the porous top of thick bedded basalts.

The relation between velocity and porosity (estimated from the density log) in the hyaloclastic units in UK154/03-01 (Table 14.8; Figure) are similar to the velocity-porosity relation of the most massive volcaniclastic sediments in the other wells.

Table 14.7. Parameters for linear trends between V_P and Φ, ($V_P = a + \Phi * b$) in intrusives.

Well	Top (m)	Bottom (m)	a	b	R
UK164/25-01z	1993.5	3432.2	6090.8	-41.8	-0.63
UK209/03-01	2092.5	2283.1	5663.1	-60.4	-0.72
UK209/09-01	1748.3	2280.8	7176.2	-121.0	-0.83

Table 14.8. Parameters for linear trends between V_P and Φ, ($V_P = a + \Phi * b$) in volcaniclastic basaltic sediments.

Well	Top (m)	Bottom (m)	a	b	R
UK164/25-01z	1835.4	1883.2	3591.4	-30.9	-0.61
UK209/03-01	1244.0	2079.5	5431.3	-64.3	-0.85
UK209/04-01	1658.9	2125.1	3652.9	-11.7	-0.34
UK209/09-01	1220.0	1266.1	5300.4	-52.0	-0.91
Glyvursnes-01	7.0	607.0	3190.6	-25.4	-0.51
Vestmanna-01	555.2	559.1	5330.2	-94.2	-0.80
Foreset breccias:					
UK154/03-01	1640.0	2041.2	5303.1	-56.6	-0.60

14.4 Gamma radiation

The levels of gamma radiation observed in the individual wells are not identical (Figure 14.15). However, in each of the wells the level of gamma radiation in the basaltic rocks are generally constant and variation around the average value are restricted to ca. 5 GAPI. This may to suggest that that the basalts in each well constitute a fairly homogenous population while there is considerable difference between the basalts from different wells. This is supported by the different trends for each well observed when pairs of porosity related parameters are analysed (e.g. Figure 14.1). However, it has not been possible to find a simple relation between the level of gamma radiation and the trends observed between pairs of porosity related parameters.

As mentioned in the description of the data from each well the volcaniclastic lava beds - and in most wells - also the lava tops are characterised by the largest gamma radiation.

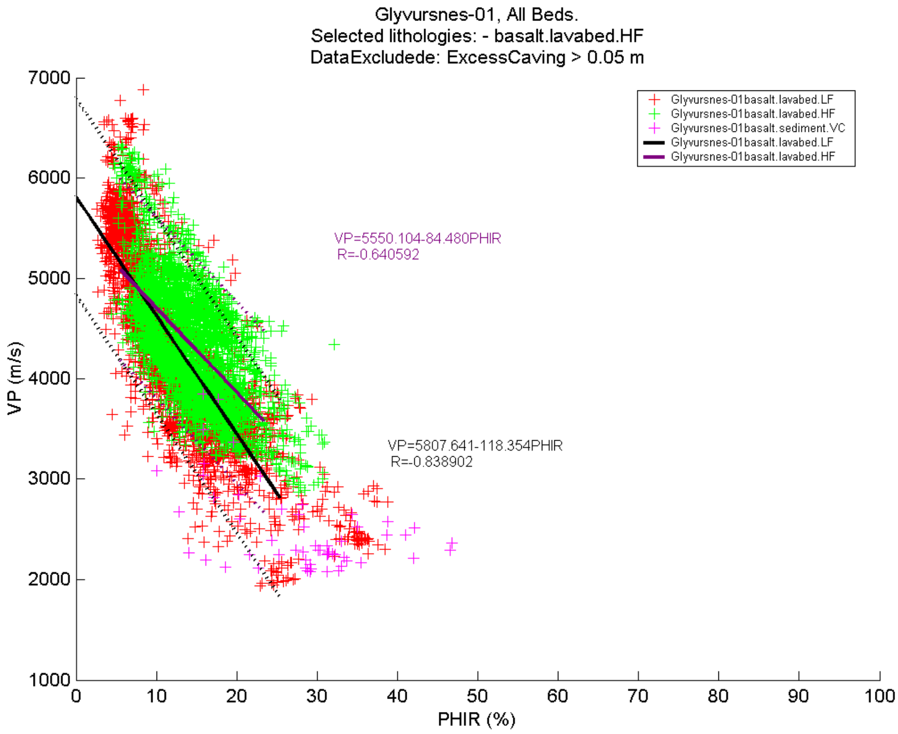

Figure 14.12. P-wave velocity versus porosity (estimated from the density log) in Glyvursnes-01. Linear trends for lava beds are inserted.

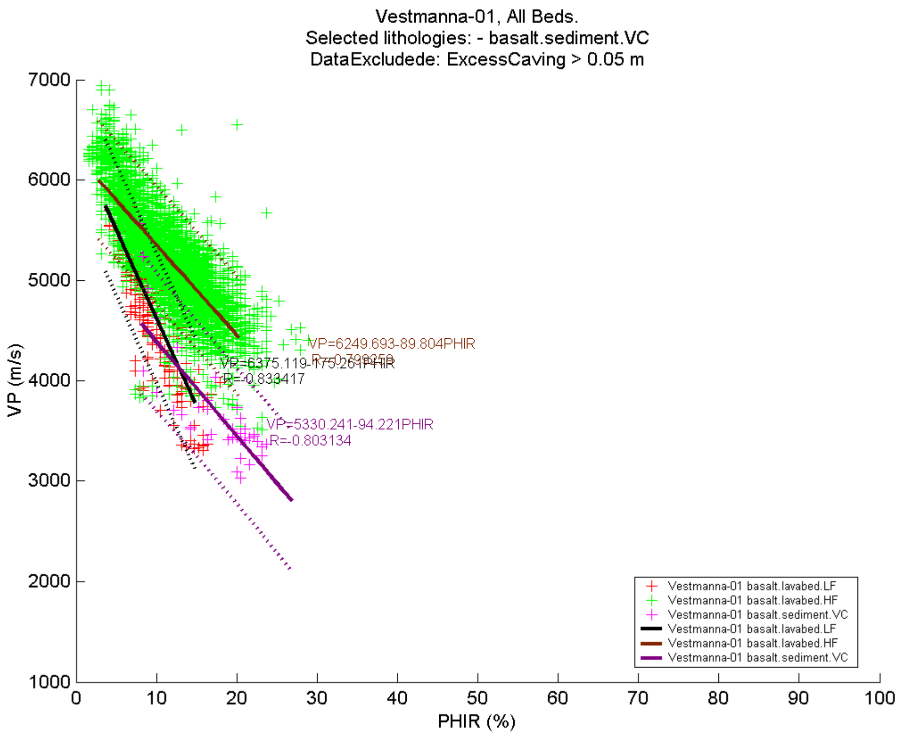

Figure 14.13. P-wave velocity versus porosity (estimated from the density log) in Vestmanna-01. Linear trends for lava beds and volcaniclastic basaltic sediments are inserted.

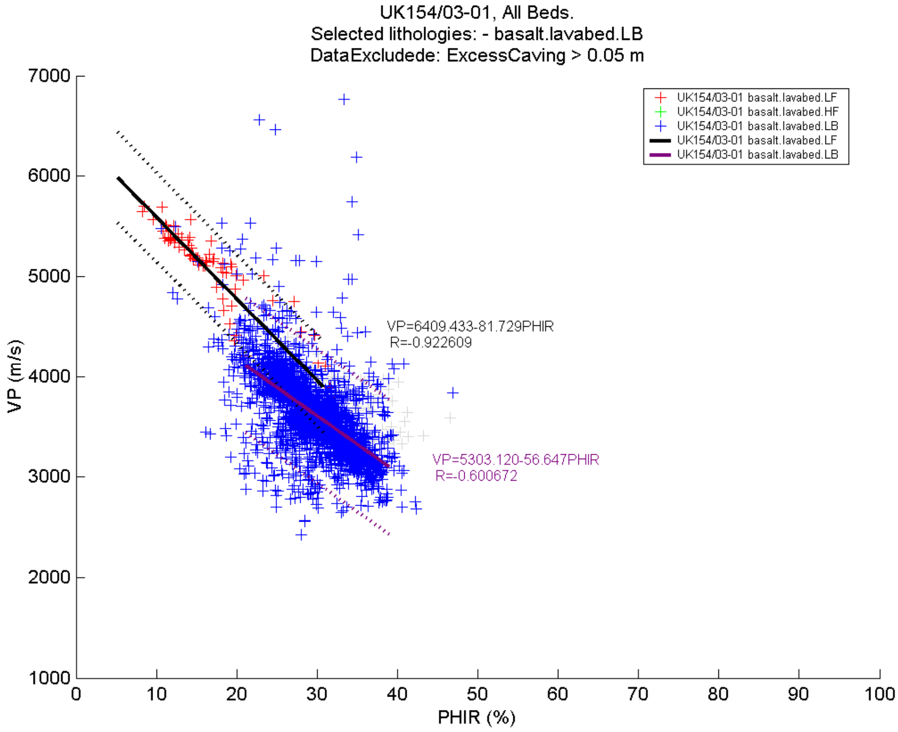

Figure 14.14 P-wave velocity versus porosity (estimated from the density log) in UK154/03-01. Linear trends for lava beds and volcaniclastic basaltic sediments (foreset breccias) are inserted.

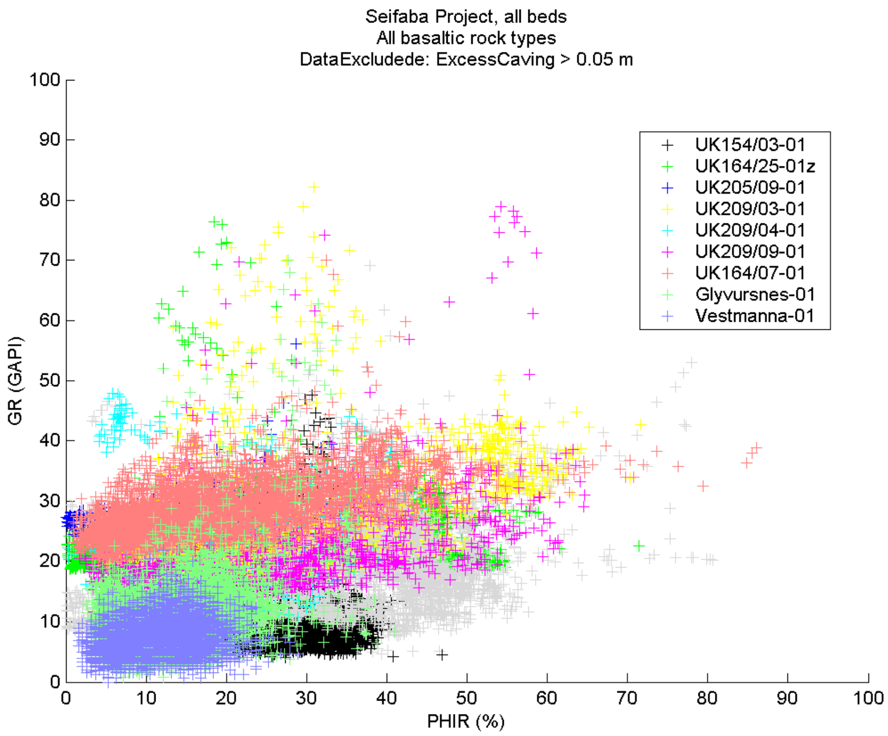

Figure 14.15. Gamma radiation versus porosity (estimated from the density log) for all nine wells.

14.5 Classes of basaltic units identified in well logs.

Five different basaltic rock classes, low frequency basaltic lava beds, high frequency basaltic lava beds, intrusives, volcaniclastic sediments and foreset breccias, have been identified in the investigated wells based on their log pattern and the magnitude of log measurements (Chapter 4). The four classes reflect the emplacement of the basalt.

Not all classes are identified in all wells, and there is considerable overlap among the different types when the data are presented in cross plots. The trends of the four classes are generally distinct in any single well.

Depth/burial may be a factor influencing the trends (see chapter 16). Although, a few examples of “basalts” of deviating “magma type” have been identified, it has neither been possible to identify any simple relation of general validity between “magma type” and physical properties. In any well or interval of a well we may identify a particular distribution of properties for basaltic units of any of the four classes mentioned above, but at present we can not associate this distribution to “magma type” or burial history.

15 Stratigraphic filters

Reverberation in the layered Earth causes dissipation and dispersion of the direct signal. This effect, which is strictly one dimensional, can be described as a stratigraphic filter (O'Doherty & Anstey 1971). Using the calculated impedance logs, the stratigraphic filters for any interval in the wells can be estimated using the invariant embedding formulation (Kennett 1974, Frazer 1994). This provides a direct estimate of the signal deterioration due to 1D scattering of seismic signals propagating vertically trough the succession penetrated by the wells. The calculated stratigraphic filters can be compared to seismic measurements of acoustic attenuation and thus provide indications of the relative importance of 1D scattering and other contributions to effective attenuation of the seismic signal.

In this chapter we present estimates of the one dimensional stratigraphic filters of the basaltic successions in the studied wells. In all wells the stratigraphic filter for any interval has been calculated using the complete impedance logs based on 0.1524 m interval in the exploration wells and 0.20 m interval in the two research wells from Faroe Islands.

The dissipation of a seismic wave travelling through a viscoelastic medium are described by a dissipation function, D(f), where f is frequency. The lower D(f) is the larger the dissipation. Although, D(f) originally is defined for viscoelastic medias, a dissipation function can also be calculated to quantify the energy/signal lost by stratigraphic filters. Often the function D(f) is inversely proportional to frequency, $D(f) = Q/f$, within a limited bandwidth. The proportionality constant, Q, is referred to as the quality factor (e.g. Maresh et al. 2003). Unfortunately the dissipation function D(f) is also referred to as the quality factor, Q(f) (e.g. Mavko et al. 1998), making the terminology of energy dissipation somewhat confusing. However, in this report the term quality factor is only used to refer to the proportionality constant, $Q = f \cdot D(f)$.

As demonstrated below stratigraphic filters are characterised by a strong "DC component". For basaltic successions the DC component is generally more significant than the dispersive component of dissipation, when the frequency is in the range normally used for deep seismic imaging (ca. 1-50 Hz). The total dissipation is thus suitably described by linear equation, $1/D(f) = 1/Q_{DC} + f \cdot 1/Q$.

In this study a relation developed by O'Doherty & Anstey (1971) is used to calculate Q(f). An alternative approach to calculate Q(f) would be to use the logarithmic decrement of the amplitude. The results of the two methods are identical.

For all the stratigraphic filters presented below, Q and Q_{DC} are estimated as the inverse slope and the inverse zero crossing for the best linear RMS-fit to 1/D(f). As 1/D(f) for most of the stratigraphic filters only is approximated by a linear function in a limited frequency range only data in the frequency range 0-40 Hz are considered. This should ensure that the coefficients Q_{DC} and Q for different filters are comparable.

The stratigraphic filter, its dissipation function, the quality factor, Q, and the DC component of dissipation have been calculated for one or more intervals in all wells investigated in this study, and are presented below.

15.1 UK154/03-01

In this well we are lacking density data. We have thus approximated the impedance log alone from the velocity data. Densities have been estimated using velocity-density relations from 164/25-01 and 164/07-01 (RHOB=1510 kg m^{-3}+VP 0.22 kg s m^{-4}).

Despite an inferior log suite – compared to the other studied wells – it is clear that the character of the basaltic succession in UK154/03-01 changes character at around 1600 m. We are thus calculating the filters for the succession 1184.4-1574.6 and the interval 1640.0-2041.1. The upper succession is comprised of lava beds of variable thickness, rarely exceeding 10 m and intercalations of volcaniclastic material, and is presumably representing sub-aerially erupted and emplaced basaltic lava beds. The lower succession is characterised by lower sonic velocities than the lava beds in the upper succession and is overall more homogeneous. This unit is interpreted as a succession dominated by volcaniclastic sediments or hyaloclastites, presumably a volcanic foreset breccia erupted sub-aerially and emplaced below sea-level (based on description of the seismic data presented in the completion report; see also chapter 5). Stratigraphic filters were calculated for the two above mentioned intervals of basaltic rocks and for comparison also in two intervals comprised of sediments.

The filter calculated for the succession of lava beds in this well is attenuating the input signal more severely than the filter calculated for the succession of “hyaloclastites” (Figure 15.1). The difference is most significant at high frequencies. The filter for the “hyaloclastites” is only slightly more severe than the filters calculated for the two sediment successions.

Although the calculated impedances are based only on the sonic velocities, we believe that the difference between the filters of the two basaltic successions most likely represents real differences.

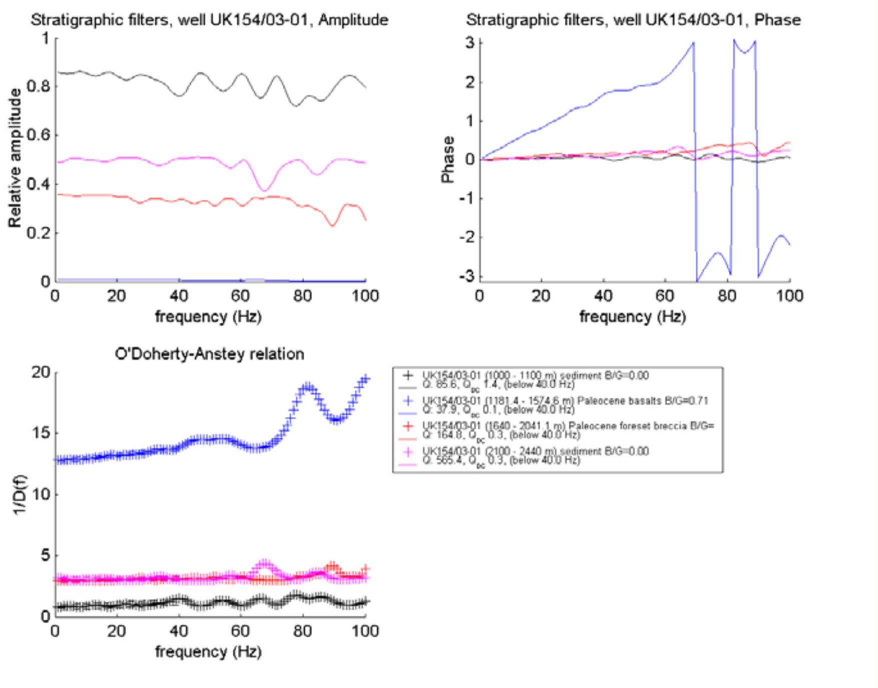

Figure 15.1. Stratigraphic filters for four intervals in the well UK154/03-01. The intervals 1181.4-1574.6 m and 1640.0-2041.1 m represent two different basaltic units in the well. According to the completion log the interval 1000-1100 m is comprised of Eocene siliciclastic sediments (dominantly siltstones) and the interval 2100-2440 is Cretaceous sediments mostly coarse clastic sediments.

15.2 UK164/07-01

This well drilled through a thick succession comprised mostly of low frequency lava beds, and we calculated stratigraphic filters for a part of this succession and for a succession of sediments deeper in the well. The sediment succession contains intervals of basaltic intrusives (sills).

Also in UK164/07-01 the stratigraphic filter calculated for the basaltic succession is more severe than that calculated for a sediment succession (Figure 15.2). However, the difference between the “basalt filter” and the “sediment filter” is not as prominent as in UK154/03-01 reflecting the presence of intrusives in the sediment succession in UK164/07-01. The quality factor, Q≈ 40, for the stratigraphic filter calculated from log data through the volcanic succession is fairly high compared to quality factors obtained from VSP data from the well, Q≈ 7-35 (Maresh et al. 2003). This indicate that dispersion is more significant than indicated by the strictly 1D calculations based on log data.

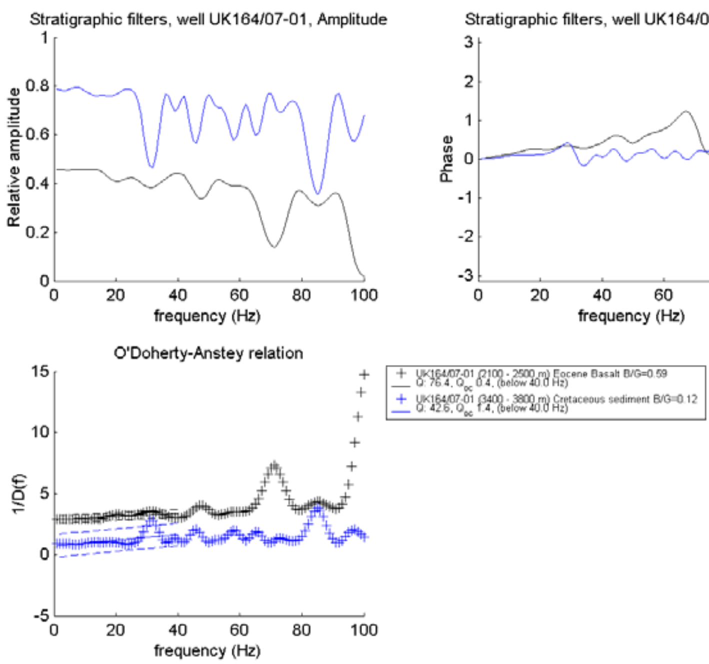

Figure 15.2. Normalised stratigraphic filters for two intervals in the well UK164/07-01. The interval 2100-2500 m represents the upper part of the thick succession of distinct lavabeds. The interval 3400-3800 m is from the upper part of the Shetland Group and mostly comprised of siliciclastic sediments.

15.3 UK164/25-01 and UK164/25-01

The volcanic successions in these two well are relatively thin (200 m of eruptive basaltic rocks – including some siliciclastic sediments). Intrusives account for a considerable part of the succession below the extrusive basalts. This is a mixed succession of sills and dykes (chapter 6), and calculating a stratigraphic filter for a succession including dykes would be invalidating the assumption of one-dimensionality.

The stratigraphic filters calculated for the two intervals in the basaltic succession are more severe in the sense that more energy is lost than the filters for the sediments above and below (Figure 15.3). There is considerable difference between the two filters for the interval 1831-1906 m. It is likely that this difference mostly is reflecting different quality of the logs in the two wells (see also chapter 6). The difference can be considered an indication of the magnitude of errors we should expect calculating stratigraphic filters if well conditions not are perfect. As there is a tendency that the more porous parts of basaltic successions cave more easily than the massive part causing to low densities in these parts of basaltic successions, it is likely that logs in imperfect boreholes will have a tendency to over emphasize the stratigraphic filters of basalt successions.

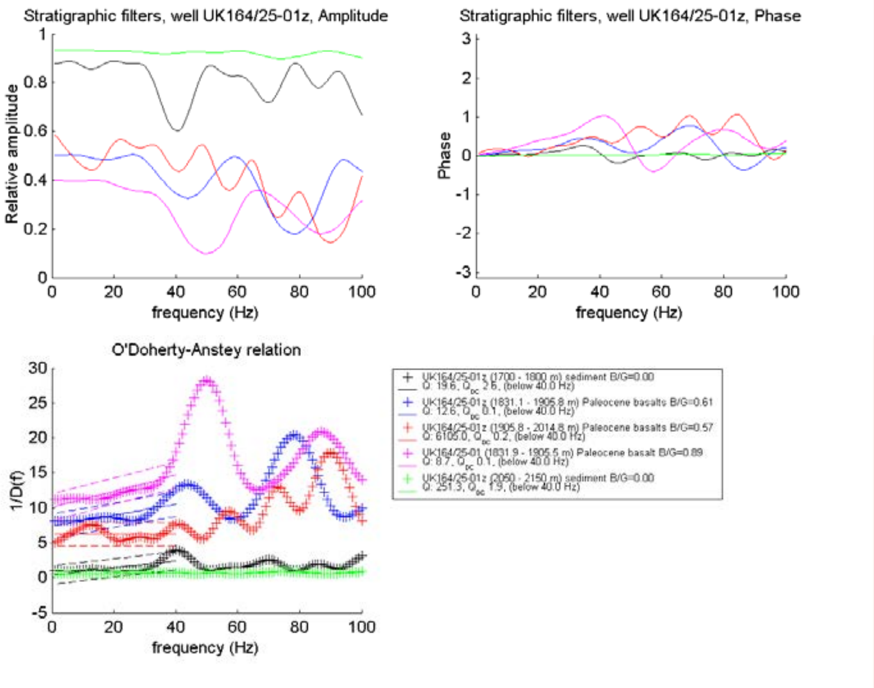

Figure 15.3. Stratigraphic filters calculated for two intervals in UK164/25-01 and four intervals in UK164/25-01z. The interval 1831.9-1905.5 m in UK164/25-01 is equivalent to the interval 1831.1-1905.08 in UK164/25-01z and t represents the upper part of the basaltic succession. Sonic log trough the lower part of the basalt succession is only available in UK164/25-01z (1905.08-2014.8 m). The interval 1700-1800 m is in both wells Eocene sediments and the interval 2050-2150 m in UK164/25-01z is Early Palaeocene sediments.

15.4 UK205/09-01

The only basaltic rocks recognised in this well are four distinct low frequency lava beds in a succession of Palaeocene clastic sediments. We calculated a stratigraphic filter for an interval around these four basaltic lava beds (Figure 15.4). Basalts comprise approximately a third of this interval, the rest is clastic sediments. In addition we have calculated filters for the sediment immediately above and below. As evident from Figure 15.4 the four basalts beds has considerable effect at high frequencies. However, at low frequencies (0-40 Hz) their effect is not significantly different for the sediment succession above.

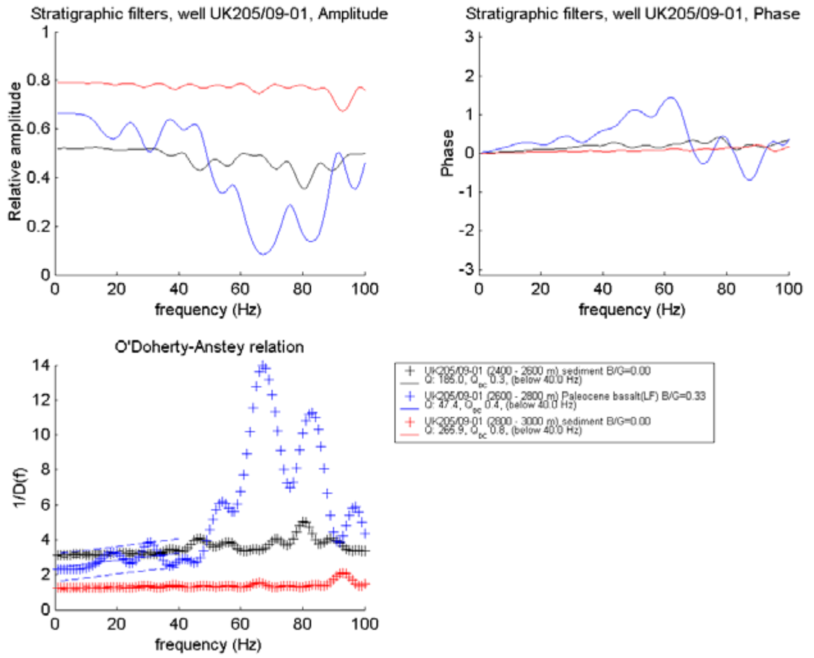

Figure 15.4. Stratigraphic filters calculated for three intervals in UK205/09-01. The interval 2600-2800 includes four basaltic lava beds (cumulated thickness 67 m). No basaltic rocks have been interpreted in the intervals above (2400-2600 m) and below (2800-3000).

15.5 UK209/03-01

In this well there is a fairly thin succession of mostly low frequency lava beds (1245-1310 m), under which we find a succession interpreted as volcaniclastic rocks (1310-1348 m) and a thick succession of high frequency lava bed units (1348-2048 m). The stratigraphic filters calculated for both the volcaniclastic sediments and the high frequency lava bed units are fairly flat (Figure 15.5). But the calculated filter for the succession of distinct lava beds is a severe highcut filter.

15.6 UK209/04-01

In UK209/04-01 there is a more than 400 m thick succession of basaltic eruptives (possibly including intermediate rocks) which overlay Cretaceous rhyolitic rocks and sediments. The upper and lower parts of the basaltic eruptives are interpreted as dominantly volcaniclastic rocks while the central part is dominated by lava beds. We have calculated the stratigraphic filters for the two intervals dominated by volcaniclastic rocks, the interval in between, characterised mostly of low frequency lava beds, and a succession of sediments above the volcanics. The filtering effect of the succession of lava beds is considerably more severe than that of both of the volcaniclastic successions and the sediment succession – especially at high frequencies (Figure 15.6).

15.7 UK209/09-01

This well is situated close to UK209/03-01 on the Erlend dome. It contains a succession of mostly low frequency lava beds with a few high frequency lava bed units (1170-1340 m). The log response is similar to that of the "upper basalts" of UK209/03-01. In Figure 15.7 we have plotted the stratigraphic filter of the basalts in UK209/09-01 together with filters from two sediment intervals in the well.

15.8 Vestmanna-01 and Glyvursnes-01

The basalts from Vestmanna-1 are from the Faroe Islands Middle Basalt Formation, which is dominated by high frequency lava beds. The lower ca. 30 m are from the Faroe Islands Lower Basalt Formation.

Part of the succession drilled in Glyvursnes-1 is from the Middle Basalt Formation, while the uppermost ca. 325 m is from the Faroe Islands Upper Basalt Formation. We have calculated stratigraphic filters for the Middle Basalt Formation in Vestmanna-01 and Glyvursnes-01 and for the Middle Basalt Formation in Glyvursnes-01 (Figure 15.8 and Figure 15.9). The stratigraphic filter for Faroe Islands Middle Basalt Formation is very similar in the two wells. The filter for the Upper Basalt Formation, which is dominated by low frequency lava beds, is more severe, especially at high frequencies (Figure 15.8). The quality factor, Q>100, for the stratigraphic filter calculated from log data through the volcanic succession is considerably higher than quality factors obtained from VSP data from the well, Q≈10-45(Shaw et al. 2004). Indicate that dispersion in this well - as in UK164/07-01 - is more significant than indicated by the strictly 1D calculations based on log data.

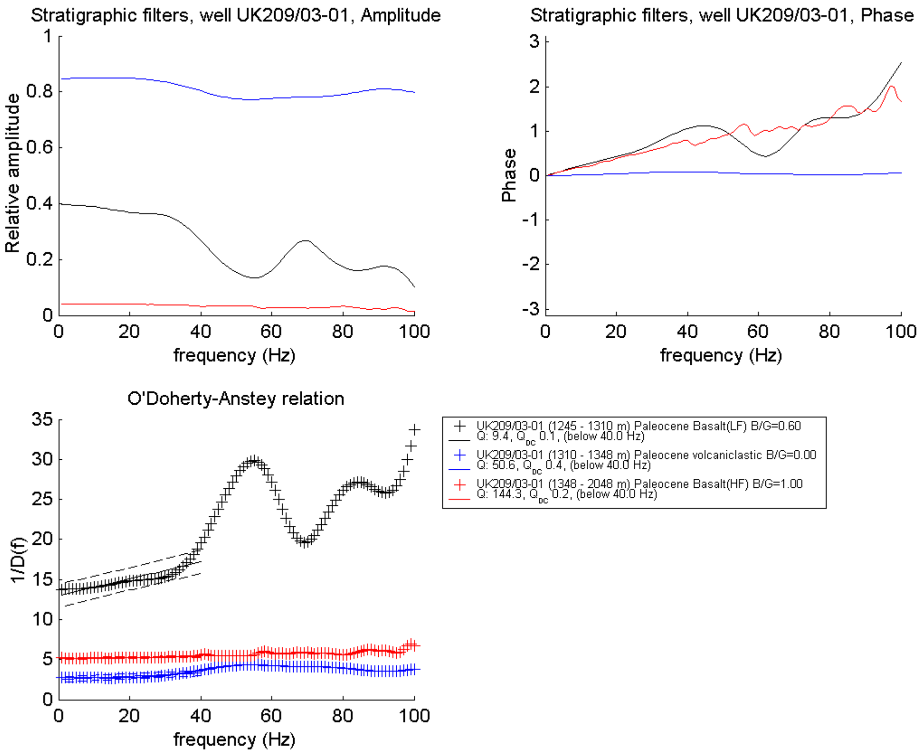

Figure 15.5. Normalised stratigraphic filters calculated for three intervals in UK209/03-1. Distinctly bedded basalts comprises the interval 1245-1310 m. The interval, 1310-1348 m, is volcaniclastic, and 1348-2048 is comprised of composite thin lava beds.

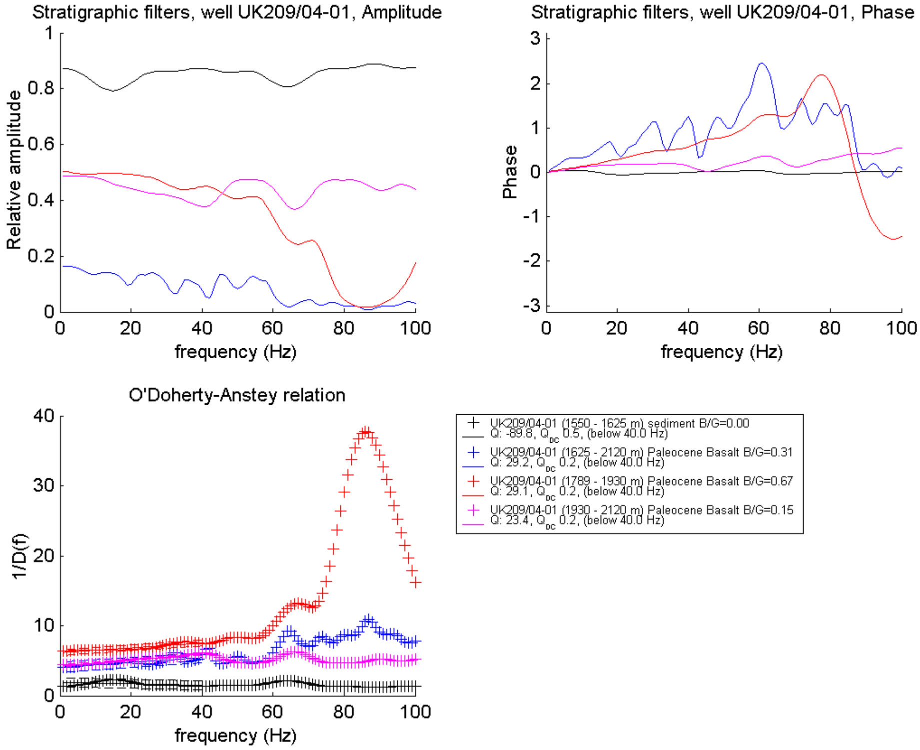

Figure 15.6. Normalised stratigraphic filters calculated for four intervals in UK209/04-1. The intervals 1650-1789 m and 1930-2100 m are dominantly volcaniclastic rocks. The interval 1789-1930 is dominated by lavabeds, and the interval 1550-1625 are Eocene siliciclastic sediments above the volcanic intervals.

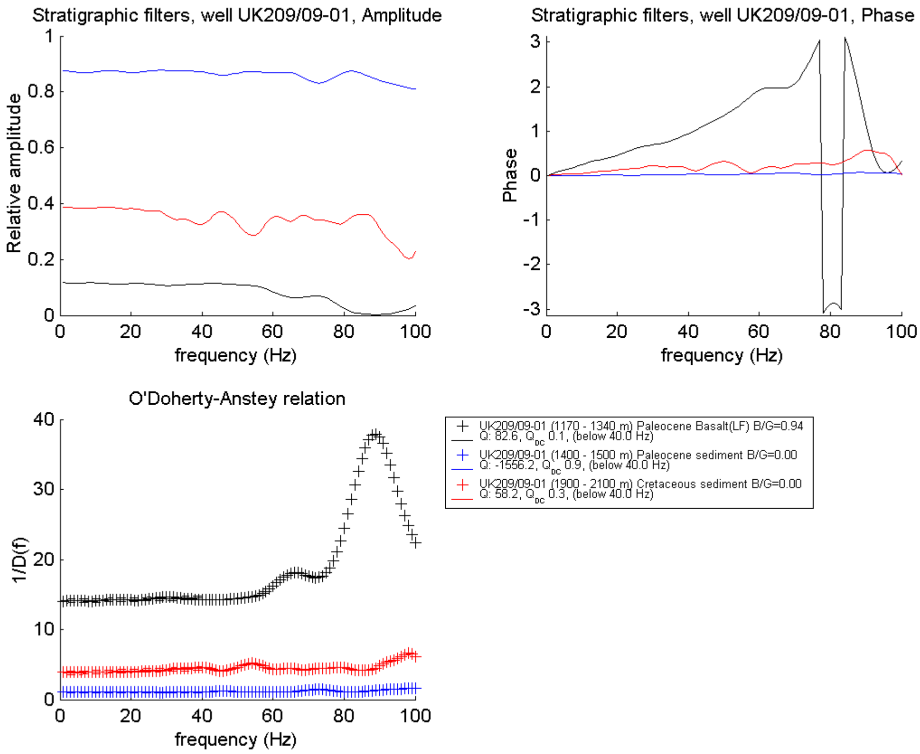

Figure 15.7. Normalised stratigraphic filters calculated for three intervals in UK209/09-1. Distinctly bedded basalts (1170-1340 m), Lower Palaeocene clastic sediments (1400-1500 m) and Cretaceous clastic sediments (1900-2100 m)

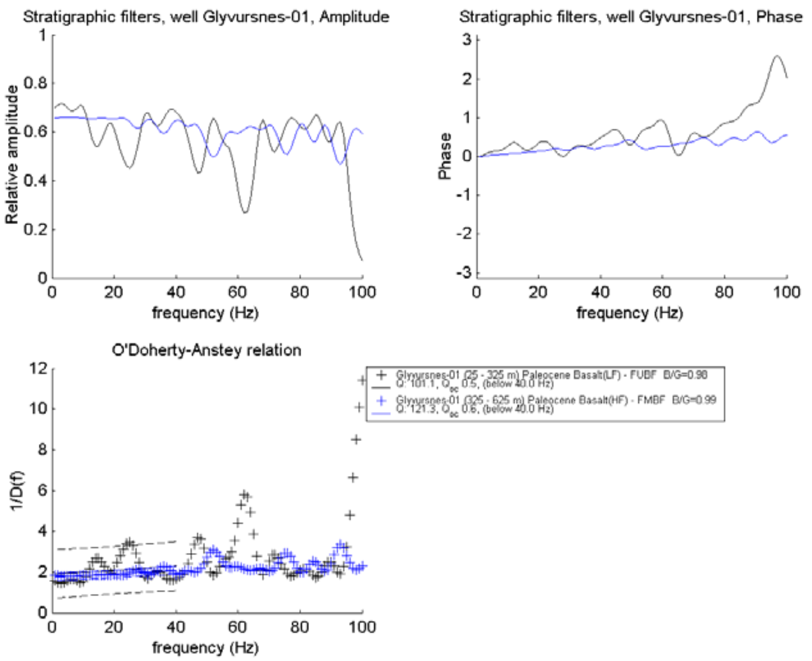

Figure 15.8. Stratigraphic filters from Glyvursnes-1 well. The interval (25-325 m) represents the Upper Basalt Formation in Glyvursnes-1. The other filter (325-625 m) represents the Middle Basalt Formation.

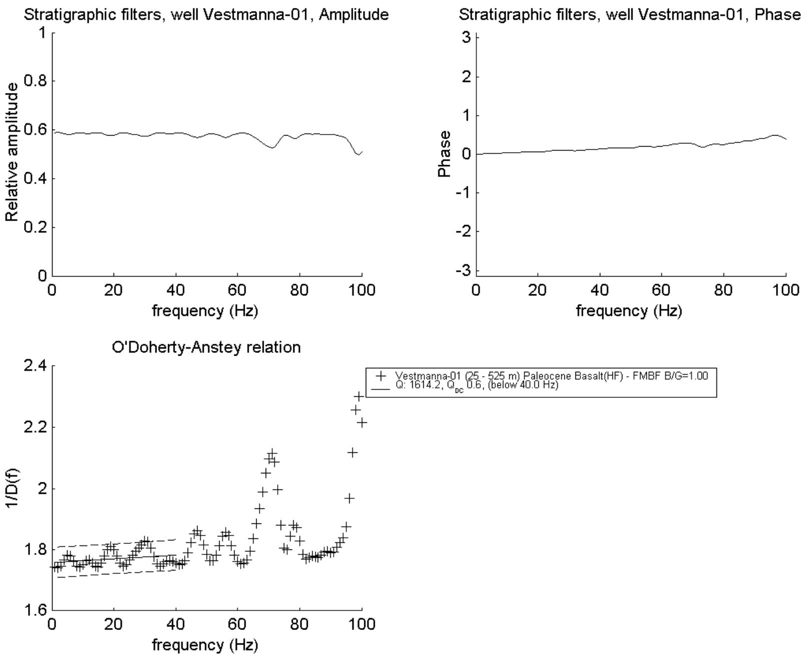

Figure 15.9. Stratigraphic filters from Vestmanna-1. The filter represents only the Middle Basalt Formation.

15.9 Overview of stratigraphic filters

Key parameters of all the stratigraphic filters presented above are given in Table 15.1. As seen in Figure 15.10, the stratigraphic filters calculated for basaltic successions generally have smaller values of Q and especially of Q_{DC} than the filters of sedimentary successions. However, the values of Q for the stratigraphic filters calculated from log data through basaltic successions are higher than values of Q calculated using VSP data. Maresh et al. (2003) obtained values of Q for basaltic successions in the range 15-35 using VSP data from UK164/07-01, and Shaw et al. (2004) obtained values in the range 10-45 using data from the Glyvursnes-01 well. In both cases values of Q obtained from VSP is lower than values obtained from log data. This indicates that some other mechanism than stratigraphic filtering accounts for a significant part of the frequency dispersion of seismic signals propagating through basalts. Lateral inhomogeneity in a succession (e.g. thickness changes of the individual layers) will scatter a seismic signal propagating through the succession and cause effective attenuation of high frequency data.

As loss of high frequency data is considered a general problem in sub-basalt imaging (e.g. White et al. In press), seismic scattering due to lateral inhomogeneities - or a similar process - is generally considered the main hindrance to sub-basalt imaging. However, the large DC component of the seismic dissipation, Q_{DC}, due to stratigraphic filtering in most of the investigated basaltic successions (Figure 16.10) indicates that successful sub-basalt imaging require a energy source, which in addition to low frequency also is characterised by a high energy content. Comparable direct measurements of the DC component of seismic attenuation of a seismic signal propagating through a basalt succession have apparently not been published.

Table 15.1. Key statistics of stratigraphic filters

Interval	Depth	Q	Q_DC	LF	HF	I	B	VS	CS
UK154/03-01 (1000 - 1100 m) sediment	1050.0	85.6	1.37	0.00	0.00	0.00	0.00	0.00	1.00
UK154/03-01 (1181.4 - 1574.6 m) Paleocene basalts	1378.0	37.9	0.08	0.18	0.53	0.00	0.00	0.00	0.29
UK154/03-01 (1640 - 2041.1 m) Paleocene foreset breccia	1840.6	164.8	0.35	0.00	0.00	0.00	0.95	0.00	0.05
UK154/03-01 (2100 - 2440 m) sediment	2270.0	565.4	0.33	0.00	0.00	0.00	0.00	0.00	1.00
UK164/25-01 (1700 - 1800 m) sediment	1750.0	31.7	2.10	0.00	0.00	0.00	0.00	0.00	1.00
UK164/25-01 (1831.9 - 1905.5 m) Paleocene basalt	1868.7	8.7	0.10	0.22	0.66	0.00	0.00	0.00	0.11
UK164/25-01z (1700 - 1800 m) sediment	1750.0	19.6	2.59	0.00	0.00	0.00	0.00	0.00	1.00
UK164/25-01z (1831.1 - 1905.8 m) Paleocene basalts	1868.4	12.6	0.14	0.10	0.51	0.00	0.00	0.00	0.39
UK164/25-01z (1905.8 - 2014.8 m) Paleocene basalts	1960.3	6105.0	0.16	0.16	0.00	0.19	0.21	0.00	0.43
UK164/25-01 (1831.9 - 1905.5 m) Paleocene basalt	1868.7	8.7	0.10	0.22	0.66	0.00	0.00	0.00	0.11
UK164/25-01z (2050 - 2150 m) sediment	2100.0	251.3	1.85	0.00	0.00	0.00	0.00	0.00	1.00
UK205/09-01 (2400 - 2600 m) sediment	2500.0	185.0	0.32	0.00	0.00	0.00	0.00	0.00	1.00
UK205/09-01 (2600 - 2800 m) Paleocene basalt(LF)	2700.0	47.4	0.42	0.33	0.00	0.00	0.00	0.00	0.67
UK205/09-01 (2800 - 3000 m) sediment	2900.0	265.9	0.83	0.00	0.00	0.00	0.00	0.00	1.00
UK209/03-01 (1245 - 1310 m) Paleocene Basalt(LF)	1277.5	9.4	0.08	0.60	0.00	0.00	0.00	0.00	0.40
UK209/03-01 (1310 - 1348 m) Paleocene volcaniclastic	1329.0	50.6	0.40	0.00	0.00	0.00	0.00	0.00	1.00
UK209/03-01 (1348 - 2048 m) Paleocene Basalt(HF)	1698.0	144.3	0.20	0.01	0.99	0.00	0.00	0.00	0.00
UK209/04-01 (1550 - 1625 m) sediment	1587.5	-89.8	0.52	0.00	0.00	0.00	0.00	0.00	1.00
UK209/04-01 (1625 - 2120 m) Paleocene Basalt	1872.5	29.2	0.25	0.23	0.08	0.00	0.00	0.00	0.69
UK209/04-01 (1789 - 1930 m) Paleocene Basalt	1859.5	29.1	0.16	0.54	0.13	0.00	0.00	0.00	0.33
UK209/04-01 (1930 - 2120 m) Paleocene Basalt	2025.0	23.4	0.24	0.15	0.00	0.00	0.00	0.00	0.85
UK209/09-01 (1170 - 1340 m) Paleocene Basalt(LF)	1255.0	82.6	0.07	0.69	0.25	0.00	0.00	0.00	0.06
UK209/09-01 (1400 - 1500 m) Paleocene sediment	1450.0	-1556.2	0.93	0.00	0.00	0.00	0.00	0.00	1.00
UK209/09-01 (1900 - 2100 m) Cretaceous sediment	2000.0	58.2	0.27	0.00	0.00	0.00	0.00	0.00	1.00
UK164/07-01 (2100 - 2500 m) Eocene Basalt	2300.0	76.4	0.35	0.41	0.16	0.02	0.00	0.00	0.41
UK164/07-01 (3400 - 3800 m) Cretaceous sediment	3600.0	42.6	1.42	0.00	0.00	0.12	0.00	0.00	0.88
Glyvursnes-01 (25 - 325 m) Paleocene Basalt(LF) - FUBF	175.0	101.1	0.53	0.57	0.40	0.00	0.00	0.00	0.02
Glyvursnes-01 (325 - 625 m) Paleocene Basalt(HF) - FMBF	475.0	121.3	0.57	0.12	0.87	0.00	0.00	0.00	0.01
Vestmanna-01 (25 - 525 m) Paleocene Basalt(HF) - FMBF	275.0	1614.2	0.57	0.27	0.73	0.00	0.00	0.00	-0.00

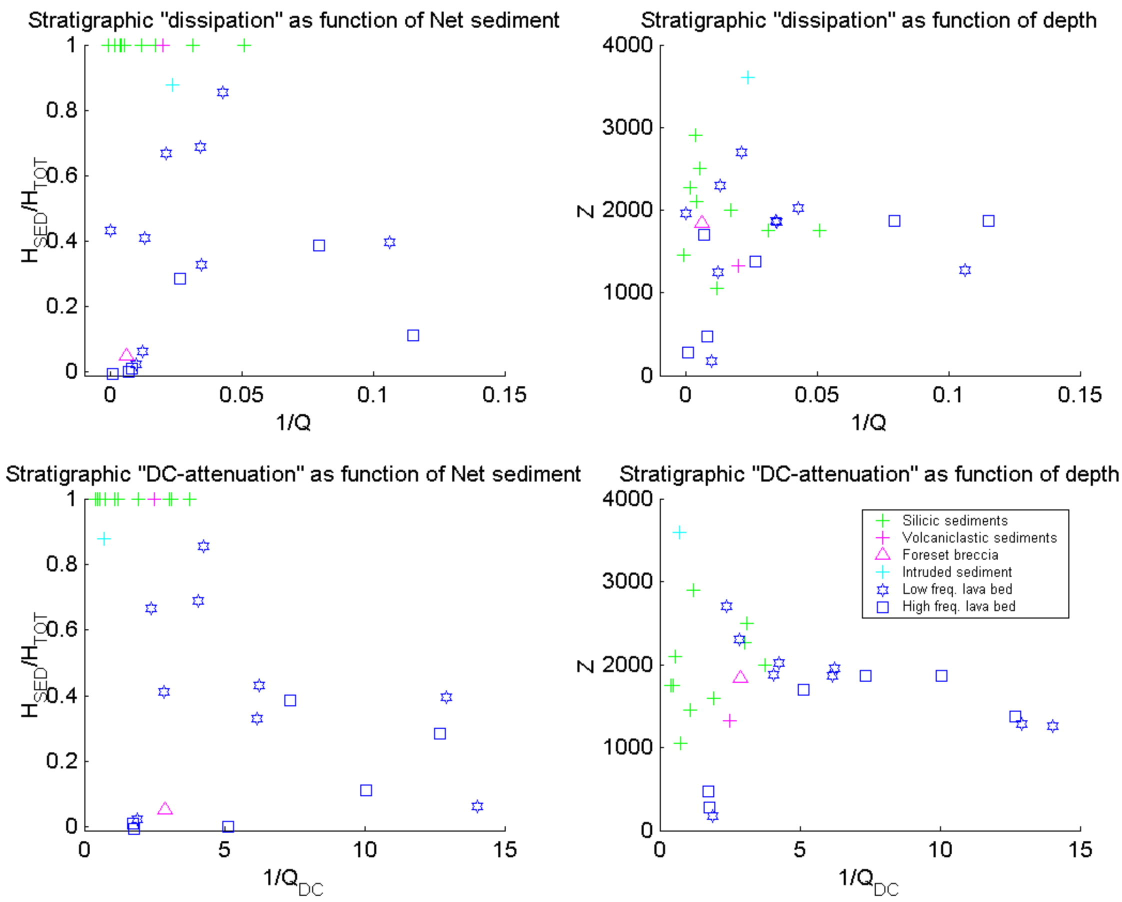

Figure 15.10. Key parameters of stratigraphic filters calculated from wireline logs in nine wells from the Faroe-Shetland Area. Upper left: Inverse quality factor, 1/Q, plotted against the relative proportion of sediments in the filtering succession. Upper right: 1/Q plotted against the mean depth of the succession. Lower left: Stratigraphic dissipation, $1/Q_{DC}$, plotted against the relative proportion of sediments. Lower right: Stratigraphic dissipation, $1/Q_{DC}$, plotted against the mean depth of the succession. Data from table Table 15.1. Key statistics of stratigraphic filters.

16 Summary, discussion and conclusions

In this study we have used data from seven exploration wells (excluding a side tracked well) from the Faroe-Shetland Channel, the Northeast Rockall Trough and two wells from the Faroe Islands to investigate the general log responses of basaltic rocks in the Faroe-Shetland Region, the variations of the log responses and how the bedding of basaltic rocks influences seismic signals.

16.1 Distinction between basaltic and non-basaltic rocks

The range of most logged properties in the basaltic rocks in the investigated wells is large and comparable to all other rock types present in the wells (e.g. Figure 16.1). However, the natural gamma radiation measured from basalts is generally lower (0-40 GAPI) than in many other rock types present in the wells, and each well is characterised by its own specific range of natural gamma radiation with a width of about 10-15 GAPI.

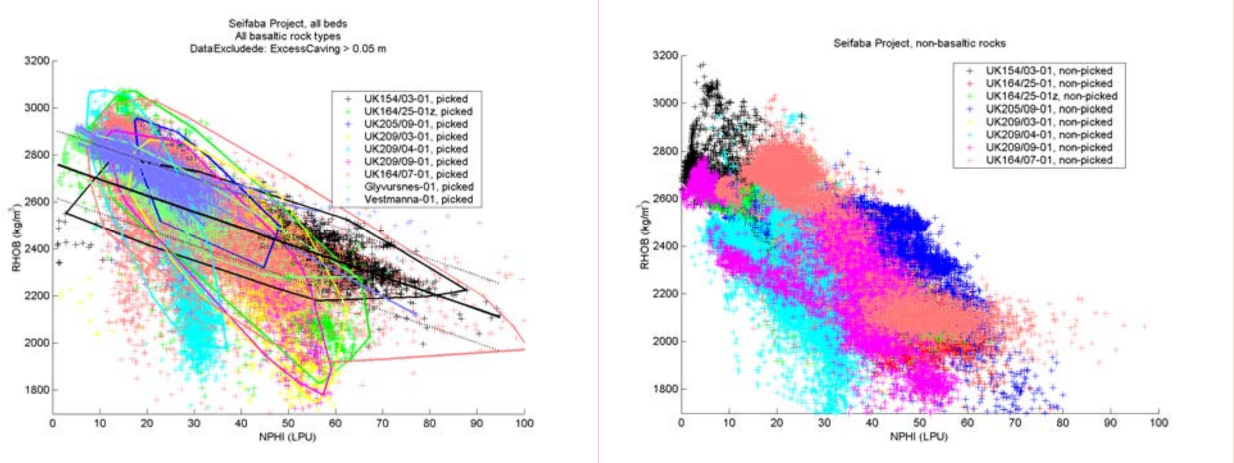

Figure 16.1. Cross plot of neutron porosity, NPHI, versus bulk density, RHOB. Left diagram: all basaltic units. Right diagram: all other data points.

In the individual wells measurements of bulk density and seismic velocity are fairly well suited to separate basaltic rocks from other rock types. Especially massive basaltic rocks characterised by neutron porosities below 30 LPU are generally well separated from other rock types by bulk density and seismic velocity (Figure 16.2; Figure 16.3).

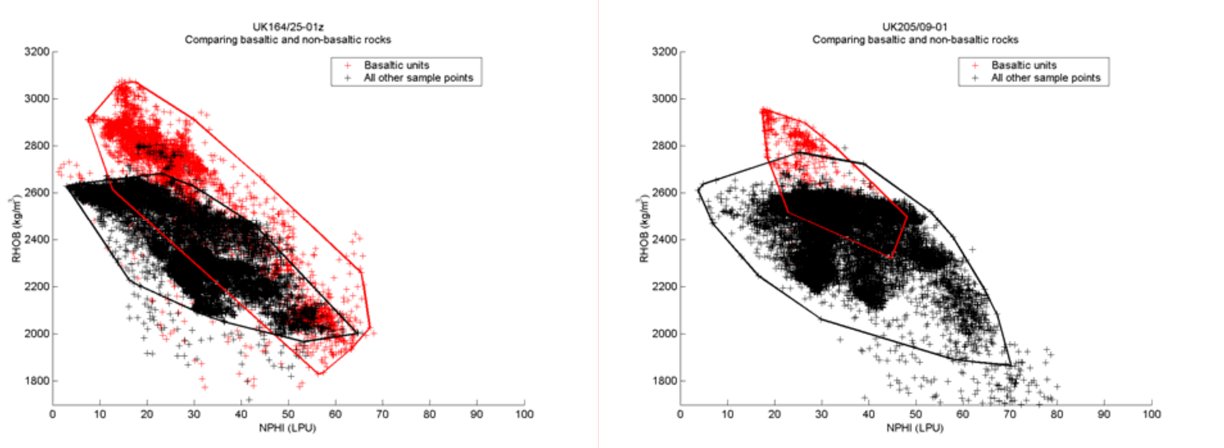

Figure 16.2: Cross plot of bulk density, RHOB, versus neutron porosity, NPHI, for data points from two wells (UK164/25-01z and UK205/09-01).

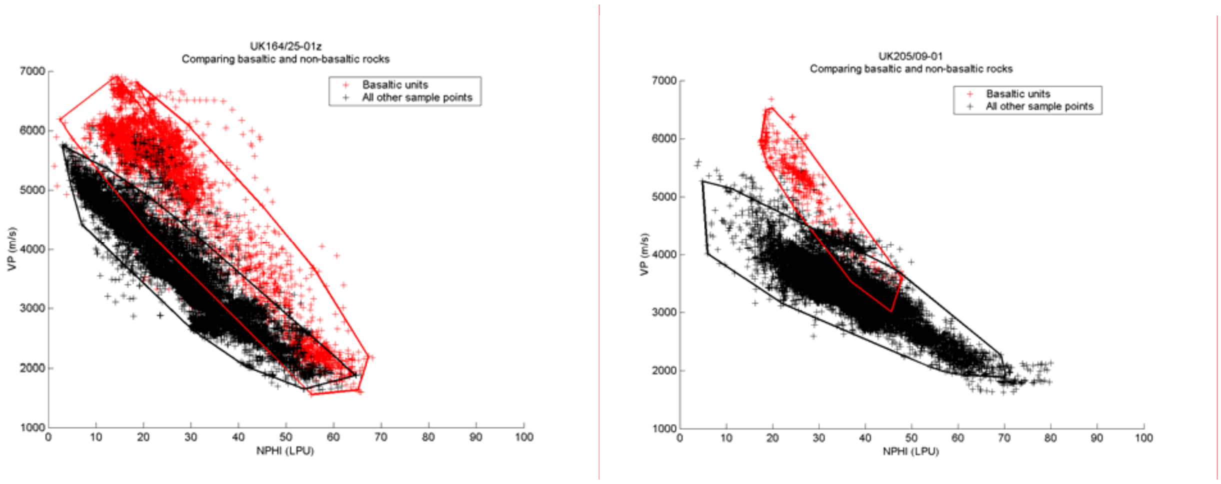

Figure 16.3. Cross plot of seismic velocity, VP, versus neutron porosity, NPHI, for data points from two wells (UK164/25-01z and UK205/09-01).

In some of the studied wells threshold values for neutron porosity, seismic velocity, bulk density and natural gamma radiation provide a fair distinction between, basaltic rocks and non-basaltic rocks (Chapter 8). However, individual basaltic units in all wells have been picked manually and classified as one of the following six types based on the overall log response:

- Low frequency lava beds
- High frequency lava beds
- Intrusives
- Volcaniclastic sediments
- Lava breccias
- Foreset breccias

16.2 Typical log responses of basaltic rock units

Alternative classifications of the log response from basaltic rocks may be suggested. In previous studies from the Northeast Atlantic focus has been on identification of individual flows and zonation of flows/lava beds (e.g. Planke et al. 1994; Delius et al. 1995). However, proper identifications of lava beds become increasingly difficult with decreasing thickness, and thin basaltic lava beds (high frequency lava beds) are generally characterised by a narrow range of seismic velocities compared to thick basaltic lava beds (low frequency lava beds). Comparison of log data and core descriptions from the Vestmanna-01 borehole indicates that many thin lava beds are not readily identified on the wireline logs (Chapter 12). The subdivision of lava beds into high and low frequency units therefore both simplify the interpretation and at the same time it focuses on seismic velocity contrast, which is an important seismic property. The rationale for the four other log response classes used in this report is likewise that interpretation is simple at the same time as we focus on seismic velocity contrast.

Examples of the six classes of log response from basaltic rocks are provided in chapters 5-13. But in order to clarify the discussion below "type sections" from these chapters are used to illustrate the six classes.

16.2.1 Low frequency lava beds

Generally low frequency lava beds are supposed to represent the effusive products of a single basaltic eruption. It comprises of three zones; a massive core and an upper and a lower crust, and is characterised by an asymmetrical response on the porosity related log traces (e.g. Planke 1994). The massive core is characterised by low values of neutron porosity and high values of bulk density, seismic velocities and resistivities. The upper and lower crust are characterised by higher neutron porosities (Figure 16.4) and lower values of bulk density, seismic velocities and resistivities. The upper crust may be subdivided into an upper part with constant low porosity and a lower part with gradually decreasing porosity. Absolute values of the measured parameters within each zone of a low frequency lava bed unit vary from well to well and bed to bed (see examples in chapters 5-13).

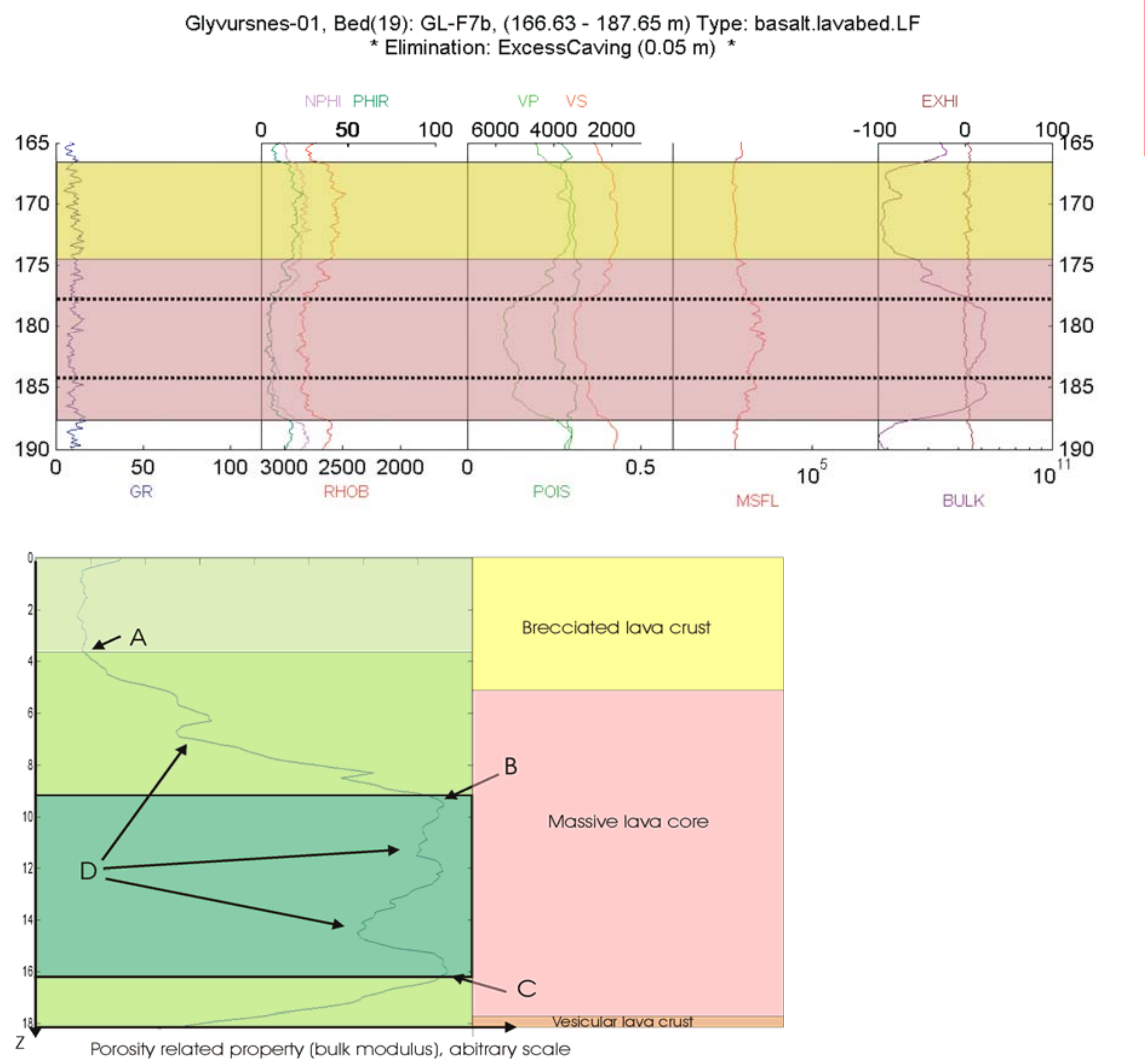

Figure 16.4. Top: "Type section" of low frequency lava bed GL-F7b (also presented as Figure 13.3). Upper part show all traces through this unit. Lower left, log response (bulk modulus). Lower right, core description: Z is depth from the top of the lava bed. The lava bed comprises an upper crust (from the top down to B) with high porosity decreasing downwards, a massive core (from B to C) with low fairly constant porosity and a lower crust (from C to the base) with downward increasing porosity. The upper crust may be subdivided into an upper part (from the top to A) with constant and high neutron porosity, and a lower part with more or less monotonously decreasing porosity. The upper low porosity part of the upper crust is not present in all low frequency lava beds. The local deviations, D, is assumed to represent zones with local concentration of vesicles. All porosity related properties are characterised by similar trends - but they are not completely correlated.

In the type section (Figure 16.4), which is from the Glyvursnes-01 well, there is a fair correlation between core description and log response, although the massive core interpreted from the logs is considerably thinner than described from the core. However, based on the data from Vestmanna-01 and Glyvursnes-01 (chapters 12 and 13), it is wrong to assume that log responses of low frequency lava bed units can be “translated” directly into lava morphological descriptions.

16.2.2 High frequency lava beds

High frequency lava beds are supposed to represent a number of thin flow units. On all log traces for porosity related properties they are characterised by oscillations with a shorter dominant wavelength than the low frequency lava beds (typically less than 5 m). In addition the amplitude of the oscillations is generally smaller than in the low frequency lava beds. This is demonstrated for P-wave seismic velocity in Figure 16.5 (chapter 12).

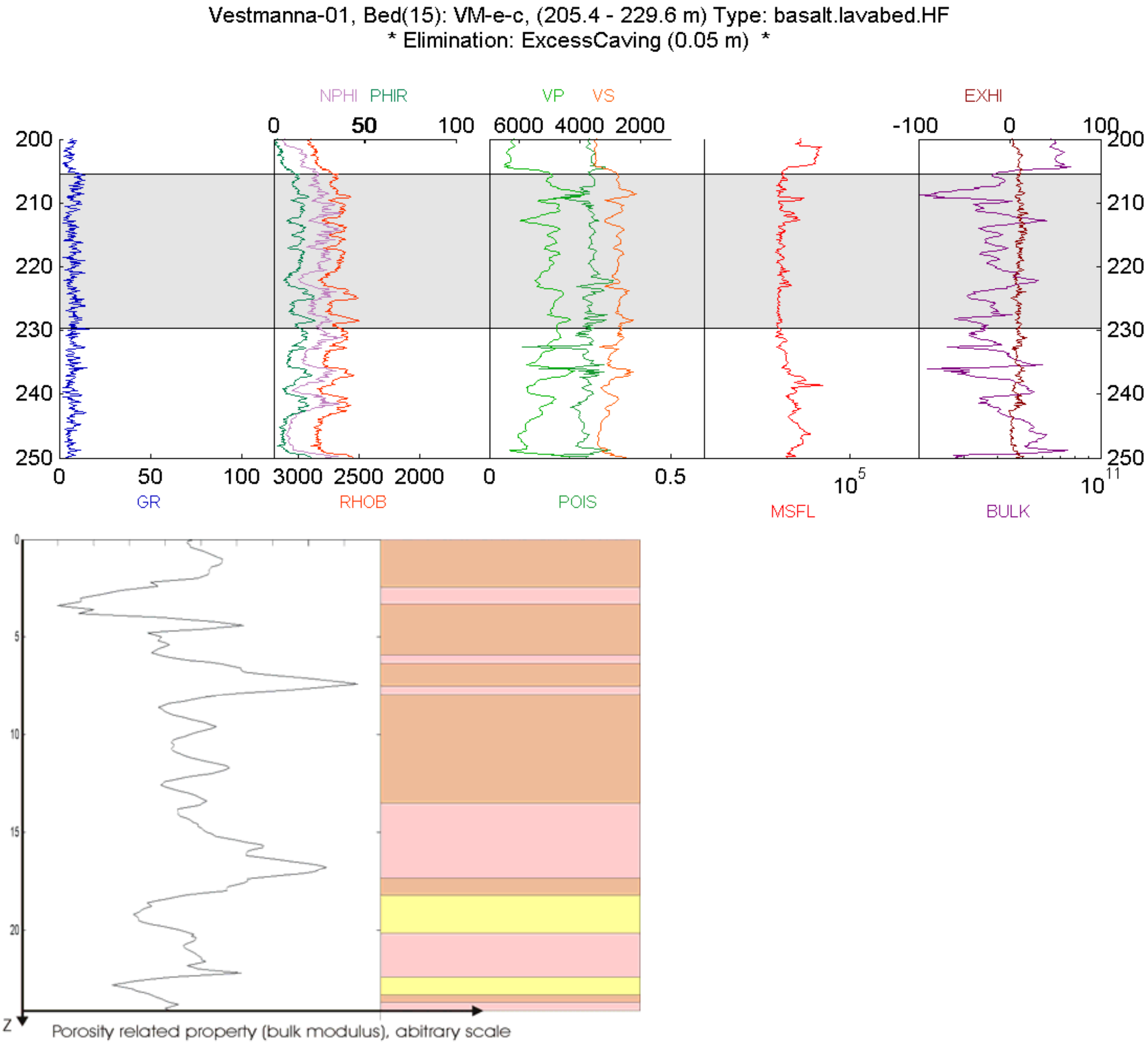

Figure 16.5. “Type section” of high frequency lava bed (VM-e-c; also presented as Figure 12.6). Upper part show all traces through this unit. Lower left: log response (bulk modulus). Z is depth from the top of the lava bed Lower right: simplified core description, pink is lava cores, orange is lava crusts and yellow is breccias. The two thick lava cores in the bottom part of the unit are fairly well correlated with local extremes of the bulk modulus. But the thin lava cores are not well correlated with local extremes. This reflects the vertical resolution of the tools used (in this case density and seismic velocity).

The thickest lava beds within units of high frequency lava beds may be identified on the log traces. Comparison of log traces and the core description from Glyvursnes-01 and Vestmanna-01 indicates that many lava beds are too thin to be identified on the logs.

Due to the thin layering in high frequency lava bed units, it is expected that thin sediment layers may be present in these units without being identified as such, unless they have distinctly higher natural gamma radiation than the basaltic rocks in the units.

16.2.3 Intrusives

Basaltic intrusives are present in several of the investigated wells. Seismic traces through a typical intrusive are shown as Figure 16.6. The overall symmetry of the log responses is characteristic. When the intrusive is emplaced in shaley sediments, it is characterised by a sharp decrease of natural gamma radiation across the boundaries, and the GR-trace is apparently well correlated with the porosity related traces. Contact metamorphic reactions are frequently indicated by a gradual increase towards the boundary of porosity related parameters in the wall rock.

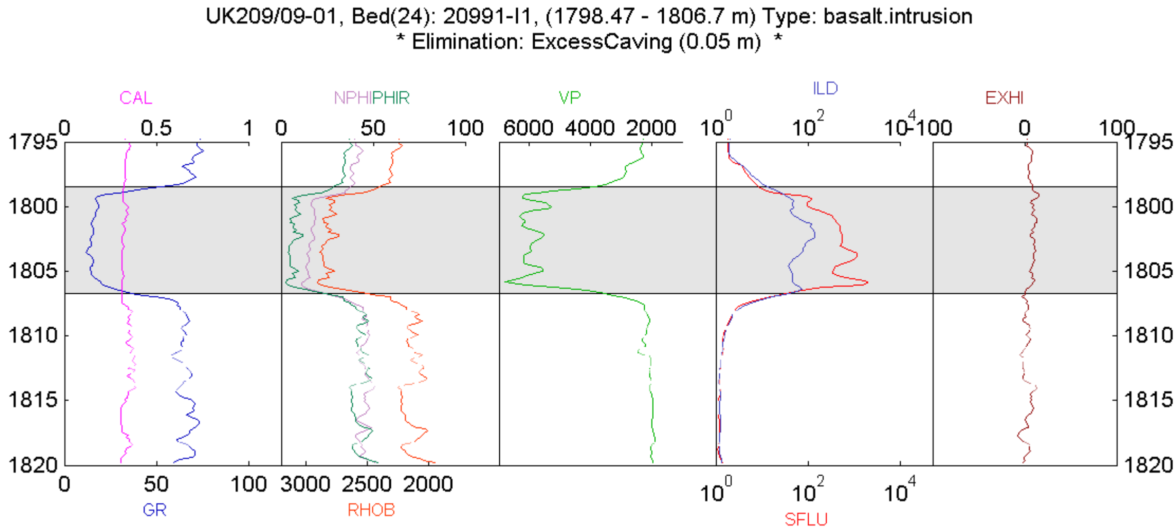

Figure 16.6. Typical log response of intrusive (20991-I1; also presented as Figure 11.9. Log traces from depth interval 1795-1820 m in well UK209/09-01 showing unit 20991-I1.) from UK209/09-01. See text for discussion.

16.2.4 Volcaniclastic sediments

Volcaniclastic sediments are found in most wells and are characterised by high neutron porosities (generally above 40 LPU, frequently exceeding 50 LPU). High neutron porosity is not on it own sufficient to identify volcaniclastic sediment intercalations. Seismic velocity, bulk density and resistivity measurements are low and seismic velocity fluctuations are generally less than in other basaltic units (Figure 16.7; Figure 16.8; Figure 16.9). In most aspects the volcaniclastic sediments are comparable to shaley sediments above and below the volcanic successions in the wells. However, the natural gamma radiation is lower, generally of the same magnitude as units of basaltic lava beds in the respective wells (Figure 16.7).

A slightly increased natural gamma radiation may be observed in some units of volcaniclastic sediment (Figure 16.8), which may be an indication that radioactive material (presumably potassium) are mixed into the sediment. When the deflection of the GR-trace at the top and bottom of volcaniclastic units is sharp as in Figure 16.8, this may indicate lateral transport and mixing volcanic and siliciclastic material. Gradually changing natural gamma radiation within volcaniclastic sediment units may also occur. Unit 16471-VS II, which is the lowest unit in the basaltic succession in UK164/07-01, is a good example of this (Figure 16.9). Several sidewall cores have been sampled in this interval, and the upward decreasing gamma radiation is apparently associated with increasing abundance of basaltic material in the sediment and not reflecting a sediment succession coarsening upwards. Fairly constant values of all porosity related logs in this interval support this interpretation.

Intercalations of sediments in the volcanic successions penetrated in boreholes are generally - but not always - recognised based on descriptions of cuttings and side wall cores. Some intervals, with cuttings and/or sidewall cores described as basalts (lava beds) have a log response, which are characteristics of sediments. For such interval it is suggested to rely on the log response.

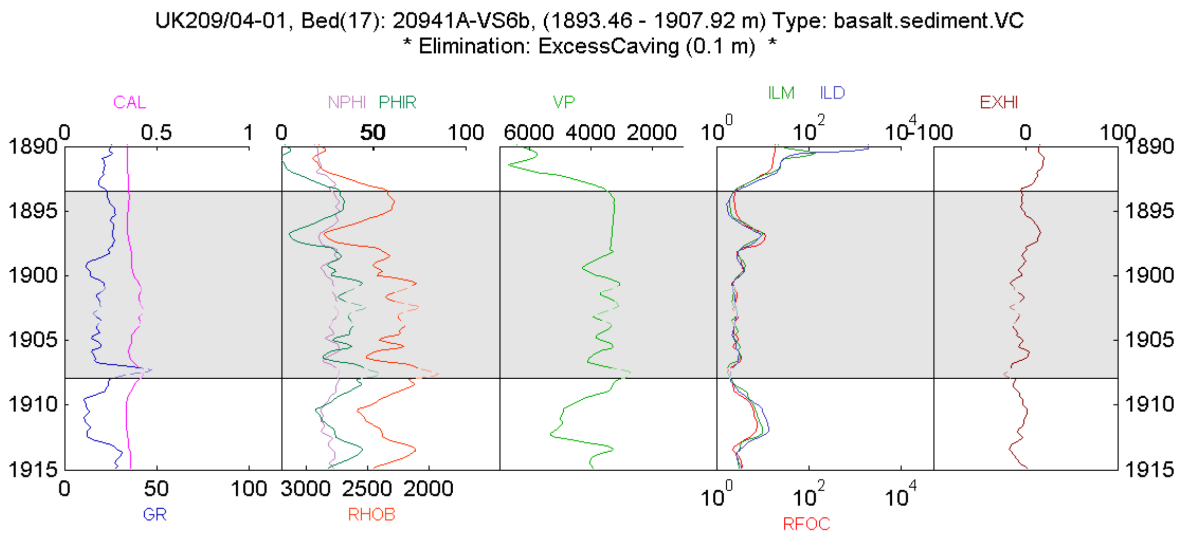

Figure 16.7. Unit of volcaniclastic sediment (unit 20941A-VS6b from UK209/04-01). Note stable low seismic velocity and resistivity.

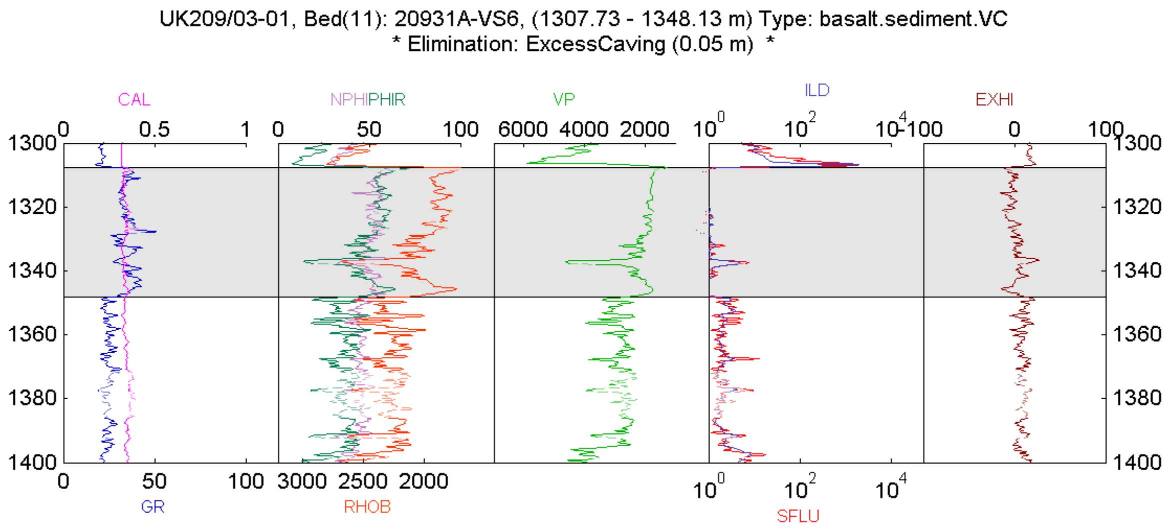

Figure 16.8. Unit of volcaniclastic sediment (unit 20931A-VS6 from UK209/03-01). Note increased gamma radiation in this unit, which help highlighting the lower boundary towards a unit of high frequency lava beds.

Volcaniclastic sediments are present in variable amounts in all wells. In the two Faroes wells, which are located close to the incipient spreading axis of the Northeast Atlantic and the presumed effusive vents, sediments are scarce and constitute less than 5 %. In the three wells around the Erlend igneous centre the amount of volcaniclastic sediments is 3 % in UK209/09-01 and 7 % in UK209/03-01 close to the centre and ca. 75 % in UK209/04-01 further away from the centre. In all of the three wells in Northeast Rockall Trough there is considerable amount of sediments within the volcanic successions. In UK164/07-01 there is estimated to be ca. 40 % volcaniclastic sediments in the volcanic succession. In UK164/25-01 there are ca. 47 % sediments. Of these ca. 30 % are characterised as siliciclastic sediments and 17 % as volcaniclastic. In UK154/03-01 there is interpreted to be ca 15 % of sediments in the succession most of these are volcaniclastic.

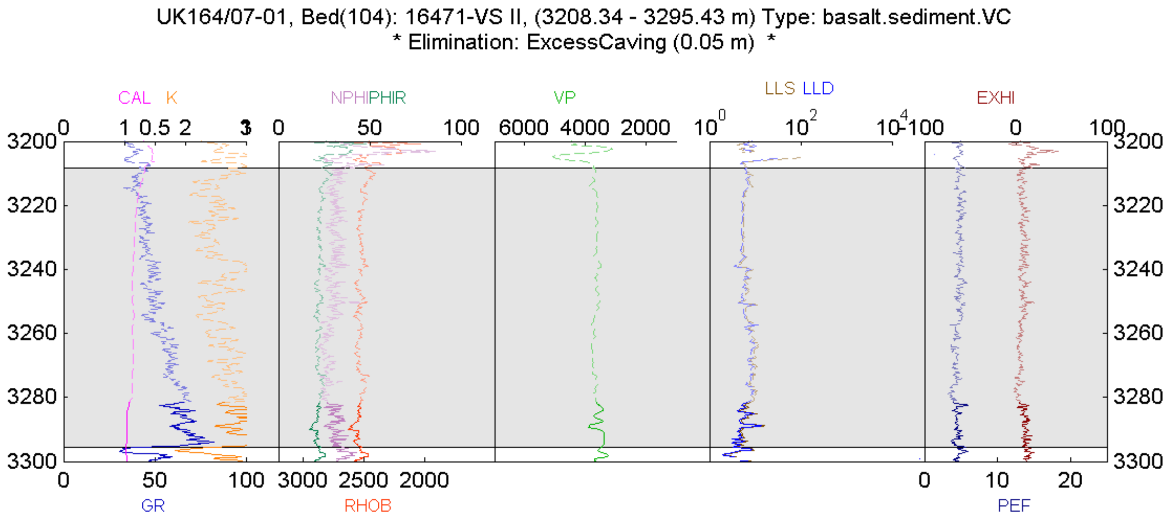

Figure 16.9. Log traces from depth interval 3200-3300 m in well UK164/07-01 showing unit 16471-VS II.

Lava breccias

This class are only used in the description of UK164/25-01 and UK164/25-01z, and are used to refer to two units with a log response somewhere between typical volcaniclastic sediments and high frequency lava beds (Figure 16.10; Chapter 7). In these two wells the use of this class helped highlighting stratigraphic correlation between the wells (enclosure 5).

16.2.5 Foreset breccias

This class is only observed in one well (UK154/03-01; chapter 5). In this well the mean seismic velocity of foreset breccias are comparable to that of high frequency lava beds. However, the fluctuations of the seismic velocity are fairly small compared to those seen in high frequency lava beds (Figure 16.11; Table 16.1). The resistivities measured (shallow and deep penetration laterologs) in the basaltic foreset breccias in UK154/03-01 is low ($R < 100\ \Omega m$). In this well high spikes on the deep penetration laterolog ($R>100\ \Omega m$) appear to be associated with massive basalt, and very few high resistivity spikes are seen in the foreset breccias indicating that large massive lava fragments in the foreset breccias are rare (Figure 16.11).

Table 16.1. Seismic velocity in high frequency lava beds and foreset breccias from well UK154/03-01. Column headings: N is total number of samples; N* is samples not rejected due to excessive caving; Mean, Median and Std. are aritmetric average, median and standard deviation around average (in m/s).

Well	N	N*	Mean	Median	Std.	Min.	Max.
High frequency lava bed	1368	1368	3875.2	3878.3	799.4	2265.3	5442.4

Foreset breccia	2914	2708	3719.1	3710.7	301.8	3010.2	5092.5

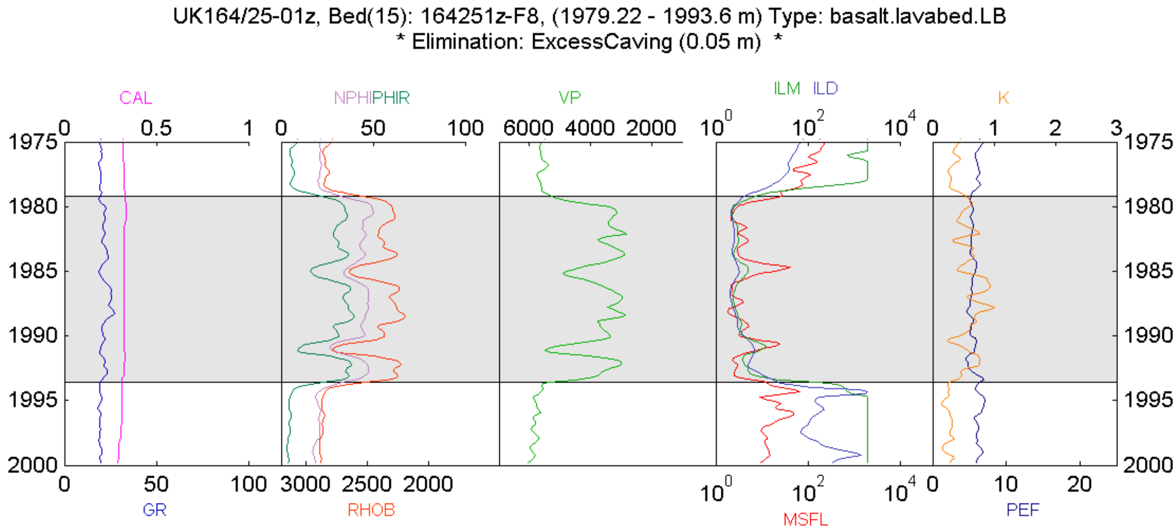

Figure 16.10. Log traces from depth interval 1975-2000 m in well UK164/25-01z showing unit 164251z-F8

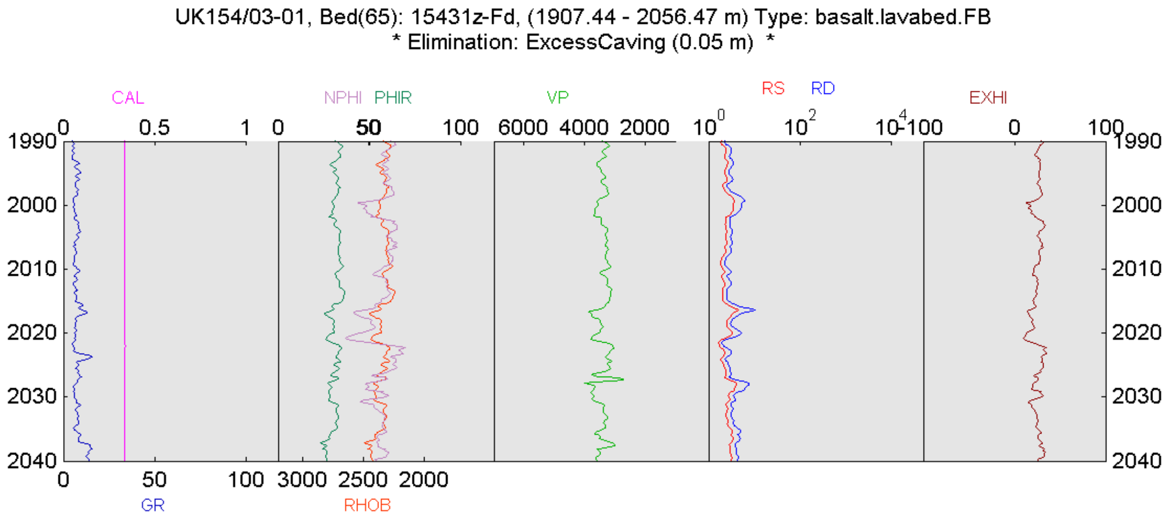

Figure 16.11. Log traces from depth interval 1990-2040 m in well UK154/03-01 showing part a foreset breccia, unit 15431z-Fd.

16.3 Primary composition, mineralogy and texture

It is well known that the primary composition, mineralogy and texture of basaltic rocks not are unique. However, all basalts are characterised by a chemical and mineralogical composition, which are distinct from siliciclastic sediments, and the data base of physical parameters of basalts is small compared to that of siliciclastic sediments. This and previous studies thus tend to consider basalts as a homogeneous petrophysical group characterised by a unique set of physical properties for the matrix, which in the individual samples are modified by the content and configuration of pores (vesicles) and the properties of the pore fluid (e.g. Planke 1994; Delius et al. 1995).

Although this approach currently is the only realistic approach in many practical applications, it is not quite correct.

Several examples of individual lava beds characterised by a natural gamma radiation different from the gamma radiation level for the majority of the lava beds are observed in this study. These lava beds are generally characterised by trends for the porosity dependent parameters that deviate from the general trend (e.g. the C-horizon in Glyvursnes-01; Figure 13.12; Figure 13.15; Figure 13.18) indicating that other matrix properties (e.g. seismic velocity and density) of the C-horizon also is different from those of the majority of the basalts in Glyvursnes-01. No general relations have been found between the level of natural gamma radiation from basalts and other matrix properties.

In the Glyvursnes-01 well some of the tentative stratigraphic units used in this study are characterised by upward increase in phenocryst size and decrease in phenocryst abundance (chapter13). It is suggested that these stratigraphic units may represent series of lavas which upwards become more and more fractionated. Within these units the trends between seismic velocity and neutron porosity changes with depth into the unit (Figure 16.12). Similar observations are also made for density and resistivity in relation to neutron porosity. Whether the change is associated with mineralogical/compositional or textural changes are not known. But the observation indicates that primary mineralogical/compositional or textural differences contribute significantly to the variability of porosity related properties of basalts.

In all the investigated wells it can be observed when neutron porosity is plotted against seismic velocity that data points for different lava bed units frequently define distinct trends which are different from the trend of other lava bed units (this may be studied in detail in the digital synopsis: Synopsis\SeiFaBa-Task3-data-documentation.html). In view of the discussion immediately above it is considered likely that primary mineralogical/compositional or textural differences are one of the main reasons for the different trends observed for different lava beds.

16.4 Alteration

The basaltic rocks in the Faroe-Shetland area are all re-crystallised (e.g. Waagstein & Hald 1984). Although logs through fresh basalts not have been available for comparison, some effects of alteration are believed to be observed in the investigated data.

16.4.1 Pre-burial alteration

A characteristic upwards increase of the natural gamma radiation is seen below the top of many lava beds from most, but not all, of the investigated wells (e.g. UK164/07-01 Figure 6.9) In a few wells, where spectral gamma tools were used, it is seen that this signature mainly is caused by changing potassium content. As it has been observed that the potassium and rubidium content increases in the upper part of the soil profile when basalts are weathered (e.g. Sheldon 2003) it is suggested that the natural gamma radiation response described above is an indications of pre-burial alteration.

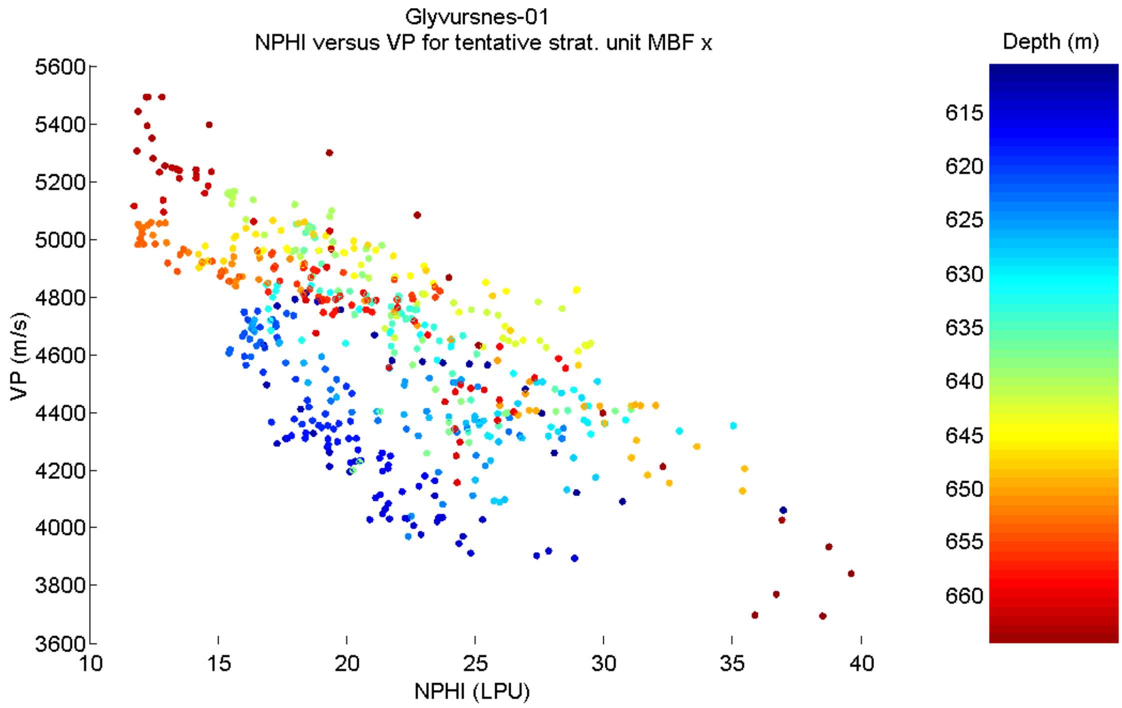

Figure 16.12. Cross plot of seismic velocity, VP, versus neutron porosity, NPHI, for data points from the tentative stratigraphic unit, MBF x, in the Glyvursnes-01 well. Data points are colour coded to the depth in the well. Note that different trends are defined by data points from different depth intervals in the well.

16.4.2 Burial effects

A few examples of possible burial effects are seen in the individual wells. The most obvious example is found in UK209/03-01, where density and seismic velocity increase with depth (Figure 16.13 and Figure 16.14). However, as mentioned above similar trends could be caused by fractionation in the magma responsible for the basaltic rocks found in the well (Chapter 13). If we plot velocity or density against depth for all investigated wells a crude correlation is seen between depth and both density and seismic velocity for all data points from the offshore exploration wells (Figure 16.13 and Figure 16.14). It is realistic to assume that no significant erosion occurred in the Eocene-Recent (e.g. Andersen et al. 2002; Sørensen 2004). The depth related changes in bulk density and seismic velocity is closely related to reduction of pore space with depth.

The trends in Figure 16.15 and Figure 16.16 are therefore interpreted as general z-VP and z-RHOB burial trends for the Faroe-Shetland Region. When the precise composition and texture is unknown (or the relationship between burial depth and composition and texture is unknown), as generally is the case, these trends may be used to calculate a crude estimate of maximum burial for successions of basaltic lava beds from this region that previously have been buried below a succession of rocks that now are removed. The two burial functions,

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

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

are provisional. Additional data in all depth ranges are needed to verify and possibly refine the functions. Foreset breccias have lower bulk densities and seismic velocities than lava beds at the same depth (Figure 16.15 and Figure 16.16). The burial functions should therefore not be used to estimate the maximum burial depth for foreset breccias (or any other rocks that not are basaltic lava beds).

Using the two burial formulas the maximum burial depth has been calculated of the basaltic succession in Glyvursnes-01 and Vestmanna-01 using bulk density and seismic velocity data from depths below 200 m.

For the Vestmanna-01 the calculated burial depths are 2534 m using seismic velocity data and 2656 m using bulk density data. These numbers are slightly higher than the denudation in the Vestmanna area estimated from structural reconstruction (ca. 2000m Andersen et al. 2002).

For the Glyvursnes-01 the calculated burial depths are 1527 m using seismic velocity data and 2333 m using bulk density data. The depth obtained using seismic velocity data are comparable with the denudation estimated in the Glyvursnes area by Andersen et al. (2002), ca. 1500 m.

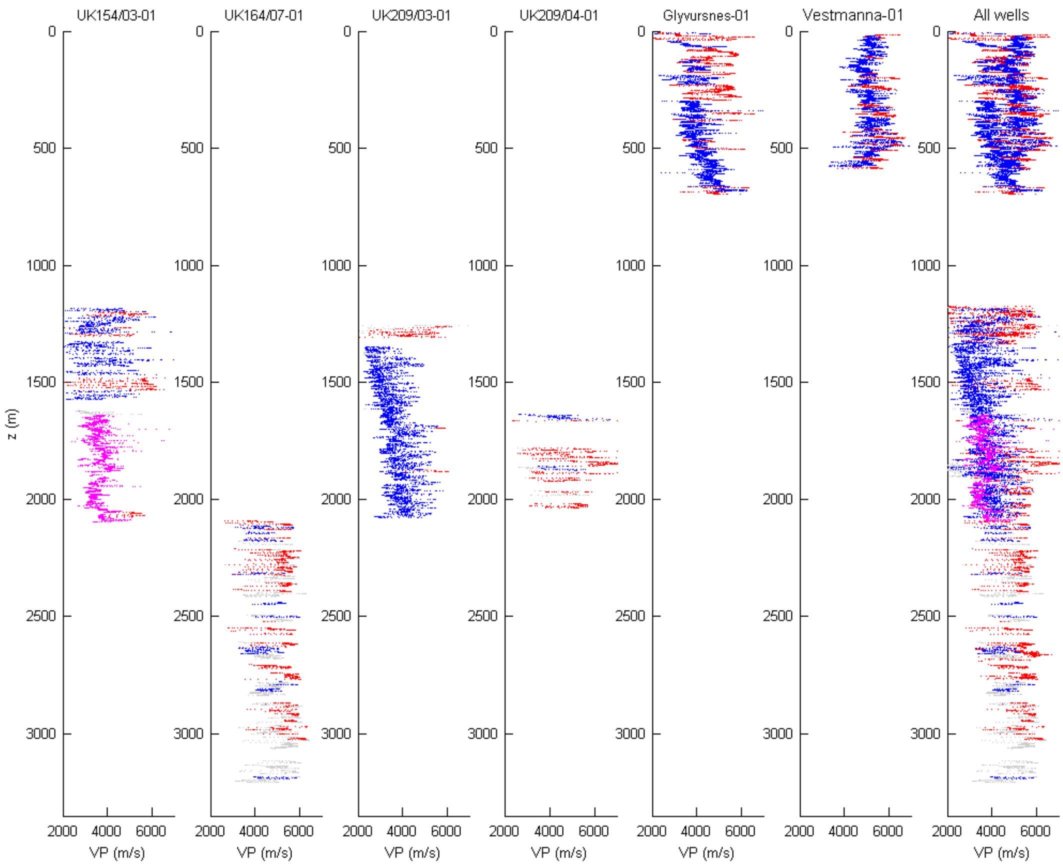

Figure 16.13. Seismic velocity, VP, versus depth, z, for exploration wells from the Faroe-Shetland region. Colour coding according to well and lithology. Sample points with caving in excess of 5 cm are plotted with grey colour and are not used in calculating the trend line: z = (VP-2499 m/s) · 1.06 s.

Although the burial estimates calculated using well data from Vestmanna-01 is in fair agreement with the independent estimate by Andersen et al. (2002), the estimates should not be considered accurate. The results from Glyvursnes-01 indicate we should consider an error margin of ca. 500 m. To improve the burial estimates obtained from well data, good knowledge of the composition of the succession in question and a function relating seismic velocity or bulk density to burial depth for that specific composition is needed. In addition we may also have to take the texture of the rocks into consideration.

Another property of the investigated basaltic rocks which apparently are influenced by burial is the DC component of dissipation, Q_{DC}, due to stratigraphic filtering (Figure 15.10). This is presumably a concequence of an overall reduction of the seismic velocity range with depth, which may be related to the simple fact that porous rocks are more succeptible to ireversible compaction than massive rocks. However, the frequency dependence term of dissipation, Q, of the liniar approximation of dissipation is apparently independent of depth. This may reflect that this term is a function of tuning of reverberations within the basaltic succession and thus of the dominant period of the internal bedding, which not is expected to change significantly during burial.

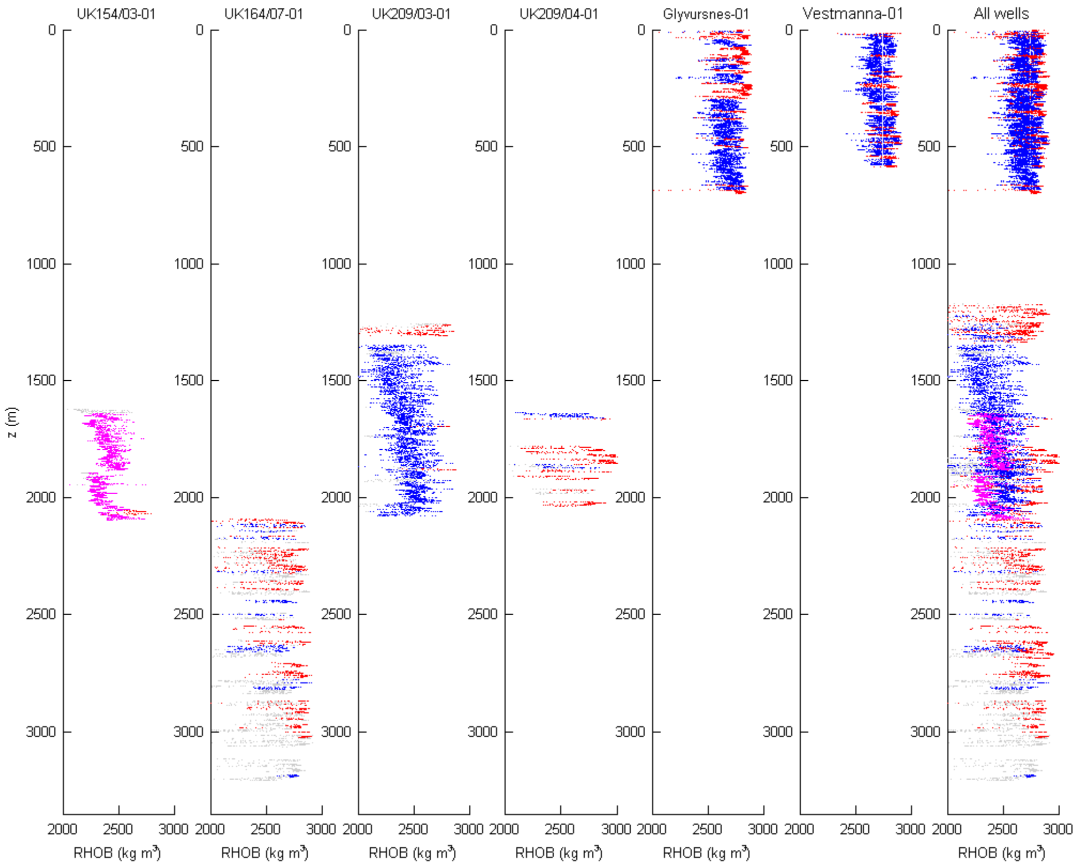

Figure 16.14. Bulk density, RHOB, versus depth, z, for exploration wells from the Faroe-Shetland region. Colour coding according to well and lithology. Sample points with caving in excess of 5 cm are plotted with grey colour and are not used in calculating the trend line: z = (RHOB-2159 kg/m^3) · 5.23 m^4/kg.

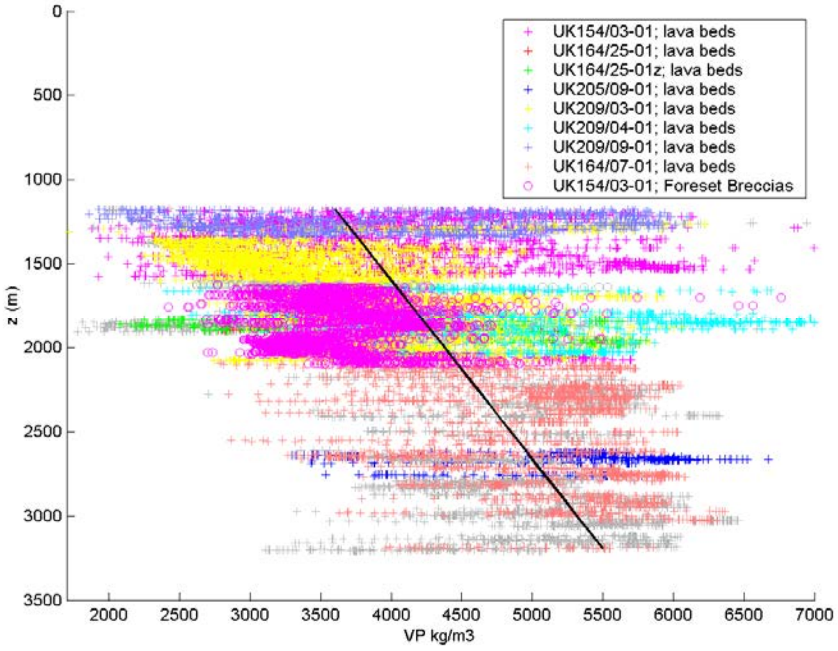

Figure 16.15. Seismic velocity, VP, versus depth, z, for exploration wells from the Faroe-Shetland region. Colour coding according to well and lithology. Sample points with caving in excess of 5 cm are plotted with grey colour and are not used in calculating the trend line: z = (VP-2499 m/s) · 1.06 s.

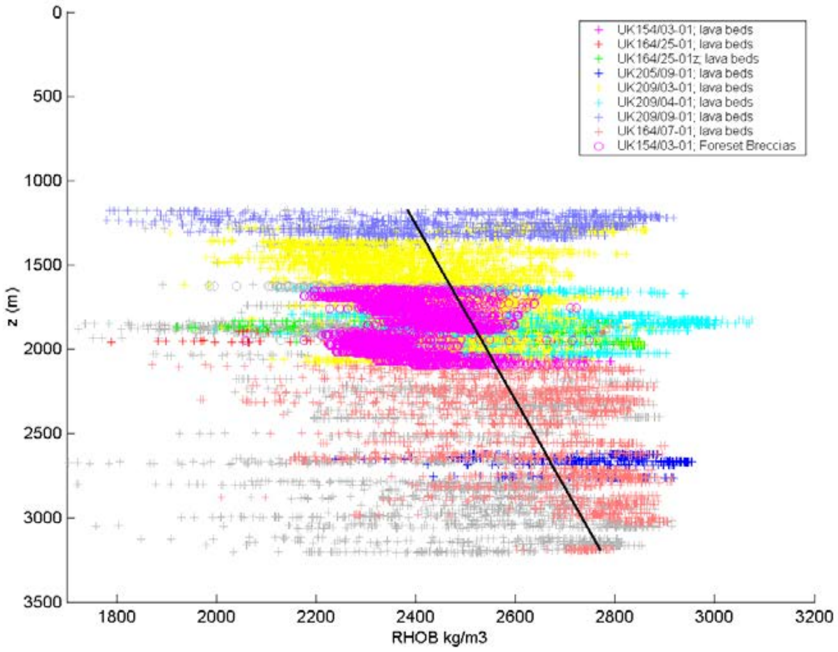

Figure 16.16. Bulk density, RHOB, versus depth, z, for exploration wells from the Faroe-Shetland region. Colour coding according to well and lithology. Sample points with caving in excess of 5 cm are plotted with grey colour and are not used in calculating the trend line: z = (RHOB-2159 kg/m^3) · 5.23 m^4/kg.

16.5 Calibrations

Although most of the observed variation of the logged properties of basalts may be explained by primary distribution of the properties and secondary changes due to alteration we should be aware that different instrument calibration may influence some properties. This may for instance be part of the explanation for the different levels of gamma radiation seen in the individual wells. We have also seen that other logged properties (NPHI and possibly RHOB) in at least one well (UK209/03-01) not appear to be well calibrated (chapter 9).

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