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Forsmark site investigation

Interpretation of geophysical borehole measurements and petrophysical data from KFM07B, KFM09A, HFM25, HFM27 and HFM28

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Abstract

This report presents the compilation and interpretations of geophysical logging data from the cored boreholes KFM09A and KFM07B, and the percussion drilled boreholes HFM25, HFM27 and HFM28. The interpretation of petrophysical data (wet density and magnetic bulk susceptibility) of 10 core samples from the cored borehole KFM09A is also presented.

The main objective of the investigation is to use the results as supportive information during the geological core mapping and as supportive information during the single-hole interpretation. The petrophysical data are used for calibration of the density and magnetic susceptibility logging data, and it is also used as supportive information in the rock type classification.

The petrophysical rock type classification corresponds well to, and supports, the geological rock type classification without any exceptions. The linear regression functions established for the calibration procedure are well defined and show little scatter in the data. However, there are significant level differences between logging and sample data prior to the calibration.

Noise levels are low for a majority of the examined logging data. The rock in the vicinities of all five investigated boreholes is dominated by silicate density indicating a mineral composition that corresponds to granite rock (< 2,680 kg/m^3), magnetic susceptibility is generally in the interval 0.001–0.01 SI and the natural gamma radiation is generally in the interval 20–36 μR/h. In 17% (c 132 m) of KFM09A the silicate density indicates a mineral composition that corresponds to granodiorite or tonalite. Subordinate short sections (< 5 m length) of rocks with higher densities occur frequently in all the boreholes. The high density sections generally coincide with decreased susceptibility and decreased natural gamma radiation and this combination of physical properties most likely indicates the occurrences of amphibolite dykes. Positive natural gamma radiation anomalies frequently occur in KFM09A and in the three percussion drilled boreholes. The anomalies generally coincide with low density and decreased magnetic susceptibility and they most likely indicate the occurrences of pegmatite or fine-grained granite dykes. Indications of felsic dykes are rare in KFM07B in comparison to the other investigated boreholes.

There is a clear pattern indicating that mafic and felsic dykes often are spatially related, and there are also indications of increased fracture frequency related to the occurrences of combined mafic and felsic dykes.

The estimated fracture frequency is generally low, or moderate, in the five investigated boreholes. Possible major deformation zones are indicated in KFM09A at c 15–65 m, 225–250 m, 275–280 m, 510–520 m and 730–790 m; in KFM07B at c 90–100 m and 165–170 m and in HFM27 at c 45–65 m. There are no indications of major deformation zones in HFM25 or in HFM28.

Sammanfattning

Föreliggande rapport presenterar en sammanställning och tolkning av geofysiska borrhålsmätningar från kärnborrhålen KFM09A och KFM07B, samt de hammarborrade hålen HFM25, HFM27 and HFM28. I rapporten presenteras även resultaten från petrofysiska mätningar (våtdensitet och volymssusceptibilitet) på 10 borrkärneprover från KFM09A.

Syftet med denna undersökning 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 dels som stödjande data vid borrkärnekarteringen samt som underlag vid enhålstolkningen. Syftet med de petrofysiska mätningarna är dels att kalibrera loggade densitets- och susceptibilitetsdata samt dessutom att fungera som stödjande data för bergartsklassificeringen.

Den petrofysiska bergartsklassificeringen visar en mycket god överensstämmelse med och stödjer till fullo den geologiska klassificeringen. De kalibreringssamband som erhållits är välbestämda och indikerar låga brusnivåer i data. Däremot finns en tydlig nivåskillnad mellan loggade data och mätningar på bergartsprover (vilken dock kompenseras bort vid kalibreringen).

De allra flesta loggdata uppvisar låga brusnivåer. Berggrunden i närheten av samtliga fem undersökta borrhål domineras till mycket stor del av en bergart med silikatdensitet < 2,680 kg/m^3, vilket indikerar en mineralsammansättning motsvarande den för granit. Magnetisk susceptibilitet ligger generellt i intervallet 0,001–0,01 SI och den naturliga gammastrålningen varierar i stort mellan 20 μR/h och 36 μR/h. Längs ca 17 % av KFM09A (ca 132 m) indikerar silikatdensiteten bergarter med en mineralsammansättning motsvarande den för granodiorit eller tonalit. Kortare sektioner (< 5 m) med avvikande hög densitet i kombination med låg naturlig gammastrålning och låg magnetisk susceptibilitet förekommer i alla de fem borrhålen. Denna kombination av fysikaliska egenskaper är i Forsmark typisk för amfibolit. Sektioner med förhöjd naturlig gammastrålning (ofta i kombination med låg densitet och låg magnetisk susceptibilitet) är vanligt förekommande i KFM09A och i de tre hammarborrade hålen, och indikerar förekomst av pegmatit eller finkornig granit. Endast ett fåtal indikationer på felsiska gångar förekommer i KFM07B.

Denna undersökning visar (liksom flera tidigare) att det finns ett tydligt rumsligt samband mellan mafiska och felsiska gångar. Dessutom finns en klar indikation på att kombinationen av mafiska och felsiska gångar ofta sammanfaller med förhöjd sprickfrekvens.

Den beräknade sprickfrekvensen är generellt låg, ibland moderat, i samtliga de fem undersökta borrhålen. Kraftigt förhöjd sprickfrekvens (troliga deformationszoner) kan identifieras i KFM09A längs ca 15–65 m, 225–250 m, 275–280 m, 510–520 m och 730–790 m; i KFM07B längs ca 90–100 m och 165–170 m och i HFM27 längs ca 45–65 m. Det finns inga indikationer på större deformationszoner i HFM25 eller i HFM28.

Contents

1 Introduction

SKB performs site investigations for localization of a deep repository for high level radioactive waste. The site investigations are performed at two sites, Forsmark and Simpevarp/Laxemar. This document reports the results gained from the interpretation of geophysical borehole logging data from the cored boreholes KFM09A and KFM07B, and the percussion drilled boreholes HFM25, HFM27 and HFM28 in Forsmark (Figure 1-1).

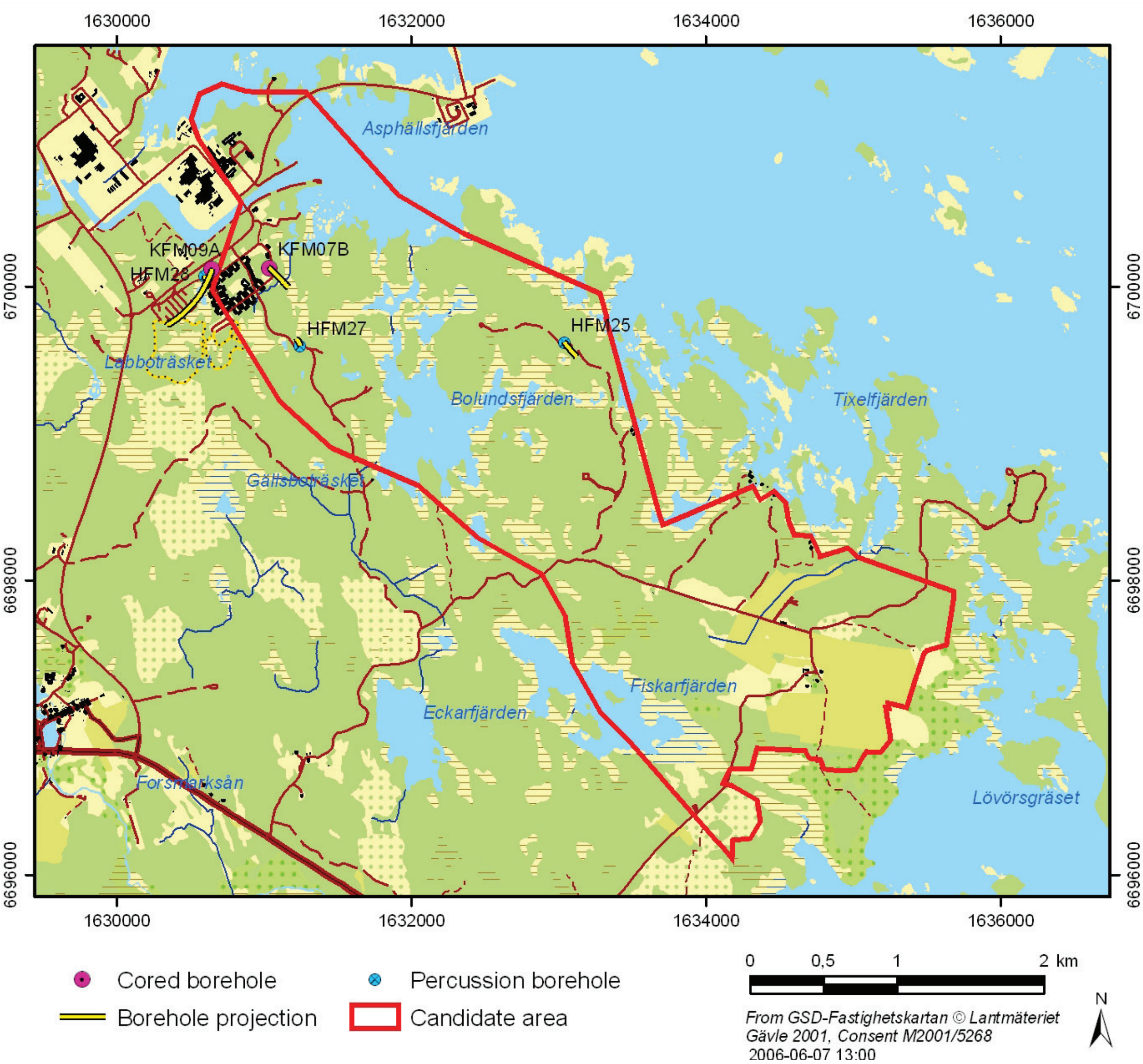


***Figure 1-1.** Map showing the location of the investigated boreholes.*

Generalized geophysical loggings related to lithological variations are presented together with indicated fracture loggings, including estimated fracture frequency. Calculations of the estimated salinity and apparent porosity are also presented for the boreholes. The logging measurements were conducted in 2005 by Rambøll /1/. Measurements of petrophysical properties were performed by the Petrophysical Laboratory at Luleå University of Technology in March 2006.

The interpretation presented in this report is performed by GeoVista AB in accordance with the instructions and guidelines from SKB (Table 1-1).

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

Activity plan	Number	Version
Tolkning av geofysiska borrhålsdata från KFM07B, KFM09A, HFM25, HFM27 och HFM28.	AP PF 400-05-118	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för bestämning av densiteten och porositeten hos det intakta berget.	SKB MD 160.002	2.0
Metodbeskrivning för mätning av bergarters petrofysiska egenskaper	SKB MD 230.001	2.0
Metodbeskrivning för tolkning av geofysiska borrhålsdata	SKB MD 221.003	2.0

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 loggings, the single point resistance (SPR), caliper and sonic loggings.

An estimation of the salinity and the apparent porosity are presented for the cored boreholes. These parameters indicate saline water and the transportation properties of the rock volume in the vicinity of the borehole.

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 "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 equipment for analyses of logging data

The software used for the interpretation are WellCad v3.2 (ALT) and Strater 1.00.24 (Golden Software), that are mainly used for plotting, Grapher v5 (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.

3.2 Description of equipment for analyses of petrophysical data

The measurements of magnetic susceptibility were performed with a KLY-3 Kappabridge from Geofyzika Brno. Masses for the density determinations were measured with a digital Mettler Toledo PG 5002. The measurements were performed by the petrophysical laboratory at Luleå University of Technology.

4 Execution

4.1 Laboratory measurements

The sampling covers 10 samples from KFM09A (Table 4-1), collected and classified by geologist Jesper Pettersson (SwedPower). Preparations of the drill cores were performed by a technician at the laboratory of the Division of Applied Geophysics, Luleå University of Technology. The measurements of the magnetic susceptibility were performed according to MD 230.001 (SKB internal controlling document). The measurements of the wet density were performed according to MD 160.002 (SKB internal controlling document). The instruction is written to conform to rock mechanical measurements on drill cores from deep drillings, where the density determinations are parts of other types of measurements, not directly relevant for the geological core logging. The time to soak the samples (48 hours in this investigation) is e.g. shorter than what is recommended in MD 160.002.

Calibration of instruments for measurements of petrophysical parameters were performed in accordance to the manual for each instrument respectively.

The laboratory measurements of petrophysical parameters produce raw-data files in ascii, binary or Microsoft Excel formats. All data files were delivered via email from the laboratory at the Luleå University of Technology to GeoVista AB. The data were then rearranged and placed in Microsoft Excel files. Back-up files of all raw-data are stored both at GeoVista AB and at the laboratory.

Sample information, section up and section low, for KFM09A is given in Table 4-1.

Table 4-1. Sample information for KFM09A.

Secup	Seclow	Rock type code	Rock type name
121.81	122.01	102017	amphibolite
174.10	174.25	101051	granite, granodiorite, tonalite, metamorphic
328.29	328.44	101057	granite to granodiorite, metamorphic
422.52	422.67	102017	amphibolite
443.16	443.31	101058	granite, aplitic, metamorphic
460.37	460.52	103076	felsic to interm. volcanic rock, metamorphic
489.50	489.65	102017	amphibolite
583.03	583.18	101057	granite to granodiorite, metamorphic
663.50	663.65	101057	granite to granodiorite, metamorphic
719.54	719.69	101057	granite to granodiorite, metamorphic

4.2 Interpretation of the logging data

The execution of the interpretation can be summarized in the following five 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 depth co-ordinates (0.1 m point distance).

The density logging data are calibrated with respect to petrophysical data from KFM09A (this investigation). The magnetic susceptibility logging data are calibrated with respect to a combination of petrophysical data from the boreholes KFM01A and KFM02A /2 and 3/.

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

   The silicate density is calculated with reference to /4/ and the data are then divided into 5 sections indicating a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to /5/. 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” (< 20µR/h), ”medium” (20 µR/h < gamma < 36 µR/h), ”high” (36 µR/h < gamma < 53 µR/h) and “very high” (> 53 µR/h).

3. For the cored boreholes the normal resistivity loggings are corrected for the influence of the borehole diameter and the borehole fluid resistivity. The apparent porosity is calculated during the correction of the resistivity loggings. The calculation is based on Archie’s law /6/; $\sigma = a\,\sigma_w^k\,\varphi^m + \sigma_s$ where σ = bulk conductivity (S/m), σ_w = pore water conductivity (S/m), φ = volume fraction of pore space, σ_s = surface conductivity (S/m) and “a”, “k” and “m” are constants. Since “a”, “k” and “m” may vary with variations in the borehole fluid resistivity, estimations of the constants are performed with reference to the actual fluid resistivity in each borehole respectively. The constants used in this investigation are presented in Table 4-2.

   The estimated water salinity is calculated as ppm NaCl in water following the simple relation from Crain’s Petrophysical Handbook where:

$$WS = \frac{400000}{(1.8t + 32)^{0.88}\sqrt{\rho}}$$

   WS = Water salinity (ppm NaCl), t = temperature (ºC) and ρ = resistivity (Ωm).

   The salinity is only calculated for cored boreholes.

Table 4-2. Values of the constants a, k and m in Archie’s law used in the calculation of the apparent porosity.

Borehole	Average fluid resistivity (Ωm)	A	k	m
KFM09A	5.7	10	0.37	1.7
KFM07B	1.7	10	0.37	1.7

4. 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 short and long normal resistivity, caliper mean, single point resistance (SPR), focused resistivity (140 and 300 cm) and sonic. 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 4-3) are selected as probable fractures. The result is presented as a column diagram where column height 0 = no fracture, 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 were estimated by correlating the weighted sum to the mapped fracture frequency in the cored boreholes KFM01A and KFM02A. The linear coefficients (weights) used are presented in Table 4-3.

Table 4-3. Threshold values and weights used for estimating position of fractures and calculate estimated fracture frequency, respectively.

	Borehole	Sonic	Focused res. 140	Focused res. 300	Caliper	SPR	Normal res. 64	Normal res. 16	Lateral res.
Threshold	KFM07B	1.1	–	1.3	0.5	1.0	4.0	2.0	–
Weight	KFM07B	4.0	–	4.0	2.0	2.56	0.24	1.75	–
Threshold	KFM09A	2.0	–	1.7	0.4	1.5	5.0	5.0	–
Weight	KFM09A	4.0	–	4.0	2.0	2.56	0.24	1.75	–
Threshold	HFM25	1.0	1.3	1.5	0.6	1.0	4.0	4.0	–
Weight	HFM25	4.0	2.56	4.0	2.0	2.56	0.24	1.75	–
Threshold	HFM27	1.0	0.7	1.0	0.5	1.0	4.0	4.0	–
Weight	HFM27	4.0	2.56	4.0	2.0	2.56	0.24	1.75	–
Threshold	HFM28	1.2	1.2	1.3	0.5	1.0	3.5	3.6	–
Weight	HFM28	4.0	2.56	4.0	2.0	2.56	0.24	1.75	–

5. Report evaluating the results.

4.3 Preparations and data handling

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

- Density (gamma-gamma)
- Magnetic susceptibility
- Natural gamma radiation
- Focused resistivity (300 cm)
- Focused resistivity (140 cm)
- Sonic (P-wave)
- Caliper mean

- SPR (Single Point Resistance)
- Short normal resistivity (16 inch)
- Long normal resistivity (64 inch)
- Fluid resistivity
- Fluid temperature

4.4 Analyses and interpretations

The analyses of the logging data are made with respect to identifying major variations in physical properties with depth 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 resistivity, sonic and caliper loggings are mainly used for identifying sections with increased fracturing and alteration. The interpretation products salinity and apparent porosity help identifying saline ground water and porous rocks.

4.5 Nonconformities

Apparent porosity calculations and corrections for the borehole diameter and fluid resistivity are not presented for the long normal resistivity loggings since the calculation show unrealistic values. Apart from this, no nonconformities are reported.

5 Results

5.1 Petrophysical properties of KFM09A

The rock type classifications diagram in Figure 5-1 shows the distribution of the magnetic susceptibility versus density for the 10 samples (including geological rock type classification) presented in Table 4-1.

The petrophysical rock type classification corresponds well to, and supports, the geological rock type classification without any exceptions. The four meta granite to granodiorite samples have an average density of 2,666 kg/m^3 and highly variable magnetic susceptibility; the three samples of amphibolite have an average density of 2,968 kg/m^3 and low magnetic susceptibility, and these values agree well with data from previous measurements of these two rock types. The sample of felsic to intermediate volcanic rock (cross symbol) is indicated at being classified as rhyodacite to dacite. The 101051 sample collected at 174 m and the aplitic granite (101058 collected at c 443 m) are both indicated having a mineral composition that corresponds to granite (or leucocratic granite).

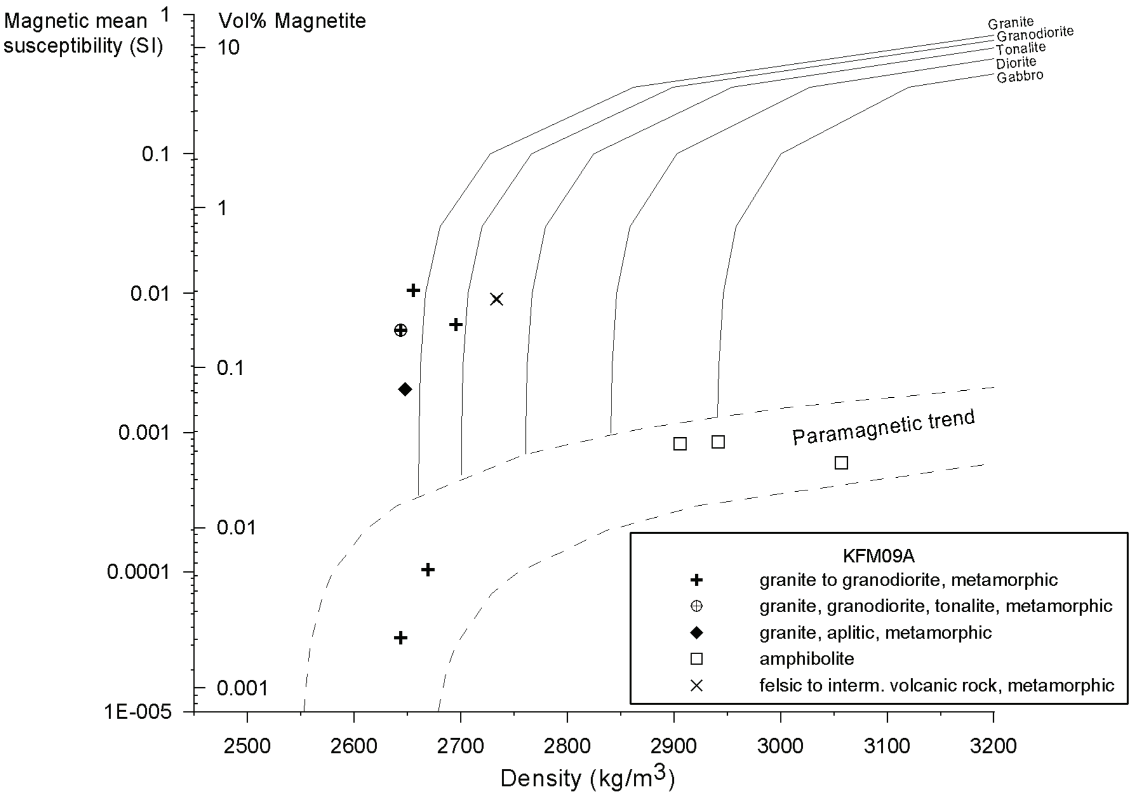


***Figure 5-1.** Susceptibility – density rock classification diagram for samples from KFM09A.*

5.2 Quality controll of the logging data

Noise levels of the raw data for each logging method are presented in Table 5-1. Noise levels are low for a majority of the logging methods. The noise levels of the natural gamma radiation logs are generally above the recommended level. However, the levels are low enough to fully allow a meaningful interpretation of the data. To reduce the influence of the noise, all logs were average or median filtered prior to the interpretation.

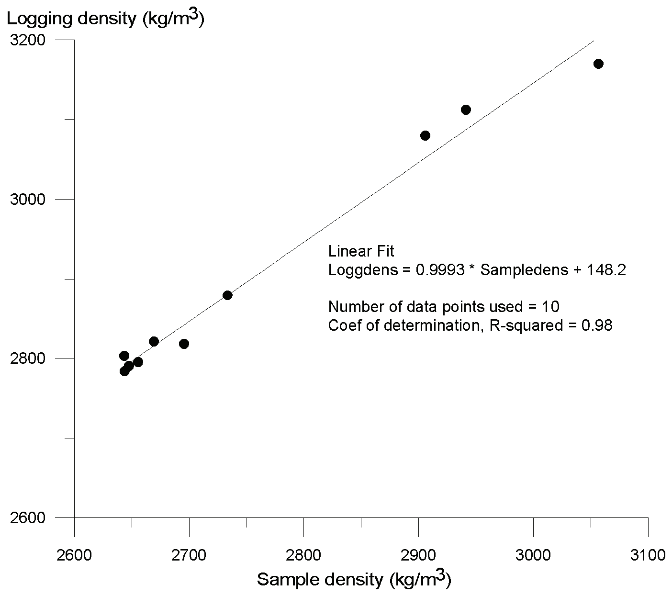
A qualitative inspection was performed on the loggings. The data were checked for spikes and/or other obvious incorrect data points. Erroneous data were replaced by null values (–999) by the contractor Rambøll prior to the delivery of the data, and all null values were disregarded in the interpretation.

The calibration of the density and susceptibility logs is performed by plotting the sample data versus the log data at the corresponding section length coordinate (a so called cross-plot), and then performing a linear regression analysis. In Figure 5-2 cross plots of the density (upper diagram) and magnetic susceptibility data of KFM09A are displayed for each property, respectively.

The density data show a nice linear distribution with a low amount of scatter and the fitted line is very well defined. The slope of the fitted line is fairly close to 1.0 (it is 0.9993) but observe the rather large density value of 148.2 kg/m^3 for the density log when the sample density equals zero. Also the magnetic susceptibility data show a nice linear distribution and the fit through the origin is statistically well defined. However, the slope of the fitted line differs significantly from 1.0. One sample, meta granite to granodiorite collected at c 663 m, strongly deviates from the general distribution and was therefore excluded in the susceptibility calibration file.

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

Logging method	KFM09A	KFM07B	HFM25	HFM27	HFM28	Recommended max noise level
Density (kg/m^3)	6	5	8	6	5	3–5
Magnetic susceptibility (SI)	2×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}
Natural gamma radiation (μR/h)	0.7	0.6	0.6	0.6	0.7	0.3
Long normal resistivity (%)	0.2	0.4	0.8	0.3	0.4	2.0
Short normal resistivity (%)	0.2	0.3	0.6	0.2	0.2	2.0
Fluid resistivity (%)	0.002	0.0004	0.03	0.04	0.02	2
Fluid temperature (ºC)	0.0006	0.0003	0.0002	0.0005	0.0001	0.01
Lateral resistivity (%)	No used	No used	No used	No used	No used	2
Single point resistance (%)	0.2	0.6	0.9	0.2	0.2	No data
Caliper (m)	6×10^{-5}	3×10^{-5}	2×10^{-4}	2×10^{-4}	1×10^{-4}	0.0005
Focused resistivity 300 (%)	13	6	8	10	15	No data
Focused resistivity 140 (%)	No data	No data	2	3	9	No data
Sonic (m/s)	6	8	18	12	8	20



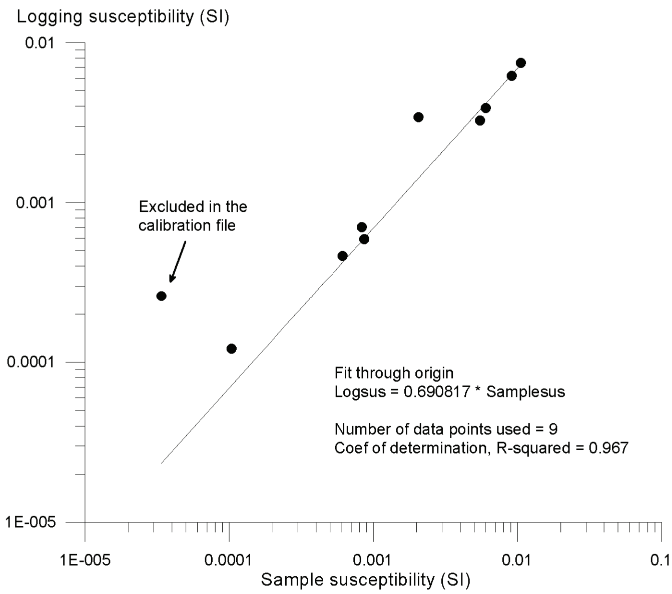


Figure 5-2. *Cross plot of logging density versus sample density for KFM09A (upper diagram) and cross plot of logging susceptibility versus sample susceptibility for KFM09A (lower diagram).*

5.3 Interpretation of the logging data

The presentation of interpretation products presented below, in the Chapters 5.3.1 and 5.3.5 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 m sections.
- Classification of estimated fracture frequency (0 to 3, 3 to 6 and > 6 fractures/m).

5.3.1 Interpretation of KFM09A

The results of the generalized logging data and fracture estimations of KFM09A are presented in Figure 5-3 below, and in a more detailed scale in Appendix 1.

The rocks in the vicinity of KFM09A are dominated by silicate density indicating a mineral composition that corresponds to granite rock (< 2,680 kg/m^3), see Table 5-2 and Figure 5-3. Subordinate short sections (< 5 m length) of rocks with higher densities occur frequently along the entire borehole length. The highest densities, those indicating diorite or gabbro rocks, generally coincide with low susceptibility and low natural gamma radiation and they most likely indicate the occurrences of amphibolite dykes. Many of the indicated amphibolite dykes occur close to positive anomalies in the natural gamma radiation that most likely correspond to pegmatite or fine-grained granite dykes, which suggests that mafic and felsic dykes are spatially related.

Table 5-2. Distribution of silicate density classes with borehole length of KFM09A.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	581	75
2,680 < dens < 2,730 (granodiorite)	93	12
2,730 < dens < 2,800 (tonalite)	39	5
2,800 < dens < 2,890 (diorite)	34	5
dens > 2,890 (gabbro)	25	3

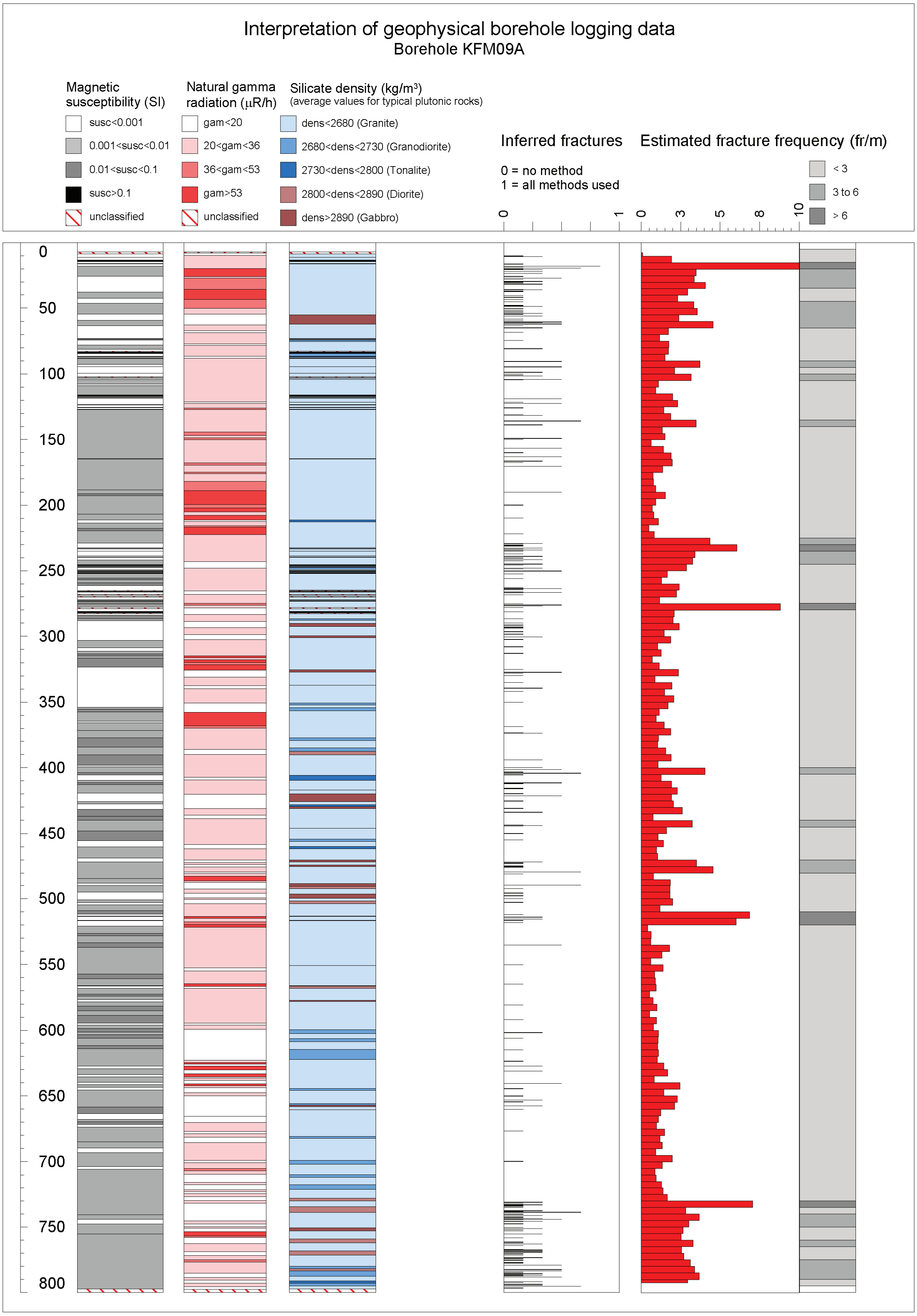


Figure 5-3. Generalized geophysical logs of KFM09A.

The natural gamma radiation is mainly in the interval 20–36 μR/h. Short sections with positive radiation anomalies occur fairly frequent in the borehole and these most likely indicate the presence of pegmatite or fine-grained granite dykes. Four significant positive radiation anomalies occur at c 20–50 m, c 190–220 m, c 314–324 m and c 358–370 m. Sections with low natural gamma radiation generally only occur in combination with increased density and decreased magnetic susceptibility, related to the probable occurrences of amphibolites.

The magnetic susceptibility is in the interval 0.003–0.01 SI for the major part of the borehole length. Long sections with decreased magnetic susceptibility (generally < 0.001) occur at c 10–128 m, 230–355 m and 733–795 m. These low magnetic intervals correspond to section with partly increased fracturing (the occurrence of fractures is often related to alteration and/or destruction of magnetite). The fairly long low magnetic section at c 330–350 m does not seem to correspond to increased fracturing, however along this section there is a slight but significant decrease in the bulk resistivity that may relate to the low susceptibility. The rocks along this section may have suffered from alteration, or there may by a difference in lithology compared to surrounding sections.

The estimated fracture frequency of KFM09A is mainly low. Increased fracturing (possible deformation zones) is indicated along the borehole sections c 15–65 m, 225–250 m, 275–280 m, 510–520 m and 730–790 m.

The section 15–65 m is characterized by a few rather narrow but distinct low resistivity and caliper anomalies (and as noted above decreased magnetic susceptibility). The sections 225–250 m, 510–520 m and 730–790 m show similar characteristics, but in combination also with a general decrease in the bulk resistivity and partly decreased P-wave velocity (c 10% decrease).The data from the section 275–280 m most likely indicate the occurrence of one single, rather narrow, fracture zone or crush zone.

The estimated apparent porosity shown in Figure 5-4 (black line) is mainly in the interval 0.5–0.6%, which is reasonable in comparison to the petrophysical data from this area. The apparent porosity was calculated only in the section 55–610 m since the large fluctuations in the fluid water resistivity (related to the salinity, green line in Figure 5-4) above and below this interval gives rise to unrealistic porosity values. Apparent porosity anomalies are few and mainly occur in the sections with indicated increased fracturing. Increased porosity is indicated at c 225–250 m, 275–278 m, 470–480 m and 512–520 m.

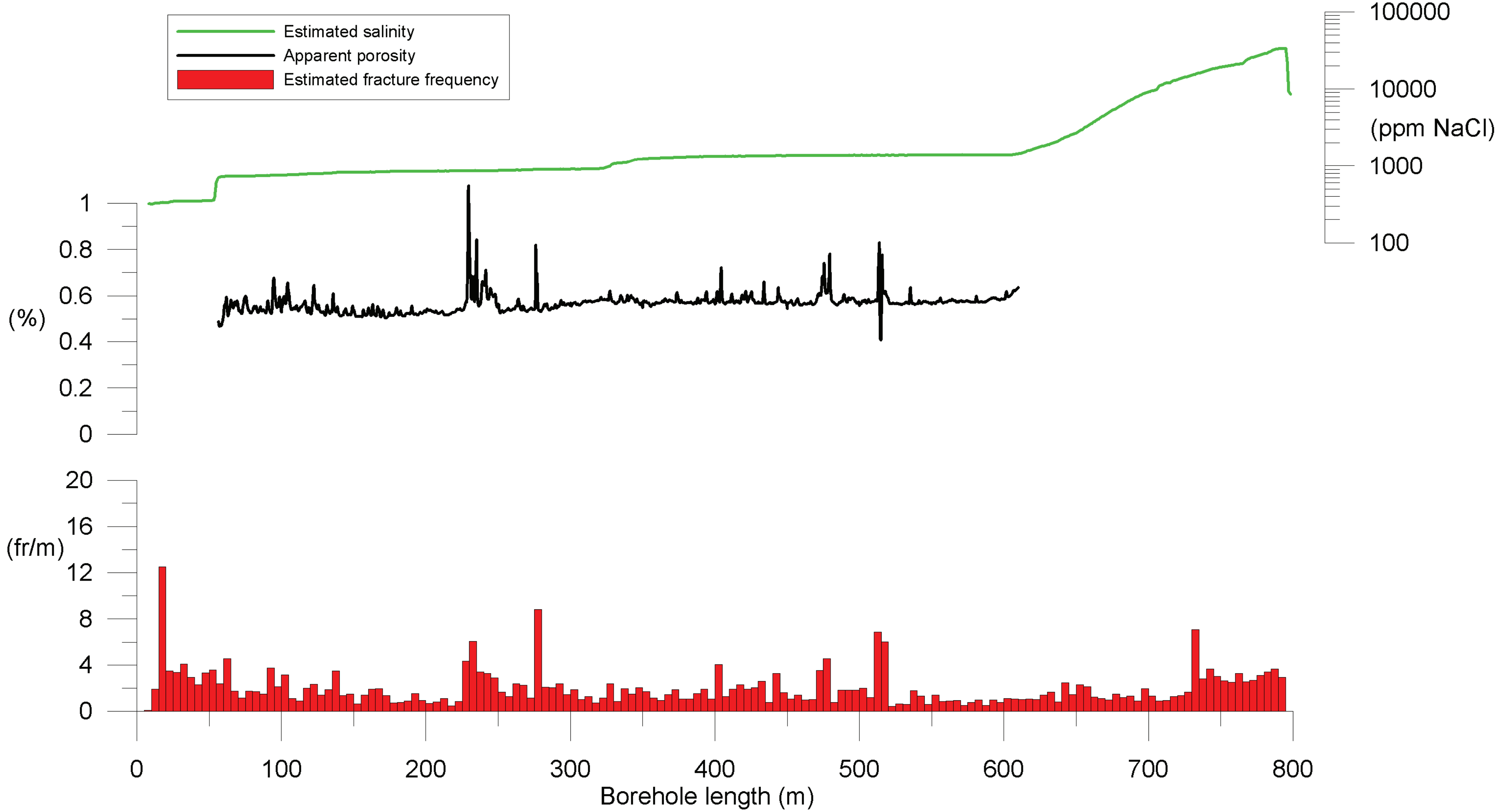


***Figure 5-4.** Estimated salinity, apparent porosity and estimated fracture frequency of KFM09A.*

5.3.2 Interpretation of KFM07B

The results of the generalized logging data and fracture estimations of KFM07B are presented in Figure 5-5 below.

The rocks in the vicinity of KFM07B are completely dominated by silicate density indicating a mineral composition that corresponds to granite rock (< 2,680 kg/m^3), see Table 5-3 and Figure 5-5. About 20 short sections of rocks with higher densities occur along the entire borehole length. These are generally < 1 m long, but two prominent sections with increased density occur at c 65–73 m and c 130–139 m. The magnetic susceptibility is anomalously low in the section 65–73 m and the average density is c 2,720 kg/m^3, which indicates that the rock is low magnetic with granodioritic composition.

The highest densities, those indicating diorite or gabbro rocks, generally coincide with low susceptibility and low natural gamma radiation and they most likely indicate the occurrence of amphibolite dykes. The spatial relation between felsic and mafic dykes that is often observed in the boreholes in the Forsmark area (see e.g. KFM09A above) is also indicated in KFM07B. However, the majority of the indicated felsic dykes are very thin.

The natural gamma radiation is mainly in the interval 20–36 μR/h. Positive radiation anomalies are fairly rare apart from the two sections 126–130 m and 259.5–262 m. These most likely indicate the presence of pegmatite or fine-grained granite dykes.

The magnetic susceptibility is mainly in the interval 0.003–0.006 SI. Several sections with decreased magnetic susceptibility occur along the entire borehole length (Figure 5-5). The majority of the low magnetic intervals coincide with indicated felsic or mafic dykes, with the exception of the section 65–73 m as noted above.

The indicated fracture frequency in KFM07B is mainly low. Two sections with strongly increased fracture frequency are indicated at c 90–100 m and 165–170 m. The section 90–100 m is characterized by greatly decreased resistivity and a slight decrease in the P-wave velocity. The section 165–170 m is mainly characterized by decreased resistivity and caliper anomalies, but also slightly increased P-wave velocity. The indicated increase in P-wave velocity appears unrealistic, especially since there is no increase in density that possibly could affect the elastic properties of the rock.

The estimated apparent porosity shown in Figure 5-6 (black line) averages at c 0.6 %, which corresponds well the petrophysical data from this area. Increased apparent porosity, related to increased fracture frequency, occurs at c 92–98 m, c 119–121 m and c 168–170 m. However, also note the decrease in the apparent porosity that occurs in the section interval c 190–210 m, which may indicate anomalously low fracturing of the rock in this part of the borehole.

The estimated salinity of the borehole fluid is c 3,400–5,400 ppm NaCl.

Table 5-3. Distribution of silicate density classes with borehole length of KFM07B.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	208	89
2,680 < dens < 2,730 (granodiorite)	15	6
2,730 < dens < 2,800 (tonalite)	7	3
2,800 < dens < 2,890 (diorite)	2	1
dens > 2,890 (gabbro)	2	1

Figure 5-5. Generalized geophysical logs of KFM07B.

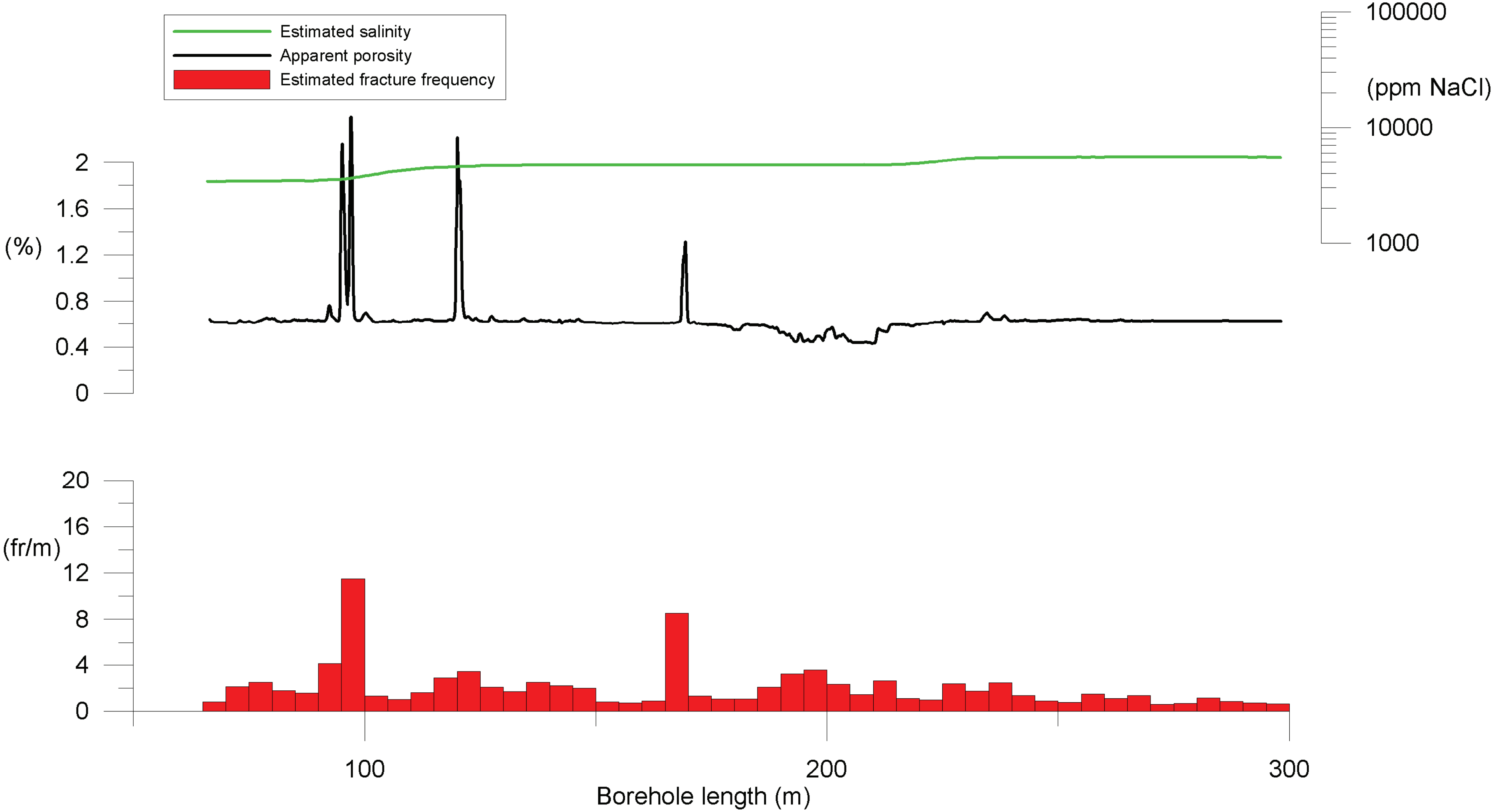


Figure 5-6. *Estimated salinity, apparent porosity and estimated fracture frequency of KFM07B.*

5.3.3 Interpretation of HFM25

The results of the generalized logging data and fracture estimations of HFM25 are presented in Figure 5-7 below.

The rocks in the vicinity of HFM25 are completely dominated by silicate density indicating a mineral composition that corresponds to granite rock (< 2,680 kg/m^3). The density (not silicate density) is fairly constant in the interval 2,590–2,630 kg/m^3 along the entire borehole length. Less than 10 short sections (< 1 m) with increased density occur with an even distribution. The high density anomalies generally coincide with decreased natural gamma radiation and also decreased magnetic susceptibility, which suggests that they are caused by amphibolites.

The natural gamma radiation is mainly in the interval 20–30 µR/h, apart from the section c 60–80 m in which the natural gamma radiation is mainly < 20 µR/h. Approximately 10 short intervals with increased natural gamma radiation are identified in HFM25. These most likely correspond to dykes of pegmatite or fine grained granite. The felsic dykes often show a clear spatial relation to the high density anomalies that indicate amphibolite dykes.

The magnetic susceptibility is generally in the interval 0.004–0.006 SI, but there is also a fairly large occurrence of sections with decreased magnetic susceptibility (0.0003–0.0006 SI). Many of the low magnetic section correspond to indicated dykes or increased fracture frequency, but some of them (e.g. 99–105 m) seem to occur in "normal fresh rock", possibly indicating mineral alteration.

The fracture frequency of HFM25 is low. Slightly increased fracturing (most likely single fractures and no deformation zone) is indicated in the sections c 15–20 m and c 165–185 m.

5.3.4 Interpretation of HFM27

The results of the generalized logging data and fracture estimations of HFM27 are presented in Figure 5-8 below.

The rocks in the vicinity of HFM27 are dominated by silicate density indicating a mineral composition that corresponds to granite rock (< 2,680 kg/m^3). In the central parts of the borehole there is a fairly large occurrence of high density anomalies that coincide with decreased magnetic susceptibility and decreased natural gamma radiation. This combination of physical properties is typical for amphibolite dykes.

The occurrence of a few felsic dykes is indicated by increased natural gamma radiation, decreased magnetic susceptibility in combination with density < 2,650 kg/m^3. The felsic dykes show a clear spatial relation with the mafic dykes.

The natural gamma radiation is mainly in the interval 20–30 µR/h, apart from the positive and negative anomalies that are related to the occurrences of felsic and mafic dykes.

The magnetic susceptibility shows large variations, mainly between the two intervals 0.0003–0.0005 SI and 0.002–0.005 SI. The majority of the low magnetic sections coincide with sections of indicated felsic or mafic dykes.

Figure 5-7. Generalized geophysical logs of HFM25.

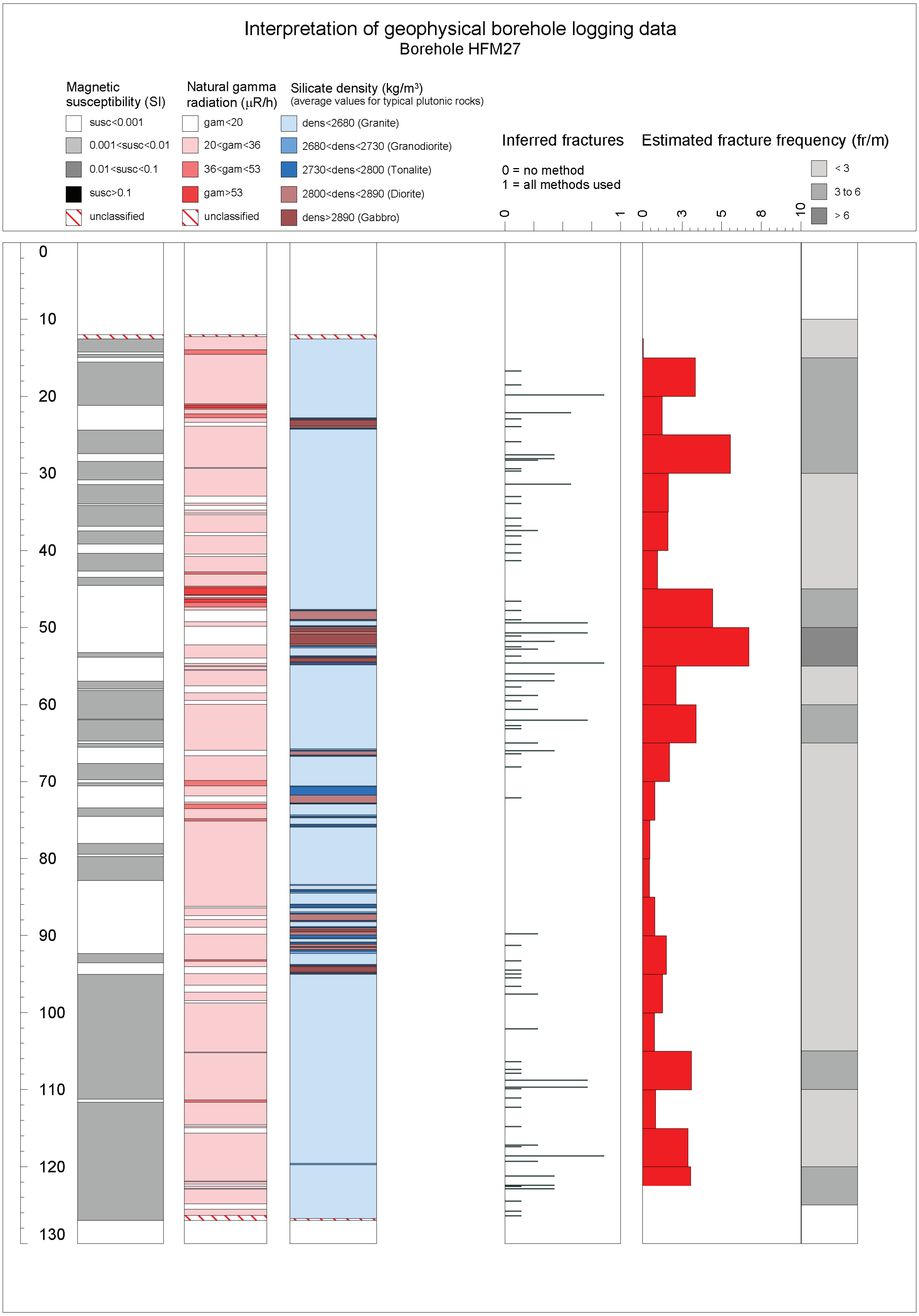


Figure 5-8. Generalized geophysical logs of HFM27.

The estimated fracture frequency of HFM27 is mainly low or moderate. Strongly increased fracturing (a possible deformation) is indicated in the section c 45–65 m. This section is characterized by several sharp low resistivity anomalies in combination with a general decrease in the bulk resistivity, and also partly decreased P-wave velocity, decreased magnetic susceptibility and several caliper anomalies. Observe the clear spatial relation between this indicated deformation zone and the combined occurrences of mafic and felsic dykes.

The occurrences of single large fractures (or possibly crushed rock) are indicted in the sections 19–22 m, 27–29 m, 108–110 m and 117–123 m. These sections are characterized by sharp low resistivity anomalies, caliper anomalies and decreased magnetic susceptibility. The sections 19–22 m and 117–123 m also show indications of partly decreased P-wave velocity.

5.3.5 Interpretation of HFM28

The results of the generalized logging data and fracture estimations of HFM28 are presented in Figure 5-9 below.

The rocks in the vicinity of HFM28 are completely dominated by silicate density indicating a mineral composition that corresponds to granite rock (< 2,680 kg/m^3). However, the section c 11–32 m (especially c 24–32 m) is dominated by increased density values and decreased natural gamma radiation. A few short sections with increased density, decreased natural gamma radiation and decreased magnetic susceptibility also occur in the lower half of the borehole. The physical properties in these sections most likely indicate the occurrences of amphibolite dykes.

The natural gamma radiation is mainly in the interval 20–36 μR/h, apart from a number of short sections with increased natural gamma radiation that most likely correspond to dykes of pegmatite or fine grained granite. An almost 10 m long section with increased natural gamma radiation occurs at c 70–80 m.

The magnetic susceptibility is generally in the interval 0.002–0.005 SI. Sections with decreased magnetic susceptibility (< 0.001 SI) generally coincide with indicated dykes. One exception is the interval 58–63 m, in which the decreased magnetic susceptibility coincides with a general decrease in the bulk resistivity. This combination of physical properties is typical for deformation zones, but could also indicate mineral alteration.

The estimated fracture frequency of HFM28 is low. Slightly increased fracturing (most likely single fractures and no deformation zone) is indicated in the sections c 15–25 m, 110–115 m and c 130–135 m.

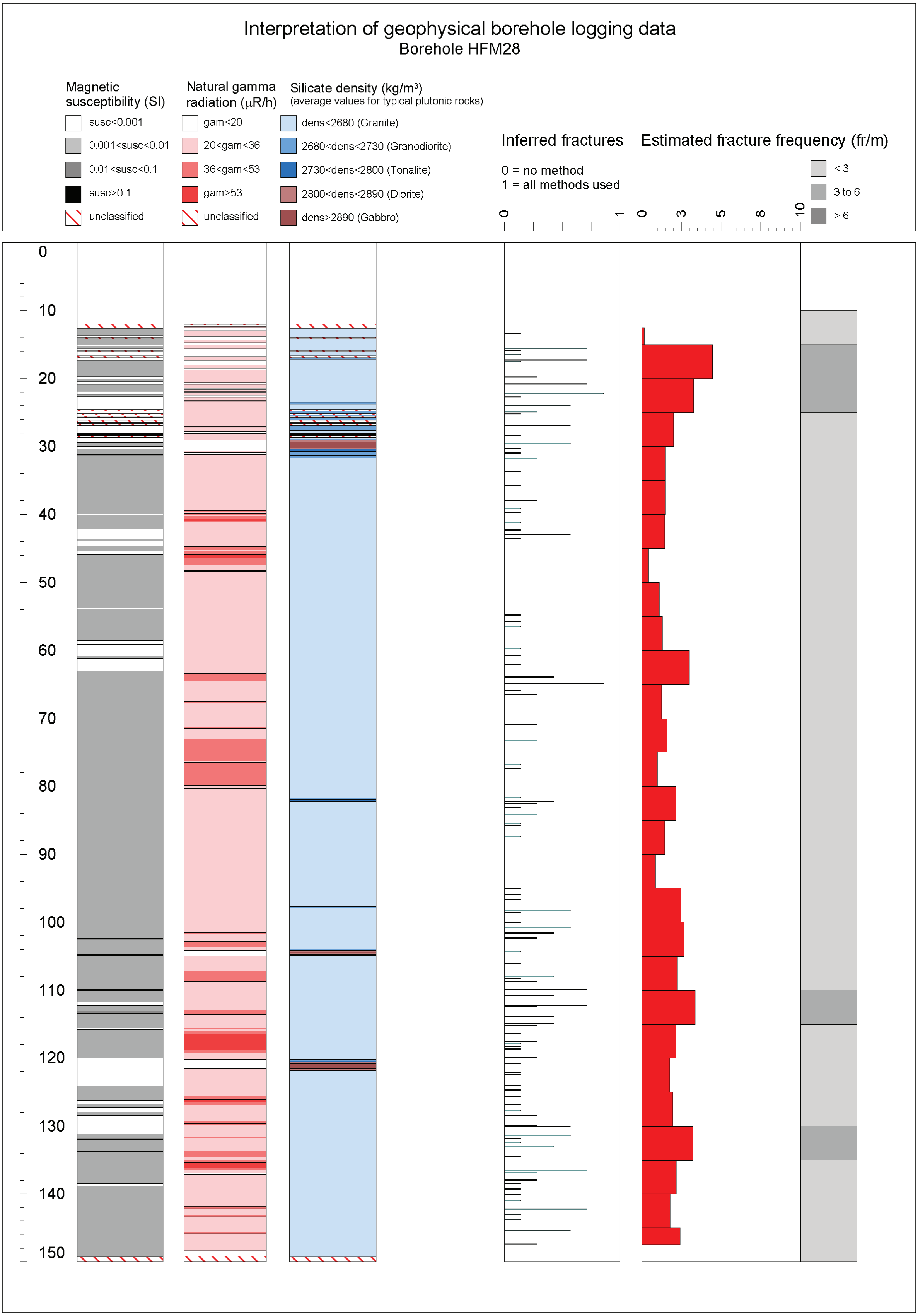


Figure 5-9. Generalized geophysical logs of HFM28.

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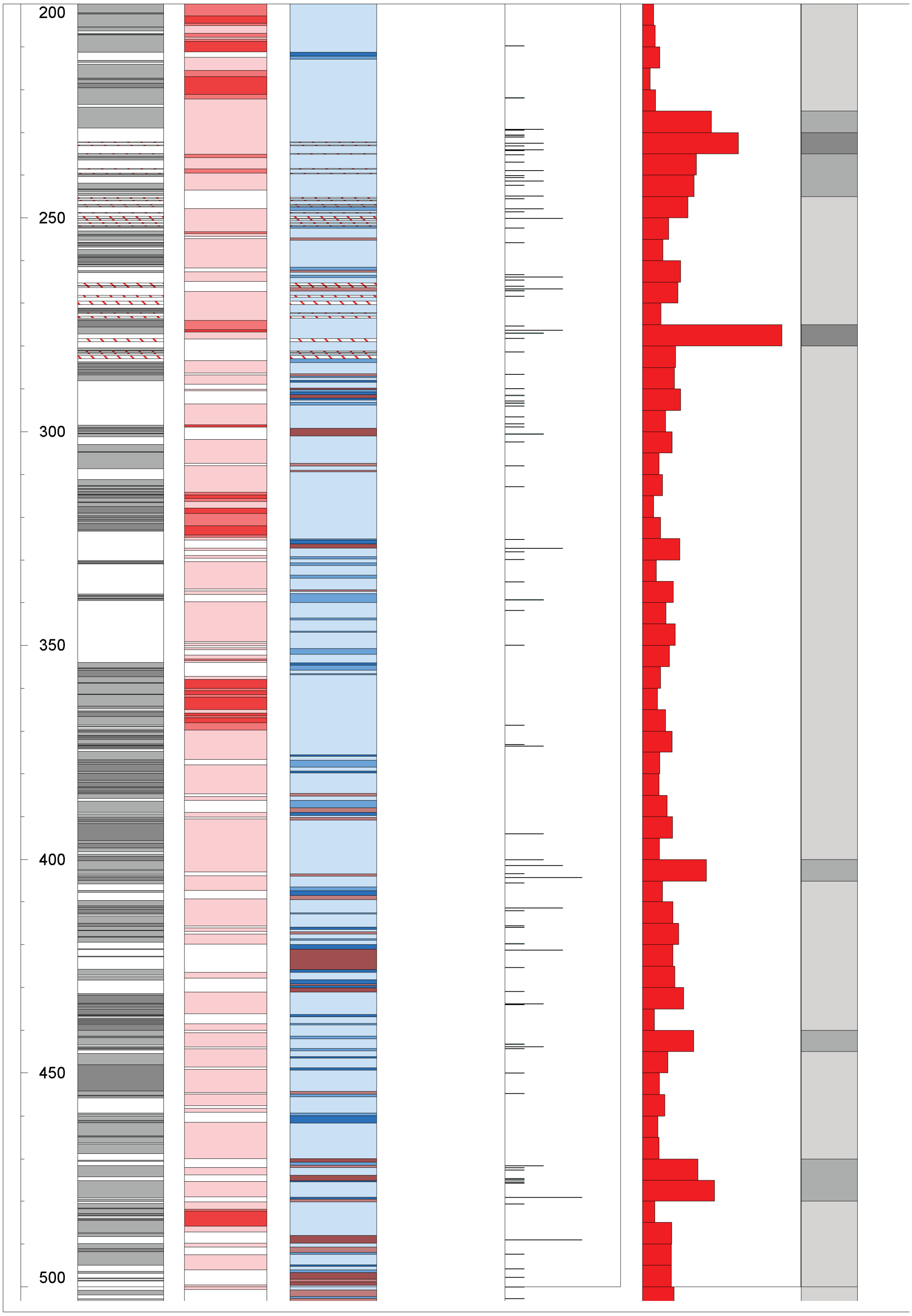
Generalized geophysical loggings of KFM09A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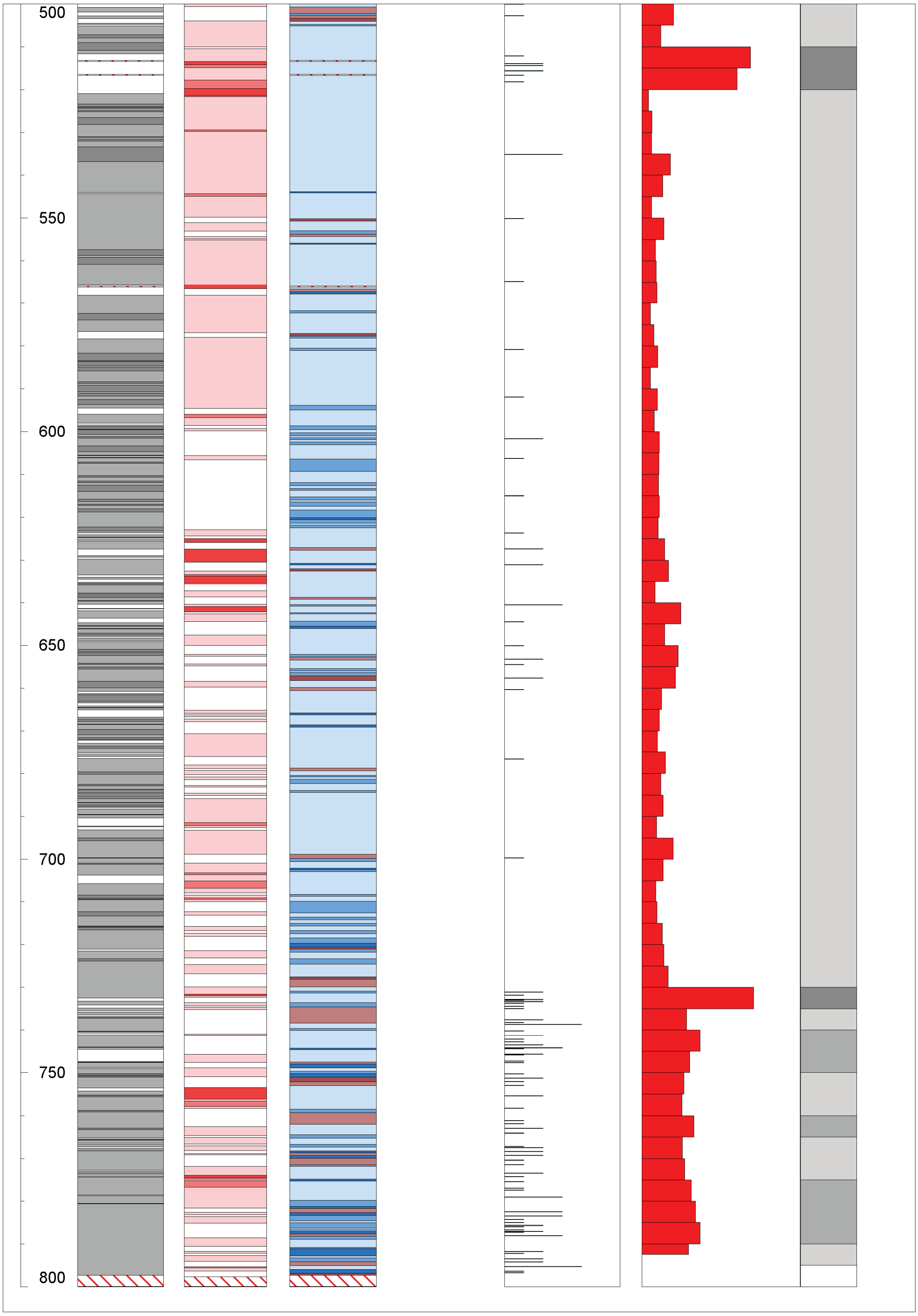
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