P-13-23

Äspö Hard Rock Laboratory

Interpretation of geophysical borehole measurements and petrophysical measurements from KA3011A01 and KA3065A01

Håkan Mattsson, GeoVista AB

May 2013

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

ISSN 1651-4416
SKB P-13-23
ID 1346452

Äspö Hard Rock Laboratory

Interpretation of geophysical borehole measurements and petrophysical measurements from KA3011A01 and KA3065A01

Håkan Mattsson, GeoVista AB

May 2013

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

Abstract

This report presents the compilation and interpretation of geophysical logging data from the cored boreholes KA3011A01 and KA3065A01, and petrophysical measurements on rock samples from the borehole KA3011A01.

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

The quality control shows significantly increased noise levels of the natural gamma radiation data. There are also quality problems with the normal and lateral resistivity logs. The data display inverted anomalies across fractures; hence these data were not used in the fracture frequency estimation.

The silicate density classification of KA3011A01 indicates a complete dominance of rocks with silicate density < 2,680 kg/m^3 and 2,680–2,730 kg/m^3, which corresponds to granite or granodiorite, most likely Ävrö granite-granodiorite. The natural gamma radiation is partly increased along the entire borehole length and there are five 1–2 m long sections with significantly increased radiation level that most likely indicate occurrences of fine-grained granite. The fracture frequency estimated for KA3011A01 is generally low or intermediate. Possible deformation zones are indicated along the sections 6–9 m, 18–20 m, 27–29 m, 33–35 m and 77–82 m. They are all characterized by decreased resistivity and p-wave velocity. At the section coordinates 29 m, 35 m and 81 m there are also distinct anomalies in fluid temperature suggesting in/out flow of water, which is most likely related to water bearing fractures.

The silicate density of KA3065A01 mainly ranges in the two intervals 2,680–2,730 kg/m^3 and 2,730–2,800 kg/m^3. The lower density interval most likely indicates occurrences of Ävrö granite-granodiorite and the higher density interval most likely correspond to Äspö diorite. In the section c 14–20 m the density is significantly increased and the natural gamma radiation and magnetic susceptibility are both decreased. The combination of properties most likely corresponds to diorite-gabbro. In the section c 84–92 m the natural gamma radiation is significantly increased and the density and magnetic susceptibility are both decreased, which most likely indicates the occurrence of a fine-grained granite dyke. The estimated fracture frequency is low to moderate. Possible deformation zones are indicated in the intervals c 9–10 m, 23–24 m and 113–117 m. In the three sections there is distinctly decreased resistivity, partly decreased p-wave velocity and clear anomalies in fluid temperature. The combination of physical properties suggests fractured rocks and in/out flow of water.

Sammanfattning

Föreliggande rapport presenterar resultat och tolkningar av geofysiska borrhålsmätningar i kärnborrhålen KA3011A01 och KA3065A01 samt petrofysiska mätningar på borrkärnebitar från borrhålet KA3011A01.

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 den geologiska enhålstolkningen.

Kvalitetskontrollen av data visar att det är kraftigt förhöjda brusnivåer i naturliga gammastrålningsdata. 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.

Klassificering av silikatdensitetdata från KA3011A01 indikerar en total dominans av data i intervallen < 2 680 kg/m^3 och 2 680–2 730 kg/m^3. Dessa silikatdensiteter indikerar förekomst av Ävrögranit-granodiorit. Den naturliga gammastrålning är generellt något förhöjd längs hela borrhålet, och det förekommer 5 st 1–2 m långa sektioner med kraftigt förhöjd naturlig gammastrålning, vilket sannolikt indikerar förekomst av finkorniga granitgångar. Den sprickfrekvensberäkning som gjorts för KA3011A01 indikerar låg eller intermediär sprickighet. Fem möjliga deformationszoner indikeras förekomma längs sektionerna 6–9 m, 18–20 m, 27–29 m, 33–35 m och 77–82 m. Samtliga fem sektioner karaktäriseras av avvikande låg resistivitet och p-vågshastighet. Vid sektionskoordinaterna 29 m, 35 m och 81 m är det kraftiga anomalier i borrhålsvätsketemperaturen vilket tyder på förekomst av vattenförande sprickor.

Tolkningen av data från KA3065A01 indikerar en huvudsaklig förekomst av Ävrögranit-granodiorit i övre delen av hålet och Äspödiorit i nedre delen. Längs sektion ca 14–20 m indikerar kraftigt förhöjd densitet i kombination med låg susceptibilitet och naturlig gammastrålning förekomst av diorit-gabbro. Längs intervallet ca 84–92 m är den naturliga gammastrålningen kraftigt förhöjd, vilket i kombination med låg densitet och magnetisk susceptibilitet, indikerar förekomst av en större finkornig granitgång. Den beräknade sprickfrekvensen för KA3065A01 är generellt låg till intermediär. Tre möjliga deformationszoner indikeras förekomma längs intervallen 9–10 m, 23–24 m och 113–117 m. De tre sektionerna karaktäriseras av avvikande låg resistivitet och p-vågshastighet samt tydliga anomalier i borrhålsvätsketemperaturen. Kombinationen av fysikaliska parametrar indikerar spröd deformation och vattenförande sprickor.

Contents

1 Introduction

This document reports the interpretations of geophysical borehole measurements and petrophysical data gained from the cored boreholes KA3011A01 and KA3065A01, which is one of the activities performed within the work of upgrading the geological model of the Äspö HRL (Figure 1-1). The work was carried out in accordance with activity plans AP TD TUD P002-11-084 and AP TD TUD P002-11-096. 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 2013a, b).

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 från KA3011A01	AP TD TUDP002-11-084	1.0
Äspö utbyggnad, DP1-Karakterisering-Tolkning av loggade geofysiska data från KA3065A01	AP TD TUDP002-11-096	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för tolkning av geofysiska borrhålsdata	SKB MD 221.003	3.0
Metodbeskrivning för geologisk enhålstolkning	SKB MD 810.003	3.0

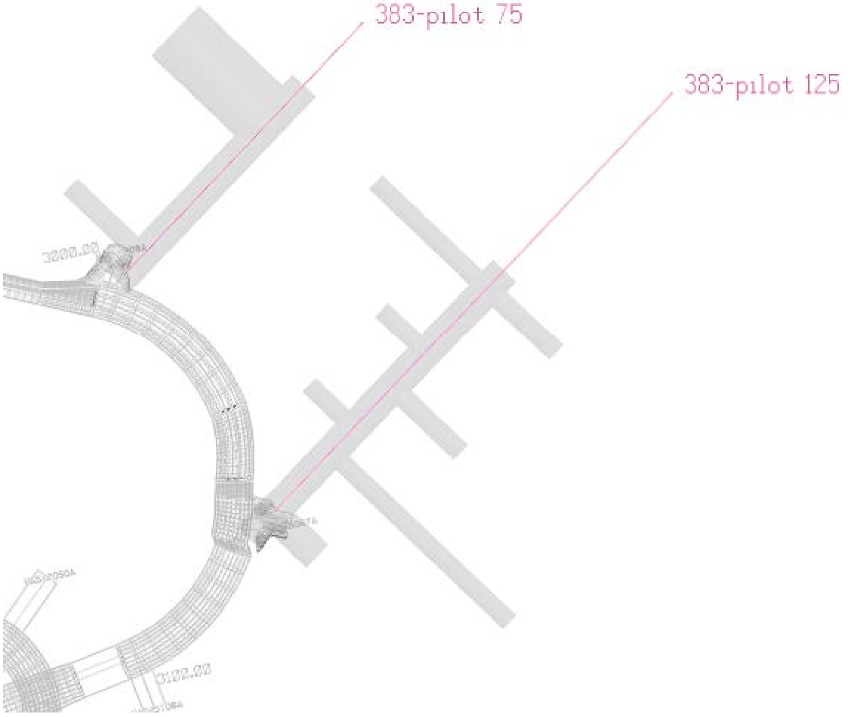

Figure 1-1. *Map of the location of the boreholes KA3011A01 (383-pilot 75) and KA3065A01 (383-pilot 125) at Äspö HRL.*

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 mapping and as supportive information during the so called "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 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 length 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 KA3065A01 were calibrated with respect to measurements on core samples from KA2051A01 in combination with sample measurements from KAS02. For borehole KA3011A01 the susceptibility logging data were calibrated with respect to sample measurements from KA2051A01 and the density measurements were calibrated with respect to sample measurements from KA3011A01; the latter reported in this report.

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. 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	Res N16
Threshold	KA3011A01	1.3	1.3	1.3	1.3	0.6	–
Power	KA3011A01	0.5	1.0	1.0	1.6	1.0	–
Weight	KA3011A01	5.0	1.0	7.1	6.7	1.0	–
Threshold	KA3065A01	1.3	0.8	1.3	1.3	0.5	1.0
Power	KA3065A01	0.5	1.0	1.0	1.6	1.0	0.5
Weight	KA3065A01	5.0	1.0	7.1	6.7	1.0	2.9

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 64 (160 cm)
- Normal resistivity 16 (40 cm)
- Lateral resistivity
- Single point resistance (SPR)
- Fluid resistivity
- Fluid temperature
- Sonic (P-wave velocity)
- Caliper mean (only KA3065A01) and Caliper 1D.

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 and in thermal properties.

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

4.4 Nonconformities

No nonconformities were reported.

5 Results

5.1 Results of the petrophysical measurements and calibration of logging data of KA3011A01

Density is an important physical parameter since it is directly related to the mineral content and hence also to rock type. Petrophysical measurements were performed on 7 samples from KA3011A01. The measurements were carried out at the petrophysical laboratory at Luleå University of Technology and include the parameter density. The results are presented in Table 5-1. The calibration procedure is performed by plotting the sample data versus the logging data at the corresponding section length coordinate (after average filtering) in a cross-plot, and then performing linear regression analysis, see Figure 5-1. The calibration is then performed by applying the linear equation achieved from the analysis to the logging data.

The density cross-plot for KA3011A01, shown in Figure 5-1, shows a linear distribution, but the regression is partly ill defined. This fact is, for example, indicated by the R-squared coefficient of 0.64. In normal to favourable cases the coefficient should be > 0.8. The residual mean, related to the absolute accuracy of the logging data, is 58 kg/m^3.

Table 5-1. Density data of core samples from KA3011A01.

Borehole id	Sample	Section from (m)	Section to (m)	Density (kg/m^3)
KA3011A01	1	21.74	21.84	2,642
KA3011A01	2	32.24	32.25	2,660
KA3011A01	3	46.77	46.87	2,664
KA3011A01	4	56.08	56.18	2,649
KA3011A01	5	62.10	62.20	2,743
KA3011A01	6	75.40	75.50	2,737
KA3011A01	7	90.00	90.10	2,728

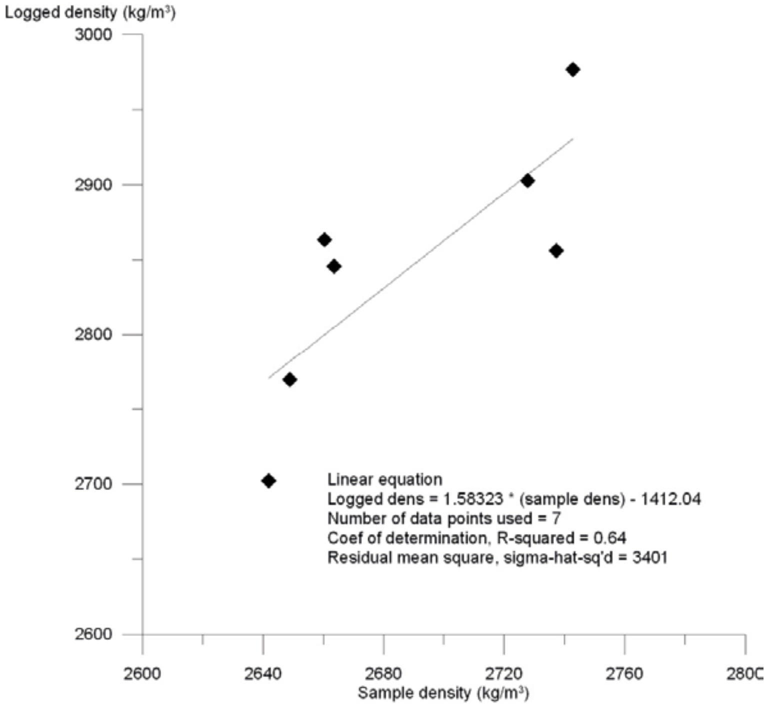

Figure 5-1. Cross-plots of density logging versus density sample data for KA3011A0, 7 samples.

5.2 Quality control of the logging data

Noise levels of the raw data for each logging method are presented in Table 5-2. For both boreholes the natural gamma radiation data have noise levels above the recommended value of 0.3 μR/h. Also the density and magnetic susceptibility data have increased noise levels. The increased noise levels may have affected the interpretation of the data, especially the response from small rock bodies such as dykes. To reduce the influence of the noise, all logs were average filtered prior to the interpretation.

The two normal and the lateral resistivity data of KA3011A01 and the short normal and the lateral resistivity log of KA3065A01 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.

The logging data of KA3011A01 and KA3065A01 are not length adjusted. Comparisons between significant natural gamma radiation anomalies and fine-grained granite dykes indicate a misfit in borehole length of approximately 0.3–0.5 m.

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).

Table 5-2. Noise levels in the investigated geophysical logging data.

Logging method	KA3011A01	KA3065A01	Recommended max noise level
Density (kg/m^3)	17	10	3 – 5
Magnetic susceptibility (SI)	$2\cdot10^{-4}$	$2\cdot10^{-4}$	$1\cdot10^{-4}$
Natural gamma radiation (μR/h)	1.8	1.4	0.3
Fluid resistivity (%)	0.1	0.04	2
Fluid temperature (°C)	$2\cdot10^{-4}$	$2\cdot10^{-4}$	0.01
SPR (%)	0.3	0.1	No data
Focused resistivity 128 (%)	11	12	No data
Focused resistivity 300 (%)	16	19	No data
Normal resistivity 16 (%)	–	–	2.0
Normal resistivity 64 (%)	–	0.2	2.0
Lateral resistivity	–	–	2.0
Sonic (m/s)	17	26	20
Caliper (m)	$5\cdot10^{-6}$	$1\cdot10^{-5}$	$5\cdot10^{-4}$

5.3.1 Interpretation of KA3011A01

The results of the generalized logging data and fracture estimations of KA3011A01 are presented in Figure 5-2 and in Table 5-3.

The silicate density classification indicates a complete dominance of rocks with silicate density < 2,680 kg/m^3 and 2,680–2,730 kg/m^3, which corresponds to granite or granodiorite, most likely Ävrö granite-granodiorite. There is no obvious division of the two density classes; the data indicate an irregular distribution between the two classes. There are few short intervals with silicate density > 2,730 kg/m^3, most likely corresponding to occurrences of Äspö diorite. The natural gamma radiation is partly increased along the entire borehole length and there are five 1–2 m long sections with significantly increased radiation level that most likely indicate occurrences of fine-grained granite. It is worth noting that the general radiation level is slightly decreased along the section 30–60 m compared to the section 60–100 m. This may indicate that the rocks along the latter section have a more felsic mineral composition compared to the rocks along the former section. The magnetic susceptibility is partly increased along the section 30–60 m, in combination with only minor variations, which indicates an increased concentration of magnetite, possibly related to a different mineral composition or that the rocks are better preserved.

The estimated fracture frequency is generally low or intermediate. There is a slight general increase in the estimated fracture frequency in the section c 0–35 m. Possible deformation zones are indicated along the sections 6–9 m, 18–20 m, 27–29 m, 33–35 m and 77–82 m. They are all characterized by decreased resistivity and p-wave velocity. At the section coordinates 29 m, 35 m and 81 m there are also distinct anomalies in fluid temperature suggesting in/out flow of water, which is most likely related to water bearing fractures.

5.3.2 Interpretation of KA3065A01

The results of the generalized logging data and fracture estimations of KA3065A01 are presented in Figure 5-3 and Table 5-4 below.

The silicate density mainly ranges in the two intervals 2,680–2,730 kg/m^3 and 2,730–2,800 kg/m^3 (Table 5-4). The lower density interval most likely indicates occurrences of Ävrö granite-granodiorite and the higher density interval most likely correspond to Äspö diorite. In Figure 5-3 we can see that the lower density interval mainly occurs in the sections 2–48 m and 108–118 m whereas the higher interval mainly occurs in the section interval 48–108 m and at the very end of the borehole. In the section c 14–20 m the density is significantly increased and the natural gamma radiation and magnetic susceptibility are both decreased. The combination of properties most likely corresponds to diorite-gabbro. In the section c 84–92 m the natural gamma radiation is significantly increased and the density and magnetic susceptibility are both decreased, which most likely indicates the occurrence of a fine-grained granite dyke.

The estimated fracture frequency is low to moderate. Possible deformation zones are indicated in the intervals c 9–10 m, 23–24 m and 113–117 m. In the three sections there is distinctly decreased resistivity, partly decreased p-wave velocity and clear anomalies in fluid temperature. The combination of physical properties suggests fractured rocks and in/out flow of water. The possible deformation zone at 113–117 m is spatially related with a small fine-grained granite dyke indicated by a positive anomaly in the natural gamma radiation data.

Table 5-3. Distribution of silicate density classes with borehole length in KA3011A01.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens< 2,680 (granite)	54	58
2,680< dens< 2,730 (granodiorite)	38	41
2,730< dens< 2,800 (tonalite)	1	1
2,800< dens< 2,890 (diorite)	0	0
dens > 2,890 (gabbro)	0	0

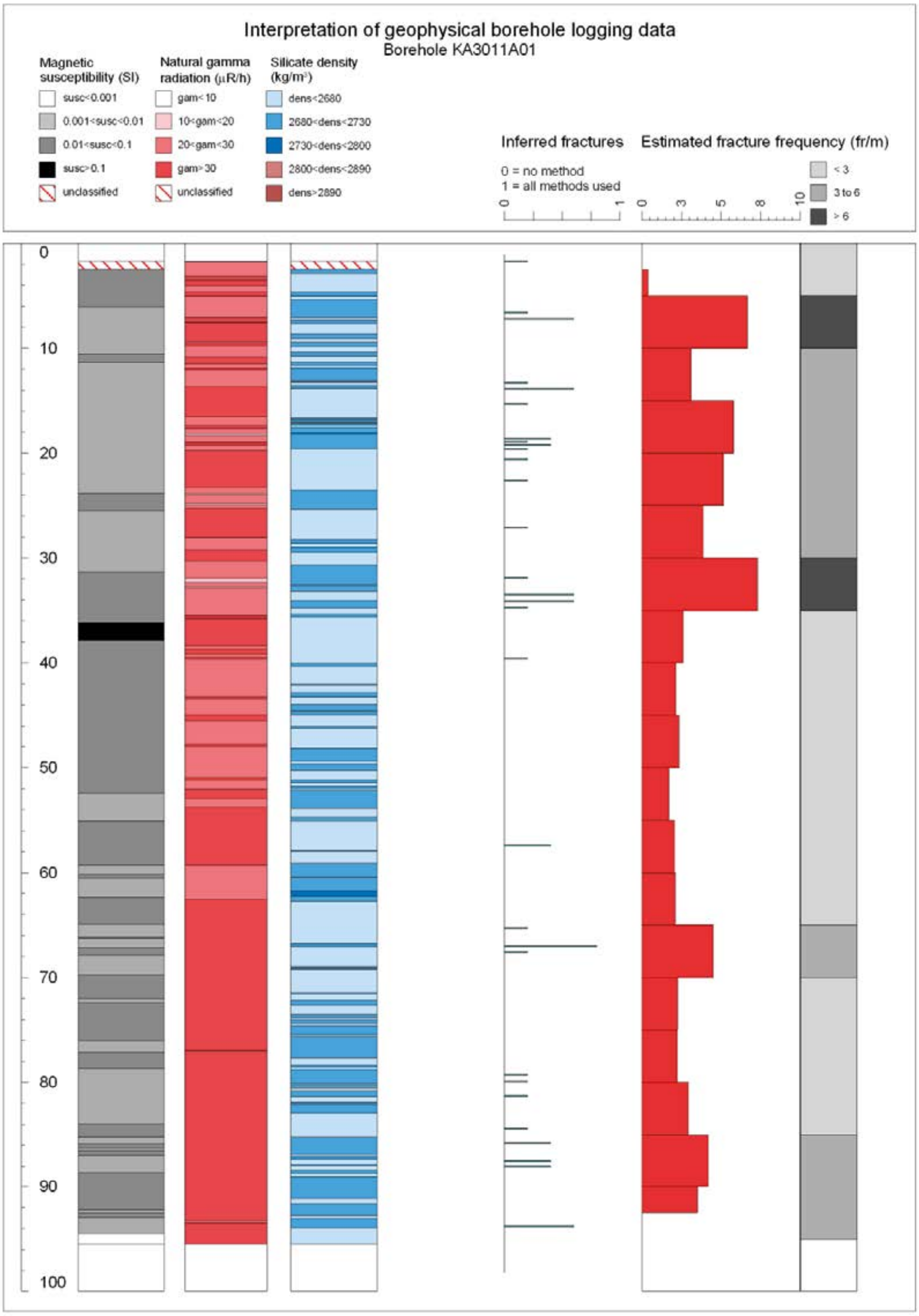

Figure 5-2. *Generalized geophysical logs of KA3011A01.*

Table 5-4. Distribution of silicate density classes with borehole length in KA3065A01.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	18	15
2,680 < dens < 2,730 (granodiorite)	44	37
2,730 < dens < 2,800 (tonalite)	49	41
2,800 < dens < 2,890 (diorite)	4	3
dens > 2,890 (gabbro)	5	4

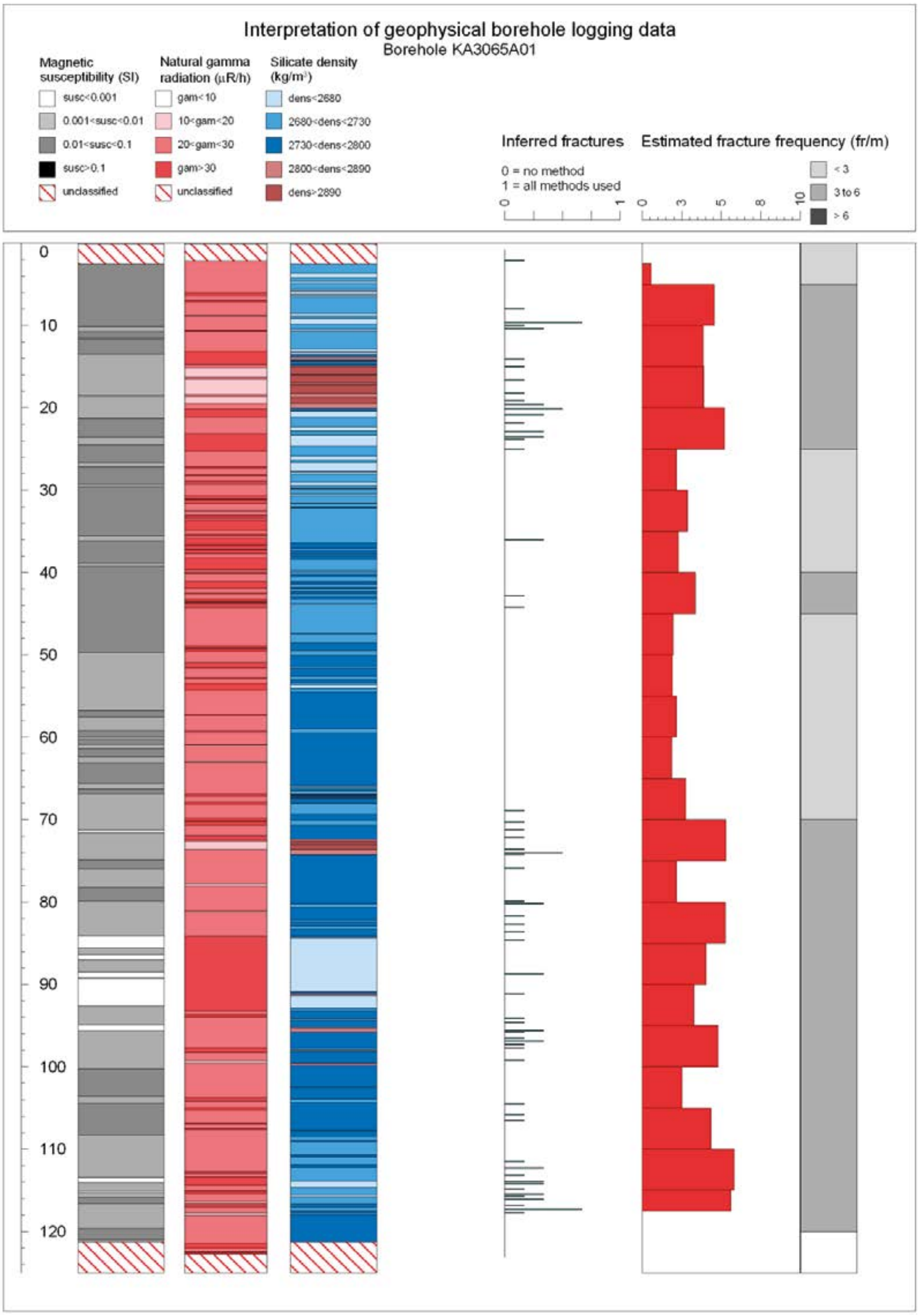

Figure 5-3. *Generalized geophysical logs of KA3065A01.*

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

Nielsen U T, Ringgaard J, 2013a. Äspö Hard Rock Laboratory. Geophysical borehole logging in borehole KA3011A01. SKB P-13-20, Svensk Kärnbränslehantering AB.

Nielsen U T, Ringgaard J, 2013b. Äspö Hard Rock Laboratory. Geophysical borehole logging in borehole KA3065A01. SKB P-13-21, Svensk Kärnbränslehantering AB.

Henkel H, 1991. Petrophysical properties (density and magnetization) of rock from the northern part of the Baltic Shield. Tectonophysics 192, 1–19.

Puranen R, 1989. Susceptibilities, iron and magnetite content of precambrian rocks in Finland. Report of investigation 90, Geological survey of Finland.