P-13-22

Äspö Hard Rock Laboratory

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ISSN 1651-4416
SKB P-13-22
ID 1332743

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Keywords: Borehole, Logging, Geophysics, Geology, Bedrock, Fractures.

Abstract

This report presents the compilation and interpretation of geophysical logging data from the cored boreholes KA2051A01, KA3007A01 and KJ0050F01 and petrophysical measurements on rock samples from the borehole KA2051A01.

The main objective of the investigation was to use the results as supportive information during the Boremap geological core mapping and as supportive information during the geological single-hole interpretation.

The quality control shows that the natural gamma radiation data in all three boreholes significantly exceeds the recommended noise level of 0.3 µR/h, which affects the interpretation, especially the response from small rock bodies such as dykes. There are also quality problems with the normal and lateral resistivity logs. The data display inverted anomalies across fractures which are physical unrrealistic; hence these data were not used in the fracture frequency estimation.

The interpretation of KA2051A01 indicates that the sections 10–120 m and 225–285 m are mainly governed by Äspö diorite with occurrences of dioritoid-gabbroid rocks in the upper section. Along the section 120–225 m the data indicate a dominant occurrence of Ävrö granite to granodiorite and in the lowermost part of the borehole there is a c 35 m long interval of fine-grained granite. The estimated fracture frequency is generally decreased or moderate. Possible deformation zones are indicated along the sections c 12–14 m, 73–77 m, 130–137 m and 173–176 m. These possible zones are mainly characterized by decreased resistivity and P-wave velocity.

The interpretation of KA3007A01 indicates a very inhomogeneous distribution of Äspö diorite, Ävrö granite to granodiorite and fine-grained granite along short intervals of the borehole. This is mainly shown by the large variations of the silicate density. The estimated fracture frequency is generally decreased or moderate. Possible deformation zones are indicated along the sections c 12–14 m, 73–77 m, 130–137 m and 173–176 m. Along the sections 130–137 m and 173–176 m there are also significant anomalies in the vertical fluid temperature gradient, which indicates the occurrence of water bearing fractures.

The interpretation of KJ0050F01 indicates a dominant occurrence of Äspö diorite, but there are also two short sections with indicated Ävrö granite to granodiorite. The fracture frequency estimation indicates no possible deformation zones in the rock along this borehole.

Sammanfattning

Föreliggande rapport presenterar resultat och tolkningar av geofysiska borrhålsmätningar i kärnborrhålen KA2051A01, KA3007A01 och KJ0050F01 samt petrofysiska mätningar på borrkärnebitar från borrhålet KA2051A01.

Syftet med undersökningen är framförallt att ta fram ett material som på ett förenklat sätt åskådliggör resultaten av de geofysiska loggningarna, s.k. generaliserade geofysiska loggar. Materialet används främst som underlag vid Boremapkarteringen liksom vid den geologiska enhålstolkningen.

Kvalitetskontrollen av data visar att den naturliga gammastrålningen har mycket hög brusnivå i alla tre borrhålen. Detta påverkar tolkningen negativt, främst med avseende på möjligheten att identifiera anomalier från mindre bergartsenheter, t.ex. gångar. Det är också uppenbara felaktigheter i data från mätningar med sonderna lateral och normal resistivitet. Anomalier över sprickzoner är inverterade och indikerar förhöjd resistivitet, vilket är fysikaliskt orimligt. Dessa data användes därför inte vid beräkningen av sprickfrekvens.

Tolkningen av data från KA2051A01 indikerar att sektionerna ca 10–120 m och 225–285 m domineras av Äspödiorit med viss förekomst av dioritoid-gabbroid bergarter i den övre sektionen. Längs intervallet ca 120–225 m förekommer i huvudsak Ävrö granit-granodiorit och längs ner i borrhålet indikerar geofysikloggarna förekomst av en ca 35 m lång sektion med finkornig granit. Den uppskattade sprickfrekvensen är generellt låg eller moderat, men data indikerar förekomst av möjliga deformationszoner längs intervallen ca 12–14 m, 73–77 m, 130–137 m och 173–176 m. De möjliga zonerna karaktäriseras i första hand av sänkt resistivitet och sänkt P-vågshastighet.

Tolkningen av data från KA3007A01 indikerar en väldigt inhomogen fördelning av Äspödiorit, Ävrö granit-granodiorit och finkornig granit längs hela borrhålslängden. Tolkningen baseras i huvudsak på de stora variationer i silikatdensitet som förekommer. Den uppskattade sprickfrekvensen är generellt låg eller moderat, men data indikerar förekomst av möjliga deformationszoner längs intervallen ca 12–14 m, 73–77 m, 130–137 m och 173–176 m. Längs sektionerna ca 130–137 m och 173–176 m förekommer också kraftiga anomalier i den vertikala temperaturgradienten vilket tyder på förekomst av vattenförande sprickor.

Tolkningen av data från KJ0050F01 indikerar att Äspödiorit dominerar bergartsfördelningen längs borrhålet. Det förekommer dock två kortare sektioner med indikerad Ävrö granit-granodiorit. Den beräknade sprickfrekvensen indikerar att det inte förekommer några signifikanta deformationszoner i berget längs borrhålet.

Contents

1 Introduction

This document reports the interpretations of geophysical borehole measurements and petrophysical data gained from the cored boreholes KA2051A01, KA3007A01 and KJ0050F01, which is one of the activities performed within the work of the expansion of Äspö HRL (Figure 1-1). The work was carried out in accordance with activity plan AP TD TUDP002-11-023. In Table 1-1 controlling documents for performing this activity are listed. Activity plans and method descriptions are SKB's internal controlling documents.

Generalized geophysical loggings related to lithological variations are presented together with indicated fracture loggings, including estimated fracture frequency. The logging measurements were conducted by Ramböll (Nielsen and Ringgaard 2013).

The interpretation presented in this report is performed by GeoVista AB in accordance with the instructions and guidelines from SKB and under supervision of Leif Stenberg, SKB.

The data and interpretation products are stored in the database Sicada and are traceable by the activity plan numbers.

Table 1-1. Controlling documents for the performance of the activity.

Activity plan	Number	Version
Äspö utbyggnad, DP1- Karakterisering-Tolkning av loggade geofysiska data samt petrofysiska data från KA2051A01, KA3007A01 samt BH3.	AP TD TUDP002-11-023	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för tolkning av geofysiska borrhålsdata	SKB MD 221.003	3.0

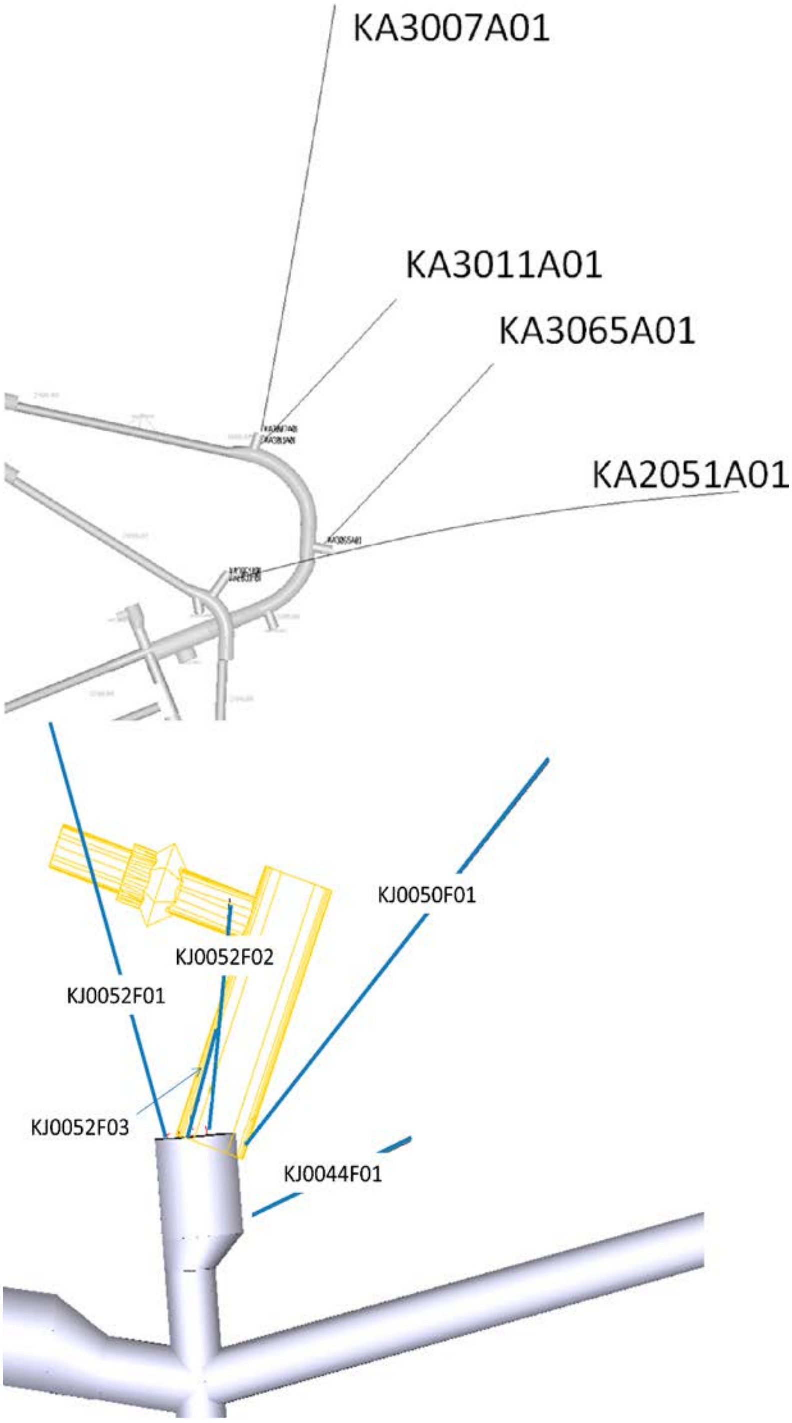

Figure 1-1. *General overview over Äspö showing the locations of the investigated boreholes KA2051A01, KA3007A01 and KJ0050F01.*

2 Objective and scope

The purpose of geophysical measurements in boreholes is to gain knowledge of the physical properties of the bedrock in the vicinity of the borehole. A combined interpretation of the lithological logging data, silicate density, magnetic susceptibility and natural gamma radiation, together with petrophysical data makes it possible to estimate the physical signature of different rock types. The three loggings are generalized and are then presented in a simplified way. The location of major fractures and an estimation of the fracture frequency along the borehole are calculated by interpreting data from the resistivity, sonic and caliper loggings.

The main objective of these investigations is to use the results as supportive information during the geological core mappings and as supportive information during the so called geological single-hole interpretation, which is a combined borehole interpretation of core logging (Boremap) data, geophysical data and radar data.

3 Equipment

3.1 Description of interpretation tools for analyses of logging data

The software used for the interpretation are WellCAD v4.0 (ALT) and Strater 1.00.24 (Golden Software), that are mainly used for plotting, Grapher v7 (Golden Software), mainly used for plotting and some statistical analyses, and a number of in-house software developed by GeoVista AB on behalf of SKB.

4 Execution

4.1 Interpretation of logging data in general

The execution of the interpretation can be summarized in the following four steps:

1. Preparations of the logging data (calculations of noise levels, median filtering, error estimations, re-sampling, drift correction, length adjustment). The length adjustment procedure was specifically important since no such processing have previously been performed on the data. The length adjustment was performed in WellCAD with reference to the geological Boremap data.

The loggings are median or mean filtered (generally 5 point filters for the resistivity loggings and 3 point filters for other loggings) and re-sampled to common lenght co-ordinates (0.1 m point distance).

The density and magnetic susceptibility logging data are generally calibrated with respect to petrophysical data from samples from the drill core. For this investigation the density and susceptibility data of all three boreholes were calibrated with respect to measurements on core samples from KA2051A01.

2. Interpretation of rock types (generalization of the silicate density, magnetic susceptibility and natural gamma radiation loggings).

The silicate density is calculated with reference to Henkel (1991) and the data are then divided into 5 sections *indicating* a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to Puranen (1989). The sections are bounded by the threshold values.

granite < 2,680 kg/m^3
2,680 kg/m^3 < granodiorite < 2,730 kg/m^3
2,730 kg/m^3 < tonalite < 2,800 kg/m^3
2,800 kg/m^3 < diorite < 2,890 kg/m^3
2,890 kg/m^3 < gabbro.

The magnetic susceptibility logging is subdivided into steps of decades and the natural gamma radiation is divided into steps of "low" (< 10 μR/h), "medium" (10 μR/h < gamma < 20 μR/h), "high" (20 μR/h < gamma < 30 μR/h) and "very high" (> 30 μR/h).

3. Interpretation of the position of large fractures and estimated fracture frequency (classification to fracture logging and calculation of the estimated fracture frequency logging are based on analyses of the "fracture loggings": SPR, sonic, resistivity and fluid temperature data. The position of large fractures is estimated by applying a second derivative filter to the logging data and then locating maxima (or minima depending on the logging method) in the filtered logging. Maxima (or minima) above (below) a certain threshold value (Table 4-1) are selected as probable fractures. The result is presented as a column diagram where column height 0 = no fracture and column height 1 = fracture indicated by all logging methods.

The estimated fracture frequency is calculated by applying a power function to the weighted sum of the maxima (minima) derivative loggings. Parameters for the power functions used in the previous site investigation at Oskarshamn were estimated by correlating the weighted sum to the mapped fracture frequency in the cored boreholes KLX03 and KLX04. The parameters were based on logging data from sonic, caliper, normal resistivity, SPR and focused resistivity measurements. However, in these Äspö data the main fracture indicative loggings used are SPR and sonic. The parameters of the power functions have therefore been adjusted to fit a back ground fracture frequency of c 2–3 fractures/m. The powers and linear coefficients (weights) used are presented in Table 4-1.

Table 4-1. Threshold values, powers and weights used for estimating position of fractures and calculate estimated fracture frequency.

	Borehole	SPR	Sonic	Foc128	Foc300	Caliper
Threshold	KA2051A01	1.0	1.5	1.3	1.3	1.2
Power	KA2051A01	0.5	1.0	1.0	1.6	1.0
Weight	KA2051A01	5.0	1.0	7.1	6.7	1.0
Threshold	KA3007A01	1.5	1.5	1.3	1.3	1.2
Power	KA2051A01	0.5	1.0	1.0	1.6	1.0
Weight	KA2051A01	5.0	1.0	7.1	6.7	1.0
Threshold	KJ0050F01	0.7	1.0	1.3	1.3	0.3
Power	KJ0050F01	0.5	1.0	1.0	1.6	1.0
Weight	KJ0050F01	5.0	1.0	7.1	6.7	1.0

4. Report evaluating the results.

4.2 Preparations and data handling

The logging data were delivered as Microsoft Excel files via email from SKB. The data of each logging method were saved separately in ASCII-files. The data processing was performed on the ASCII-files. The data used for interpretation were:

- Density (gamma-gamma)
- Magnetic susceptibility
- Natural gamma radiation
- Focused resistivity 128
- Focused resistivity 300
- Normal resistivity (160 cm)
- Normal resistivity (40 cm)
- Lateral resistivity
- Single point resistance (SPR)
- Fluid resistivity
- Fluid temperature
- Sonic (P-wave velocity)
- Caliper mean (bore hole diameter).

The density and susceptibility logging data were calibrated with reference to petrophysical measurements made on core samples from KA2051A01. The logging data at the same section coordinate as the sample core location were extracted from the data files and a cross-plot was created with logging data on one axis and the petrophysical data on the other. Linear regression technique was applied to establish a calibration equation, which then was applied to the logging data.

4.3 Analyses and interpretations

The analyses of the logging data were made with respect to identifying major variations in physical properties with length as indicated by the silicate density, the natural gamma radiation and the magnetic susceptibility. Since these properties are related to the mineral composition of the rocks in the vicinity of the borehole they correspond to variations in lithology.

The SPR, sonic, resistivity, caliper and fluid temperature (including the vertical fluid temperature gradient) loggings were mainly used for identifying sections with increased fracturing and thermal properties.

4.4 Nonconformities

No nonconformities were reported.

5 Results

5.1 Results of the petrophysical measurements and calibrations of logging data

Density is an important physical parameters since it is directly related to the mineral content and hence also to rock type. Petrophysical measurements were performed on 10 samples from KA2051A01. The measurements were carried out at the petrophysical laboratory at Luleå University of Technology and include the parameters density and magnetic susceptibility. The magnetic susceptibility was measured with a handheld susceptibility meter and the data were corrected for being collected on a cylindrical core specimen.

Density – susceptibility classification diagram is presented in Figure 5-1. The ten samples include three Ävrö granite-granodiorite, two Äspö diorite, one gabbroid-dioritoid and four fine-grained granite samples. The fine-grained granite has very low magnetic susceptibility and density in the range 2,620–2,630 kg/m^3. The density of the Ävrö granite-granodiorite is 2,680-2,690 kg/m^3, which differs from the Äspö diorite with a density in the range 2,720–2,745 kg/m^3.

The susceptibility and density logging data were calibrated with reference to the sample data presented in Figure 5-1. The calibration procedure is performed by plotting the sample data versus the logging data at the corresponding section length coordinate (after length adjustment an average filtering) in a cross-plot, and then performing linear regression analysis, see Figure 5-2. The calibration is then performed by applying the linear equation achieved from the analysis to the logging data.

The density cross-plot for KA2051A01 that is shown in Figure 5-2 a) shows a linear distribution, but the fact that the majority of the samples have density values in the same range makes the regression ill defined. The magnetic susceptibility cross-plot in Figure 5-2 b) shows a statistically well defined distribution, after removing one sample which was close to a gradient in the data. The calibration equations were applied to the logging data of all three boreholes.

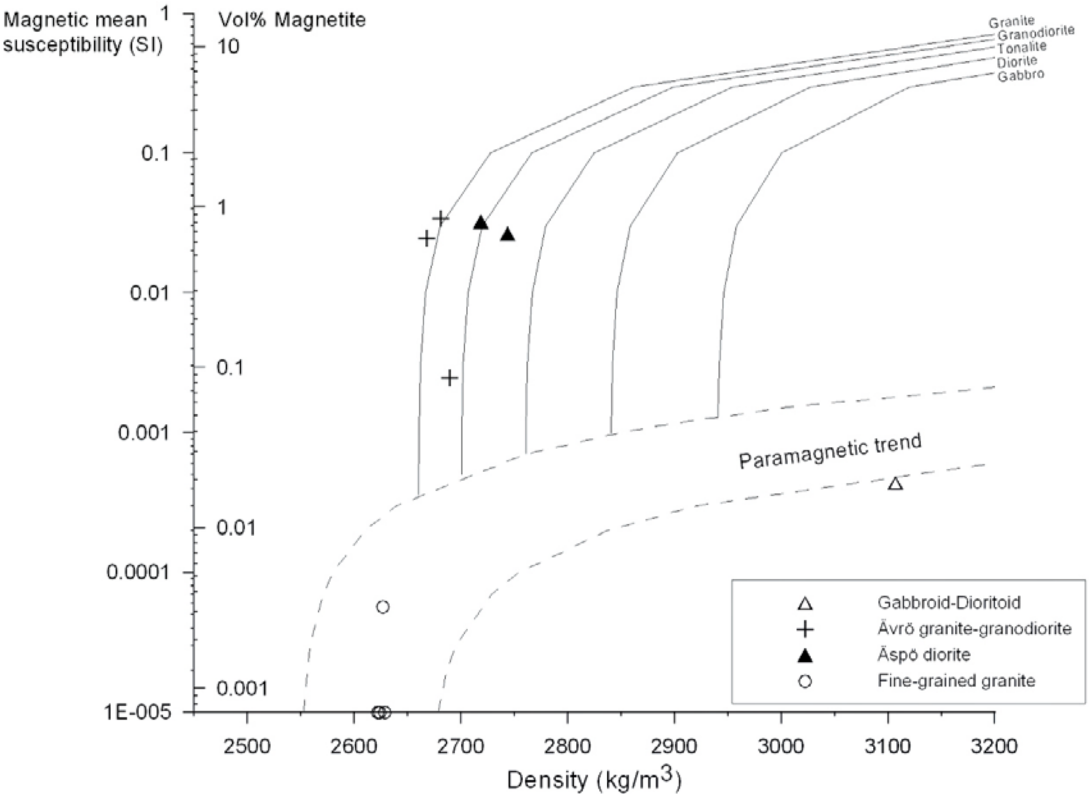

Figure 5-1. Density – susceptibility classification diagram of 10 rock samples from KA2051A01.

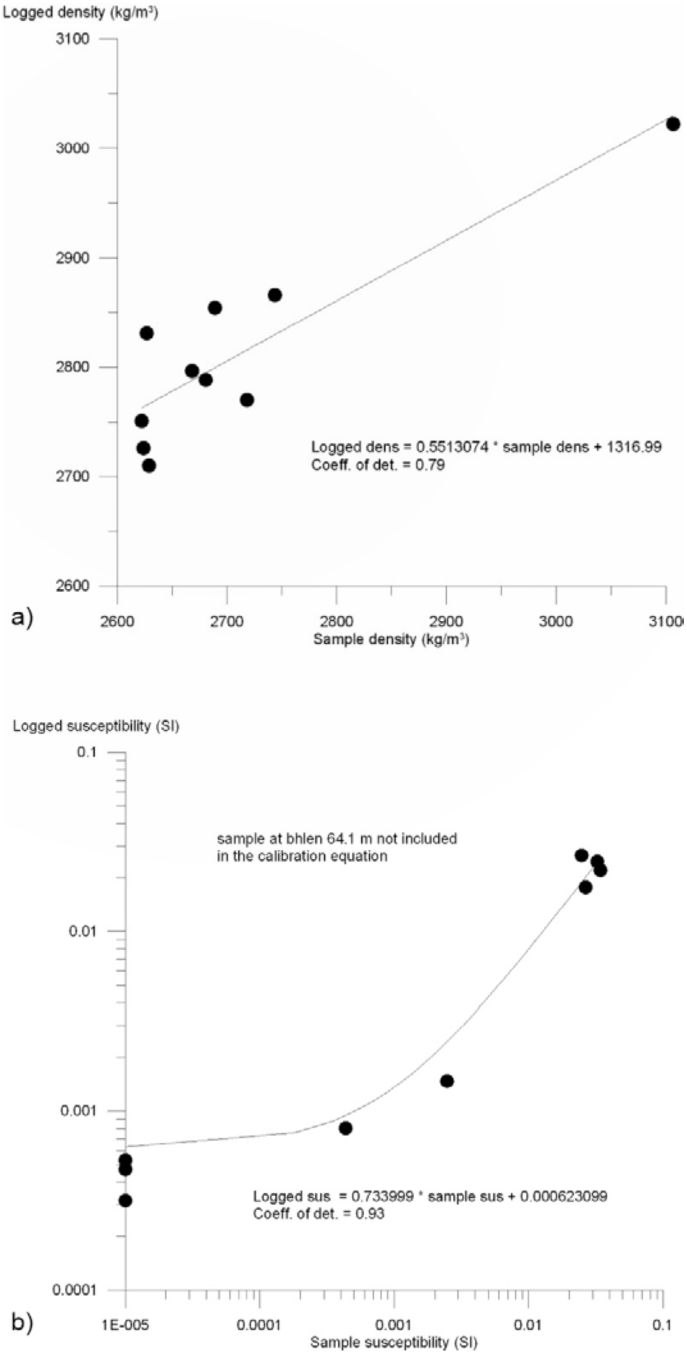

Figure 5-2. *Cross-plots of logging versus sample data from KA2051A01 for a) density and b) magnetic susceptibility.*

5.2 Quality control of the logging data

Noise levels of the raw data for each logging method are presented in Table 5-1. For all boreholes the natural gamma radiation data have noise levels above the recommended value 0.3 μR/h. For KA3007A01 the noise level of the natural gamma radiation is almost 20 times higher than the recommended level. These increased noise levels may have affected the interpretation of the data, especially the response from small rock bodies such as dykes. The susceptibility and density data generally have noise levels close to, or slightly above, the recommended level, and most other parameters have noise levels below the recommended levels. To reduce the influence of the noise, all logs were average filtered prior to the interpretation.

Table 5-1. Noise levels in the investigated geophysical logging data.

Logging method	KA2051A01	KA3007A01	KJ0050F01	Recommended max noise level
Density (kg/m^3)	10	10	10	3–5
Magnetic susceptibility (SI)	$2 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$1 \cdot 10^{-4}$
Natural gamma radiation (μR/h)	1.6	5.9	1.1	0.3
Fluid resistivity (%)	0.05	0.05	0.01	2
Fluid temperature (ºC)	$2 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	0.01
SPR (%)	0.1	0.3	0.2	No data
Focused resistivity 128 (%)	8	11	0.8	
Focused resistivity 300 (%)	12	14	1.7	
Normal resistivity 16 (%)	–	–	–	2.0
Normal resistivity 64 (%)	–	–	–	2.0
Lateral resistivity	–	–	–	2.0
Sonic (m/s)	8	9	7	20
Caliper (m)	$1 \cdot 10^{-5}$	$3 \cdot 10^{-5}$	$1 \cdot 10^{-4}$	$5 \cdot 10^{-4}$

The normal and lateral resistivity data are erroneous. A clear indication of this is that along subsections of the borehole, where most other logging methods indicate the existence of a fracture the normal and lateral resistivity is significantly increased, which is physically unreliable. These data were not used in the interpretation.

A qualitative inspection was performed on the loggings. The data were checked for spikes and/or other obvious incorrect data points. Erroneous data were replaced by null values (–999), and all null values were disregarded in the interpretation.

5.3 Interpretation of the logging data

The presentation of interpretation products presented below includes:

- Classification of silicate density
- Classification of natural gamma radiation
- Classification of magnetic susceptibility
- Position of inferred fractures (0 = no method, 1 = all methods)
- Estimated fracture frequency in 5 metre sections
- Classification of estimated fracture frequency (0 to 3, 3 to 6 and > 6 fractures/m).

5.3.1 Interpretation of KA2051A01

The results of the generalized logging data and fracture estimations of KA2051A01 are presented in Figure 5-3 and in Table 5-2. The silicate density classification indicates that along c 54% of the borehole length there is a dominant occurrence of rocks with a density corresponding to that of granite or granodiorite (light blue sections in Figure 5-3). The data most likely indicate the occurrences of Ävrö granite to granodiorite. However, in the lower most part of the borehole (285–320 m) the decreased density coincides with decreased magnetic susceptibility and increased natural gamma radiation, which indicates that the rock along this section is fine-grained granite. There are two long sections with increased density, c 10–120 m and 225–280 m, shown by dark blue and brown colors. In the section c 225–280 m the silicate density is mainly in the range of 2,730–2,800 kg/m^3 and the magnetic susceptibility is partly increased, which most likely indicates the occurrence of Äspö diorite. The significantly increased density along the section 65–95 m indicates the occurrence of dioritiod and/or gabbroid rocks. Along this section there are short intervals of decreased density that coincide with increased natural gamma radiation, which suggests that there is a combination of mafic and felsic rocks (composite dykes) in this part of the borehole.

Table 5-2. Distribution of silicate density classes with borehole length in KA2051A01.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	121	38
2,680 < dens < 2,730 (granodiorite)	51	16
2,730 < dens < 2,800 (tonalite)	90	29
2,800 < dens < 2,890 (diorite)	31	10
dens > 2,890 (gabbro)	22	7

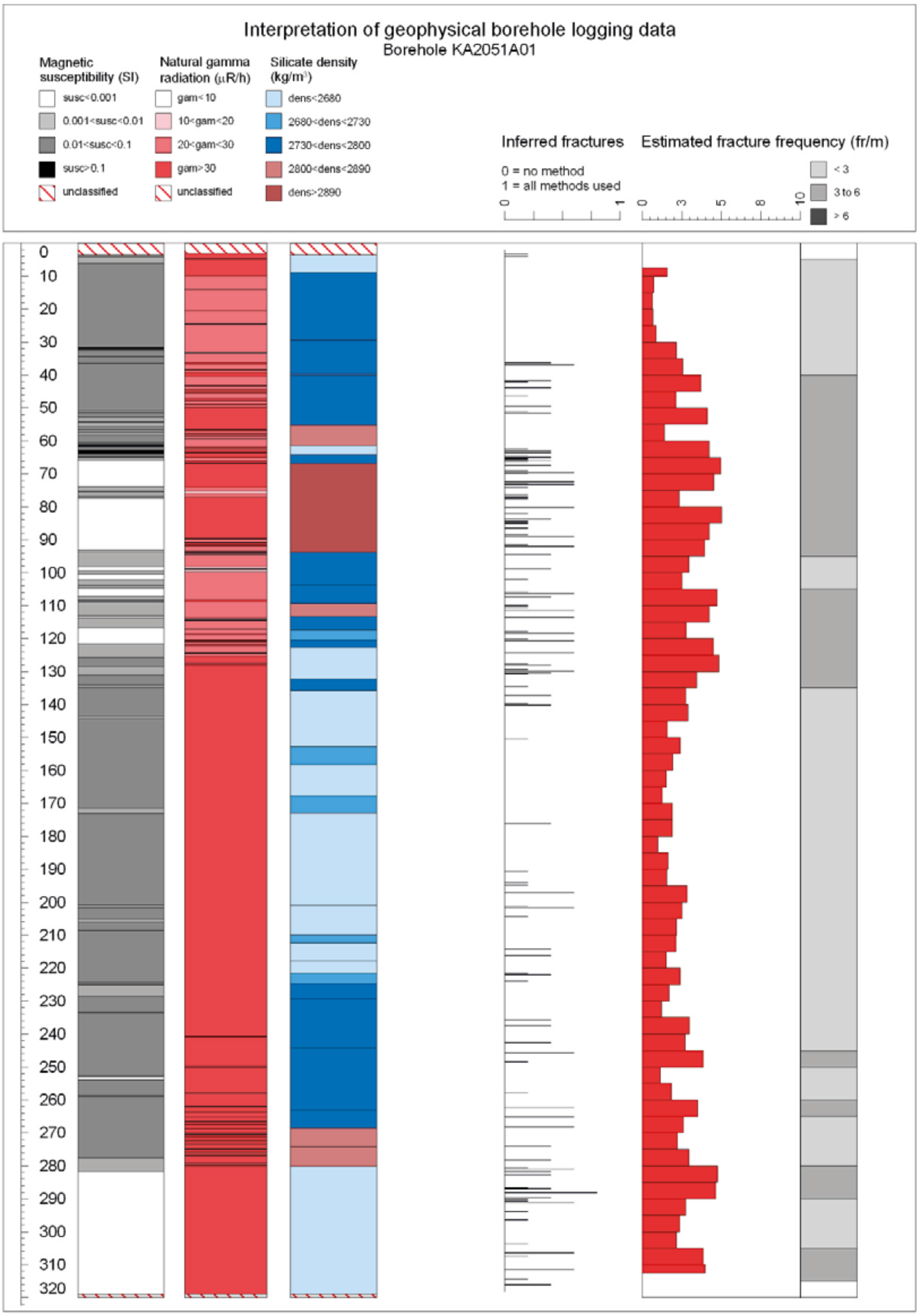

Figure 5-3. Generalized geophysical logs of KA2051A01.

The estimated fracture frequency is generally low or intermediate. Possible deformation zones are indicated along the sections 68–78 m, 82–89 m, 280–282 m and 305–308 m. All these sections are characterized by decreased resistivity, decreased P-wave velocity and caliper anomalies. Along the sections 68–78 m and 82–89 m the anomalies in the geophysical data are significant and there is also a decrease in magnetic susceptibility and distinct anomalies in the fluid temperature data. The data indicate the occurrences of alteration, water bearing fractures and distinctly increased porosity/fracturing.

The natural gamma radiation is increased along the entire borehole. The background level is c 20–30 μR/h, which is c 10–15 μR/h higher than what normally are expected with reference to previous logging surveys. The reason for the increased radiation level has not been investigated.

5.3.2 Interpretation of KA3007A01

The results of the generalized logging data and fracture estimations of KA3007A01 are presented in Figure 5-4 and Table 5-3 below. The silicate density, natural gamma radiation and the magnetic susceptibility together indicate that the rocks along the borehole vary greatly in mineral composition. The length distribution of the silicate density classes presented in Table 5-3 shows that four of the five classes are almost equally represented. In Figure 5-4 we can see that the silicate density varies markedly along rather short sections. The logging data indicate an inhomogeneous distribution of fine-grained granite (decreased density and magnetic susceptibility and increased natural gamma radiation), Ävrö granite-granodiorite (silicate density of 2,680–2,730 kg/m^3), Äspö diorite (silicate density of 2,750–2,850 kg/m^3) and dirotoid-gabbroid rocks (silicate density > 2,890 kg/m^3) and decreased natural gamma radiation).

The estimated fracture frequency is generally decreased or moderate. Possible deformation zones are indicated along the sections c 12–14 m, 73–77 m, 130–137 m and 173–176 m. These possible zones are mainly characterized by decreased resistivity and P-wave velocity. Along the two lower sections (130–137 m and 173–176 m) there are also significant anomalies in the vertical fluid temperature gradient, which indicates the occurrence of water bearing fractures.

5.3.3 Interpretation of KJ0050F01

The results of the generalized logging data and fracture estimations of KJ0050F01are presented in Figure 5-5 and Table 5-4 below. Approximately 60–70% of the borehole length is governed by silicate density in the range of 2,750–2,850 kg/m^3, which most likely indicates the occurrence of Äspö diorite. The silicate density is lower along the intervals c 19–24 m and 39–46 m. Along these sections the silicate density is mainly in the range of 2,650–2,750 kg/m^3 and together with the magnetic susceptibility of 0.02–0.06 SI and natural gamma radiation in the range of c 20–25 μR/h, the logging data indicate the occurrences of Ävrö granite-granodiorite.

The estimated fracture frequency is generally low. In the section interval c 12–20 m the fracture loggings indicate an increased occurrence of single fractures, but the logging data do not indicate any occurrences of possible deformation zones along the borehole.

Table 5-3. Distribution of silicate density classes with borehole length in KA3007A01.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	47	22
2,680 < dens < 2,730 (granodiorite)	43	20
2,730 < dens < 2,800 (tonalite)	63	29
2,800 < dens < 2,890 (diorite)	49	22
dens > 2,890 (gabbro)	15	7

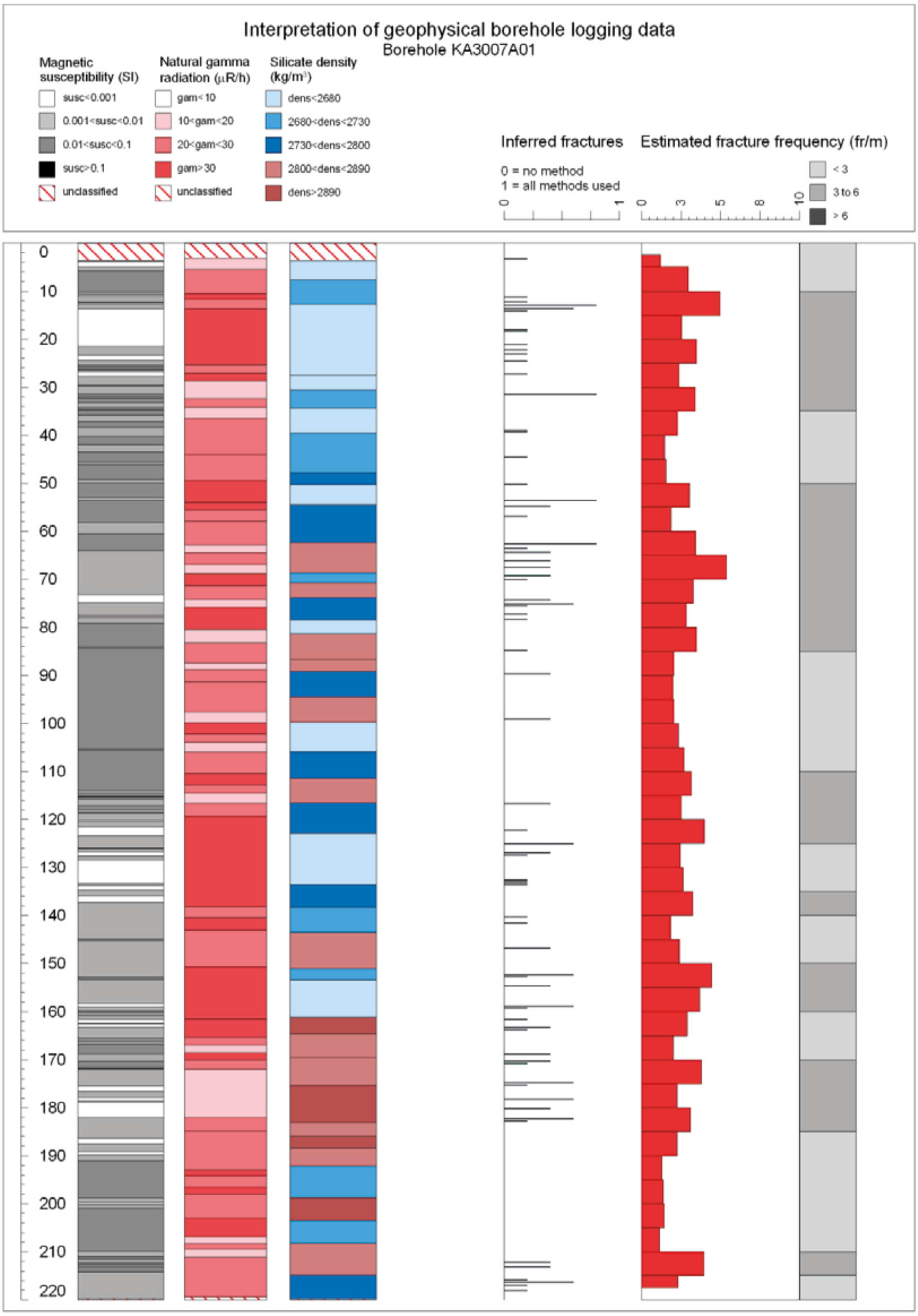

Figure 5-4. *Generalized geophysical logs of KA3007A01.*

Table 5-4. Distribution of silicate density classes with borehole length in KJ0050F01.

Silicate density interval (kg/m³)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	3	7
2,680 < dens < 2,730 (granodiorite)	12	27
2,730 < dens < 2,800 (tonalite)	18	41
2,800 < dens < 2,890 (diorite)	11	25
dens > 2,890 (gabbro)	0	0

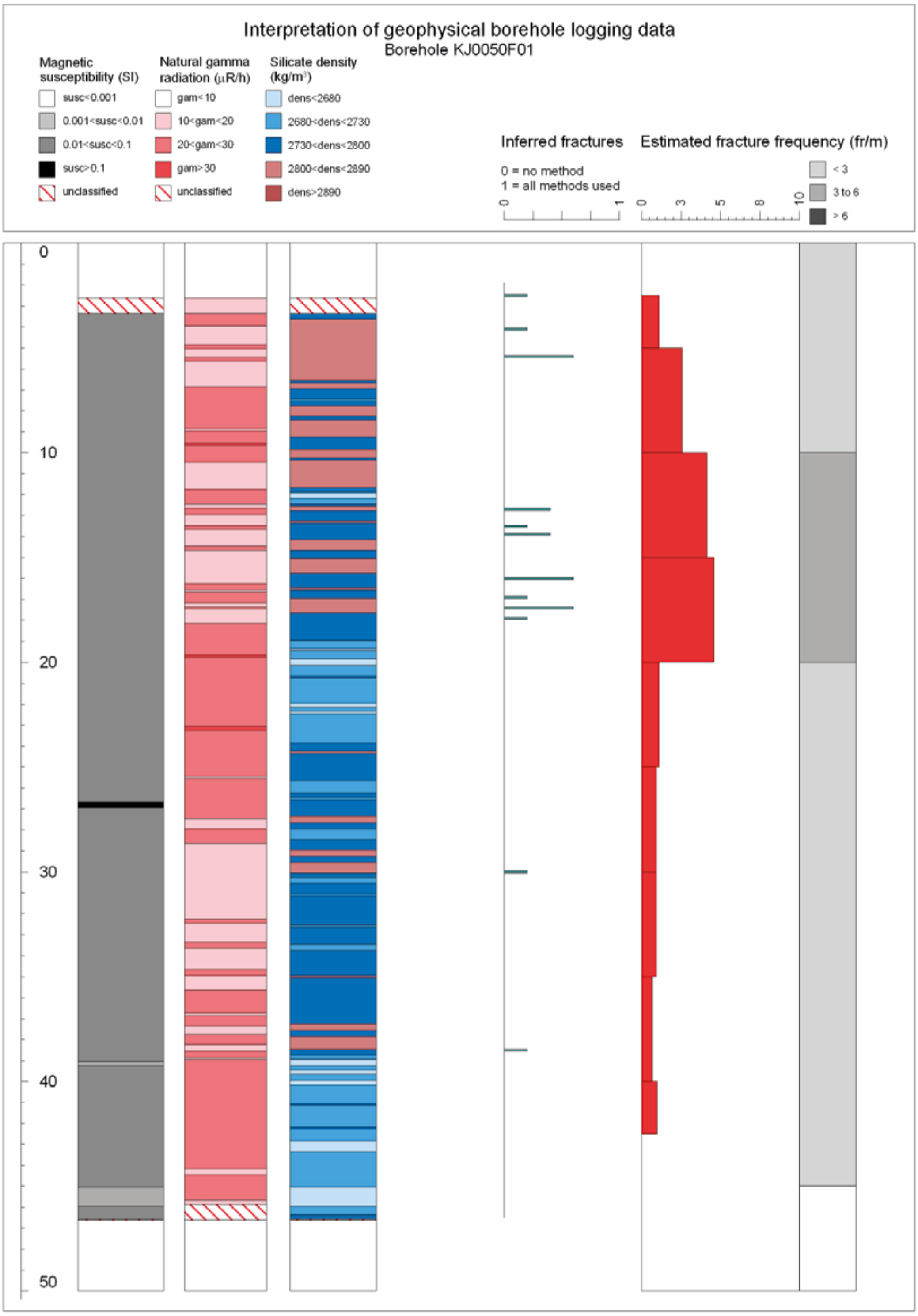

Figure 5-5. *Generalized geophysical logs of KJ0050F01.*

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