P-04-80

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Interpretation of borehole geophysical measurements in KFM01A, KFM01B, HFM01, HFM02 and HFM03

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June 2004

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ISSN 1651-4416
SKB P-04-80

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Keywords: Borehole, Logging, Geophysics, Geology, Bedrock, Fractures, Salinity, Temperature gradient, AP PF 400-03-48, AP PF 400-03-90. Field note: Forsmark 335; 344.

Abstract

This report presents the compilation and interpretations of geophysical logging data from the cored boreholes KFM01A (including the percussion drilled uppermost 100 m), KFM01B and the percussion drilled boreholes HFM01, HFM02 and HFM03.

The main objective of these investigations is to provide supportive information to the geological core mapping and to the single-hole interpretation. Another purpose of this investigation is to compare duplicate logging data from HFM01 and HFM02 obtained by the two contractors Malå GeoScience and Rambøll.

The bedrock in the vicinity of all five boreholes shows with few exceptions silicate densities indicating granitic composition. The exceptions indicated are occurrences of both high-density rocks (probably amphibolite and tonalite) and high radiation rocks (pegmatite or fine-grained granite) often as thin veins. The fracture frequency is in general low in all boreholes. However, the top c. 120 m of KFM01B, section 100-220 m of KFM01A and section c. 35-65 m of HFM01 clearly show an increased fracturing. Distinct geophysical anomalies, including temperature gradient, infer the presence of water bearing fractures.

The comparison of logging data between the two contractors Malå GeoScience and Rambøll, indicates some significant deviations. In HFM01 there are two distinct positive anomalies in the Malå density log data that do not occur in the Rambøll log, and no corresponding high density rocks are indicated in the Boremap data. Such indications of erroneous data are important since they could transfer into faulty rock classifications of the boreholes, especially for the percussion drilled holes where the geophysical logs play a more important role. Level differences in the natural gamma radiation logs and the magnetic susceptibility logs of the two contractors are also reported.

Sammanfattning

Denna rapport presenterar resultatet av tolkningen av geofysiska loggdata från kärnborrhålen KFM01A, inklusive den översta hammarborrade delen (0-100 m), och KFM01B samt hammarborrhålen HFM01, HFM02 och HFM03.

Det huvudsakliga syftet med detta arbete är att ta fram resultat som kan tjäna som stödjande underlag vid kärnkarteringen och dessutom vid enhålstolkningen av de aktuella borrhålen. Ett annat syfte med undersökningen är att jämföra två uppsättningar loggdata, den ena insamlad av Malå GeoScience och den andra av Rambøll, i borrhålen HFM01 och HFM02. Detta görs bland annat för att identifiera eventuella icke- geologiskt relaterade skillnader mellan de två entreprenörernas mätningar.

Berggrunden runt samtliga undersökta borrhål domineras helt av bergarter med en silikatdensitet motsvarande mineralsammansättningen hos granit. Relativt tunna sektioner, ofta < 1 m, av bergarter med hög densitet (motsvarande tonalit, diorit eller gabbro), eller hög naturlig gammastrålning, är dock vanligt förekommande. Tidigare undersökningar har visat att dessa ibland kan kopplas samman med förhöjd sprickighet. Sprickfrekvensen är generellt sett låg. Tydliga indikationer på förhöjd sprickfrekvens finns dock längs de översta ca. 120 m av KFM01B, längs sektionen 100-220 m av KFM01A och längs 35-65 m djup i HFM01. De geofysiska loggarna (inklusive beräknad vertikal temperaturgradient) indikerar att flera sprickor är vattenförande.

Jämförelserna mellan loggdata producerade av Malå GeoScience respektive Rambøll påvisar en del skillnader. En viktig skillnad är två tydliga positiva anomalier i Malå GeoSciences densitetsdata för HFM01 vilka inte finns i Rambølls data, och ej heller går att påvisa i den geologiska karteringen. Denna typ av missvisande anomalier skulle kunna ge upphov till felaktiga bergartsklassificeringar, åtminstone i hammarborrhål där geofysikloggarna spelar en avgörande roll för den geologiska karteringen. Jämförelsen påvisar även skillnader i nivåer på de två naturlig gamma strålningsloggarna och de magnetiska susceptibilitetsloggarna mellan Malå GeoSciences och Rambølls mätningar.

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. This document reports the results gained from the interpretation of borehole geophysical logging data from the cored boreholes KFM01A and KFM01B, and the percussion drilled boreholes HFM01, HFM02 and HFM03 at Forsmark (Figure 1-1).

Generalized geophysical logs related to lithological variations are presented together with indicated fracture logs (including estimated fracture frequency). Vertical temperature gradient and estimated salinity logs are also calculated. The logging measurements in the two cored boreholes were conducted by Rambøll /1/. In the percussion drilled holes HFM01 and HFM02 measurements were performed both by Rambøll /1/ and by Malå GeoScience /2/. The percussion drilled boreholes HFM03 and the uppermost part (0-100 m) of KFM01A were logged only by Malå GeoScience /2/.

The interpretation presented in this report is performed by GeoVista AB in accordance with the instructions and guidelines presented by SKB in the method description MD 221.003 and activity plan AP PF 400-03-48 and 400-03-90 (SKB internal controlling documents).

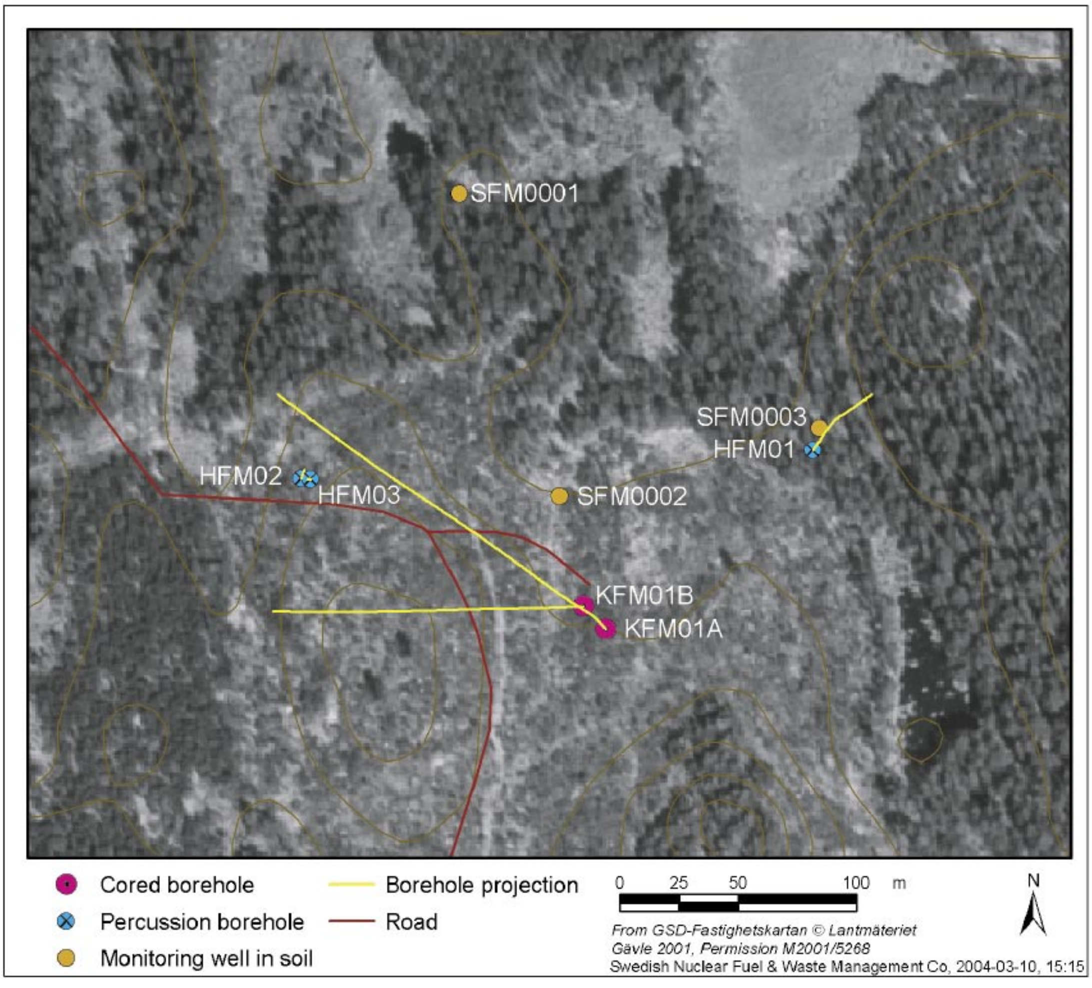


Figure 1-1. *Aerial photo of drill-site one in Forsmark showing the positions of the boreholes.*

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 logs are generalized and 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 logs, the single point resistance (SPR), caliper mean and sonic logs.

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

A secondary purpose with the current investigation is to compare and evaluate the same type of logging data measured separately by Rambøll and by Malå GeoScience in the boreholes HFM01 and HFM02. The reason for this comparison is an indication from previous measurements, of differences in data measured in the same boreholes by the two logging contractors.

3 Execution

The software used for the interpretation are WellCad v3.2 (ALT), which is mainly used for plotting, Grapher v4 (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.

3.1 Preparation of logging data

3.1.1 Data provided by Rambøll: KFM01A (100-1000 m), KFM01B, HFM01 and HFM02

The logging data were partly retrieved from SICADA and partly delivered by Rambøll via email. The data used for interpretation are:

Density (gamma-gamma)
Magnetic susceptibility
Natural gamma radiation
Long normal resistivity
Short normal resistivity
SPR (Single-point-resistance)
Focused resistivity (300 cm and 140 cm)
Sonic
Caliper mean
Fluid resistivity
Fluid temperature

The levels of the gamma-gamma and magnetic susceptibility logs were adjusted by use of petrophysical data from KFM01A and KFM02A. Sonic data have been rejected for some sections. There are no SPR or long normal resistivity data measured in KFM01B. No resistivity or SPR measurements were performed by Rambøll in HFM01 and HFM02.

3.1.2 Data provided by Malå GeoScience: KFM01A (0-100 m), HFM01, HFM02 and HFM03

The logging data were retrieved from SICADA. Data from KFM01A (0-100m) and HFM03 were used to produce generalized logs. The data from HFM01 and HFM02 were only used for the comparison with Rambøll's data. The logging data used for interpretation are:

Lateral resistivity
Short normal resistivity
SPR (Single-point-resistance)
Magnetic susceptibility
Natural gamma radiation
Fluid resistivity
Fluid temperature
Density (gamma-gamma)
Caliper

As pointed out by Thunehed in /3/ the density, resistivity and SPR equipment used by Malå GeoScience in the percussion drilled holes are not up to the standards required for these types of loggings, which has also been pointed out by the contractor before the surveys. The electrical logs, especially the short normal and the SPR, give anomalies of sometimes peculiar shape and unrealistic magnitude. They have still been used in the interpretation of HFM03 since the anomalies seem to occur at low resistivity features related to fracture zones.

The level of the magnetic susceptibility log of HFM03 was adjusted based on a comparison of data from HFM02 (Rambøll data compared to Malå GeoScience data). The levels of the gamma-gamma and magnetic susceptibility logs were then adjusted by using petrophysical data from KFM01A and KFM02A. The natural gamma radiation data of KFM01A (0-100m) and HFM03 were adjusted by multiplication of a constant, see also /3/.

3.2 Interpretation of the logging data

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

1. Preparations of the logging data (calculations of noise levels, average filtering, error estimations, re-sampling, drift correction, calculation of salinity, calculation of vertical temperature gradient).

The logs are average (or median) filtered (3 to 5 point triangular filters, where shorter filters have been used for methods with short wave-length anomalies). The residual from these filter operations were used as estimates of the noise levels.

The vertical temperature gradient (in degrees/km) is calculated from the fluid temperature logging for 9 meter sections /4/:

$$TempGrad = \frac{1000\left[9 \quad zt - \sum z \sum t\right]\sin\varphi}{9\sum z^2 - \left(\sum z\right)^2}$$

where z = depth co-ordinate (m), t = fluid temperature (ºC) and φ = borehole inclination.

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

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

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

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 /5/ and the data are then divided into 5 intervals indicating a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to /6/. The intervals are bounded by the threshold values

granite < 2680 kg/m^3
2680 kg/m^3 < granodiorite < 2730 kg/m^3
2730 kg/m^3 < tonalite < 2800 kg/m^3
2800 kg/m^3 < diorite < 2890 kg/m^3
2890 kg/m^3 < gabbro

The magnetic susceptibility logging is subdivided into steps of decades and the natural gamma radiation is divided into ”low”, ”medium”, ”high” or “very high” radiation by setting threshold values at 20.5, 36.3 and 52.8 µR/h respectively. The threshold values for each level have been adjusted with respect to the geological environment in the candidate area.

3. Interpretation of large fractures and estimated fracture frequency

Interpretation of large fractures and estimation of the fracture frequency is based on: focused resistivity, caliper mean, resistivity, SPR and sonic data for the cored boreholes and lateral resistivity, short normal resistivity, SPR and caliper for the percussion drilled holes.

The position of large fractures is estimated by applying a second derivative filter (deconvolution filter for lateral resistivity) to the log data and then locating maxima (or minima depending on type of log) in the filtered log. Maxima (or minima) above (below) a certain threshold value are selected as inferred fractures. The result is presented as a column diagram where column height 0 = no fracture, column height 1 = fracture indicated by all logs and intermediate values corresponds to fractures inferred by some, but not all, logs. The estimated fracture frequency is calculated as a weighted sum of the maxima (minima) derivative logs in 5 metres sections. The weighted sum has been calibrated to the core mapped frequency of natural fractures in KFM01A and KFM02A. No corresponding calibration has been possible to make for the percussion drilled holes, which means that the fracture frequency estimates for these holes might be biased. Estimated fracture frequencies have also been classified into three classes corresponding to <3, 3 to 6 and >6 fractures per metre.

Table 3-1 shows the threshold values used for the interpretation of fractures and fracture frequency. The threshold values refer to the output of the filters above. These outputs have also been normalised with respect to their mean and standard deviation in order to make different logging methods more comparable. The thresholds have been set by a trial-and-error procedure with the aim of locating possible fractures that produce significant geophysical anomalies but avoiding those anomalies that might be due to instrumental noise or very narrow fractures. The same threshold values will most likely be used for other boreholes in the investigation area. The weights in Table 3-1 refer to the calibration to core mapped frequency as described above.

Table 3-1. Threshold values, in GeoVista in-house programs fract_det, fract_normres and fract_latres, and weights used for estimating position of fractures and calculation of estimated fracture frequency, respectively.

	Borehole	Sonic	Focused res. 300	Focused res. 140	Caliper	Short norm. resist.	Long norm. resist.	Later. resist.	SPR
Threshold	KFM01A,	1.2	1.35	1.0	1.0	2.5	--	--	2.0
	KFM01B	0.6	1.0	1.0	0.6	--	--	--	--
Weight	KFM01A,	4.0	4.0	2.56	--	1.75	0.48	--	2.56
	KFM01B	4.0	4.0	2.56	6.67	--	--	--	--
Threshold	HFM01,	1.1	0.6	0.25,1.25*	0.06	--	--	--	--
	HFM02	0.6	0.6	0.6	0.2	--	--	--	--
Weight	HFM01,	4.0	4.0	2.56	6.67	--	--	--	--
	HFM02	4.0	4.0	2.56	6.67	--	--	--	--
Threshold	HFM03	--	--	--	1.0	4.0	--	1.0	1.0
Weight	HFM03	--	--	--	6.67	1.75	--	4.0	2.56

* Different threshold values were used for two parts of the borehole due to the large difference in amplitude of the log data above and below a change in the fluid resistivity.

4 Results

4.1 Control of the log data

4.1.1 Noise levels and qualitative control

Noise levels of the raw data for each log method are presented in Table 4-1 and 4-2. Noise levels are only presented for the data used in the interpretation. For a majority of the log data (except density) the noise is lower, or slightly higher, than the recommended level. The noise levels are probably over-estimated for methods with many short wave-length anomalies like magnetic susceptibility and natural gamma radiation. The higher than recommended noise level for the density log will have the effect that a subtle density anomaly with short wave-length will be insignificant.

A qualitative inspection was performed on the logs. The data were checked for spikes and/or other obvious incorrect data points. Such erroneous data points were discovered in the sonic log of KFM02A. Most sections with bad sonic data from this hole were short but the data from depths of 339 to 377 m and 907 to 979 m had to be rejected. Sonic data were also rejected for a large portion of the uppermost 100 metres of KFM03A where the borehole diameter is large.

Table 4-1. Noise levels in geophysical logging data for cored boreholes.

Logging method	KFM01A (below 100m)	KFM01B	Recommended max noise level
Density (kg/m^3)	17	11	3 – 5
Magnetic susceptibility (SI)	$0.9\cdot10^{-4}$	$0.2\cdot10^{-3}$	$1\cdot10^{-4}$
Natural gamma radiation (µR/h)	0.6	0.6	0.3
Fluid resistivity (%)	0.02	0.07	2.0
Fluid temperature (ºC)	$0.8\cdot10^{-3}$	$2\cdot10^{-3}$	0.01
Caliper (mm)	0.02	0.015	0.5
Long normal resistivity (%)	0.3	--	2.0
Short normal resistivity (%)	0.2	0.3	2.0
SPR (%)	0.09	--	--
Focused resistivity 300 (%)	8.0	12	---
Focused resistivity 140 (%)	2.4	4	---
Sonic (m/s)	16	19	20

Table 4-2. Noise levels in geophysical logging data for percussion drilled boreholes (HFM01-02 data from Rambøll, HFM03 and KFM01A data from Malå GeoScience).

Logging method	HFM01	HFM02	HFM03	KFM01A (0-100m)	Recommended max noise level
Density (kg/m^3)	27	30	35	8	3 – 5
Magnetic susceptibility (SI)	$2 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$3 \cdot 10^{-5}$	$9 \cdot 10^{-6}$	$1 \cdot 10^{-4}$
Natural gamma radiation (μR/h)	0.9	1.1	2.3	1.6	0.3
Fluid resistivity (%)	0.08	0.06	0.02	0.04	2.0
Fluid temperature (ºC)	$9 \cdot 10^{-4}$	0.002	0.005	$8 \cdot 10^{-4}$	0.01
Caliper (mm)	0.2	0.1	0.1	0.03	0.5
Sonic (m/s)	25	29	--	--	20
Focused resistivity 300 (%)	9	8	--	--	--
Focused resistivity 140 (%)	2	4	--	--	--
Lateral resistivity (%)	--	--	3.9	0.5	2.0
Short normal resistivity (%)	--	--	2.5	0.3	2.0
SPR (%)	--	--	0.5	0.2	---

4.1.2 Comparison between logging and petrophysical data for KFM02

A quality control of the gamma-gamma and the magnetic susceptibility logs was performed by comparing the log data to the petrophysical data at the corresponding depths. In Figure 4-1 the gamma-gamma (density) log is plotted versus wet density sample measurements for data from KFM01A and KFM02A. The correlation is good except for one sample that was located at a density gradient in the log and two samples of low-density vuggy granite. A linear fit to the data (solid line in Figure 4-1) was used to calibrate the density logs performed by Rambøll. The accuracy of the fit, excluding the three deviating data points mentioned above, is better than 30 kg/m^3. This number indicates the absolute accuracy of the density log data.

A similar plot between the susceptibility logging and susceptibility measured on core samples is shown in Figure 4-2. There is an excellent correlation between logging and petrophysical data, the slope of the fitted line is however 0.662, which indicates that the logging measurements underestimate the true magnetic susceptibility. The fit was used to calibrate the logging data measured by Rambøll. The accuracy of the fit is around 10^{-3} SI.

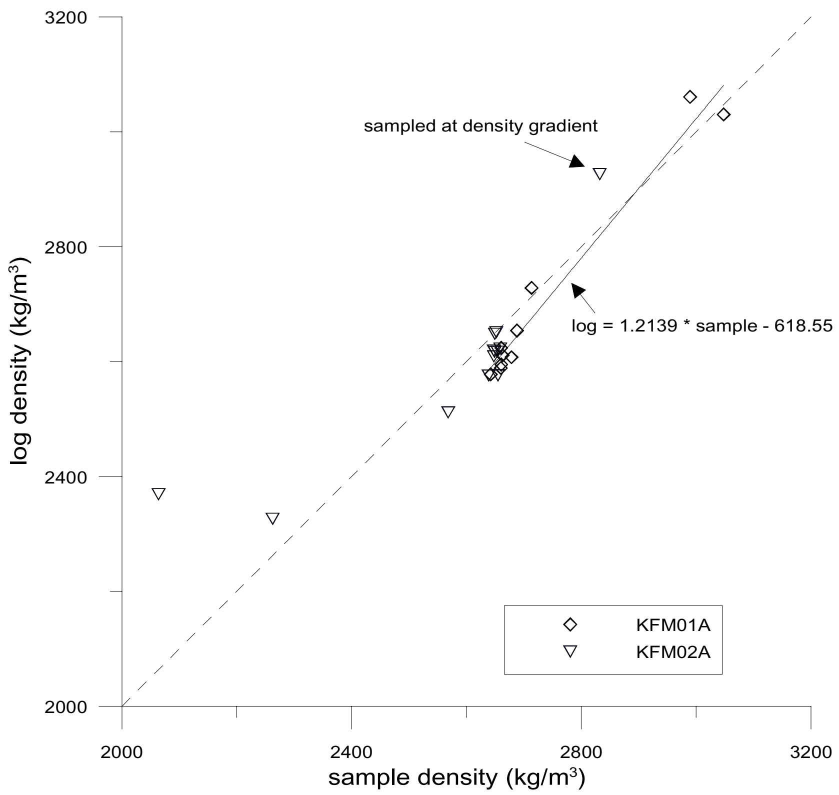


Figure 4-1. *Cross plot of density logging data versus density data from core samples.*

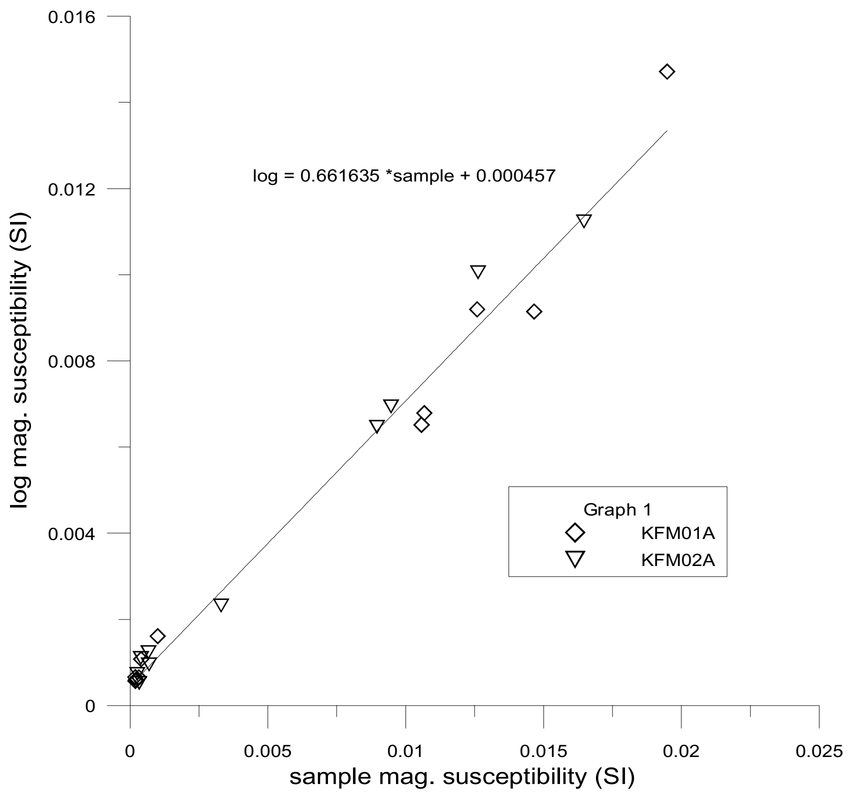


Figure 4-2. *Cross plot of magnetic susceptibility logging data versus susceptibility data from core samples*

4.2 Comparison between log data from HFM01 and HFM02 measured by Rambøll and Malå GeoScience

The boreholes HFM01 and HFM02 were logged by both logging contractors Rambøll and Malå GeoScience, which allows an independent comparison between the same kind of log data from the two separate measurements. The focus was put on the lithological logs (density, magnetic susceptibility and natural gamma radiation), since these perhaps are the most important logs and also because no normal or lateral resistivity loggings were performed by Rambøll in these boreholes.

In both boreholes there is a missmatch in depth of c. 0.5-0.7 m between the data from the two contractors. Prior to the comparison, each Malå GS log was therefore adjusted with respect to the corresponding log method of Rambøll. The logs were then resampled to common depth co-ordinates. Cross plots for HFM01 of the three log methods are shown in Figure 4-3 and data plots versus depth are shown in Figure 4-4. The general level of the density is fairly uniform for the two logs, but it is worth noting that there is a slight missmatch between log density and petrophysical data indicated in the cored boreholes KFM01 and KFM02, see Section 4.1.2. The density cross plot (Figure 4-3a) indicates a poor correlation between the data of the two contractors, which is indicated by the circular shape of the data distribution. In the depth-plot (Figure 4-4a) there are several things worth noting. Both logs are rather noisy, which counteracts a correlation between minor anomalies but from Figure 4-4a it is clear that the most pronounced anomalies are distinct in both logs. However, there are also two distinct positive anomalies in the Malå GS data (indicated by the arrows) that do not occur in the Rambøll log and no corresponding high density rocks are indicated in the Boremap data. The Malå GS log also displays a drift with increasing density with depth that do not occur in the Rambøll data, especially for the uppermost part of the hole.

The magnetic susceptibility logs show a fairly good correlation (Figures 4-3b and 4-4b). The Malå GS susceptibiity log however indicates approximately 3 times lower level of the susceptibility than the Rambøll data. This is important since the Rambøll log underestimates the susceptibility in the cored boreholes KFM01 and KFM02 by c. 30 % (see Section 4.1.2). When adjusting the Malå GS data with respect to the slope of the fitted line in the cross plot (Figure 4-3b), we can see that the two logs become almost identical (Figure 4-4b).

The Rambøll and Malå GS natural gamma radiation logs correlate nicely with each other (Figures 4-3c and 4-4c). However, the radiation level of the Rambøll log is only c. 2/3 of the level of the Malå log. It has not been possible to determine which of the two logs that shows the most correct radiation level. However, the Rambøll natural gamma log has given very consistent background levels in a large number of borehole in the Forsmark area.

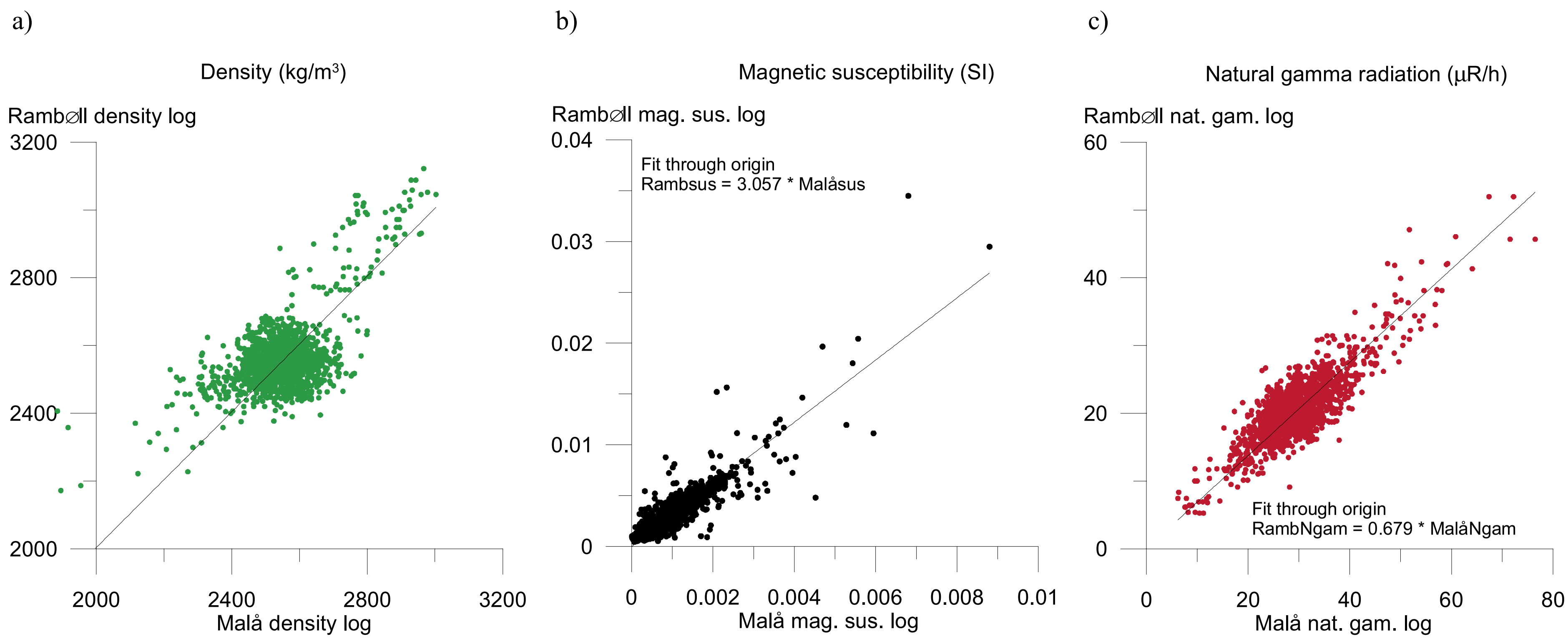


Figure 4-3. *Cross plots of log data for HFM01. a) density log b) magnetic susceptibility log c) natural gamma radiation log. See the text for explanation*

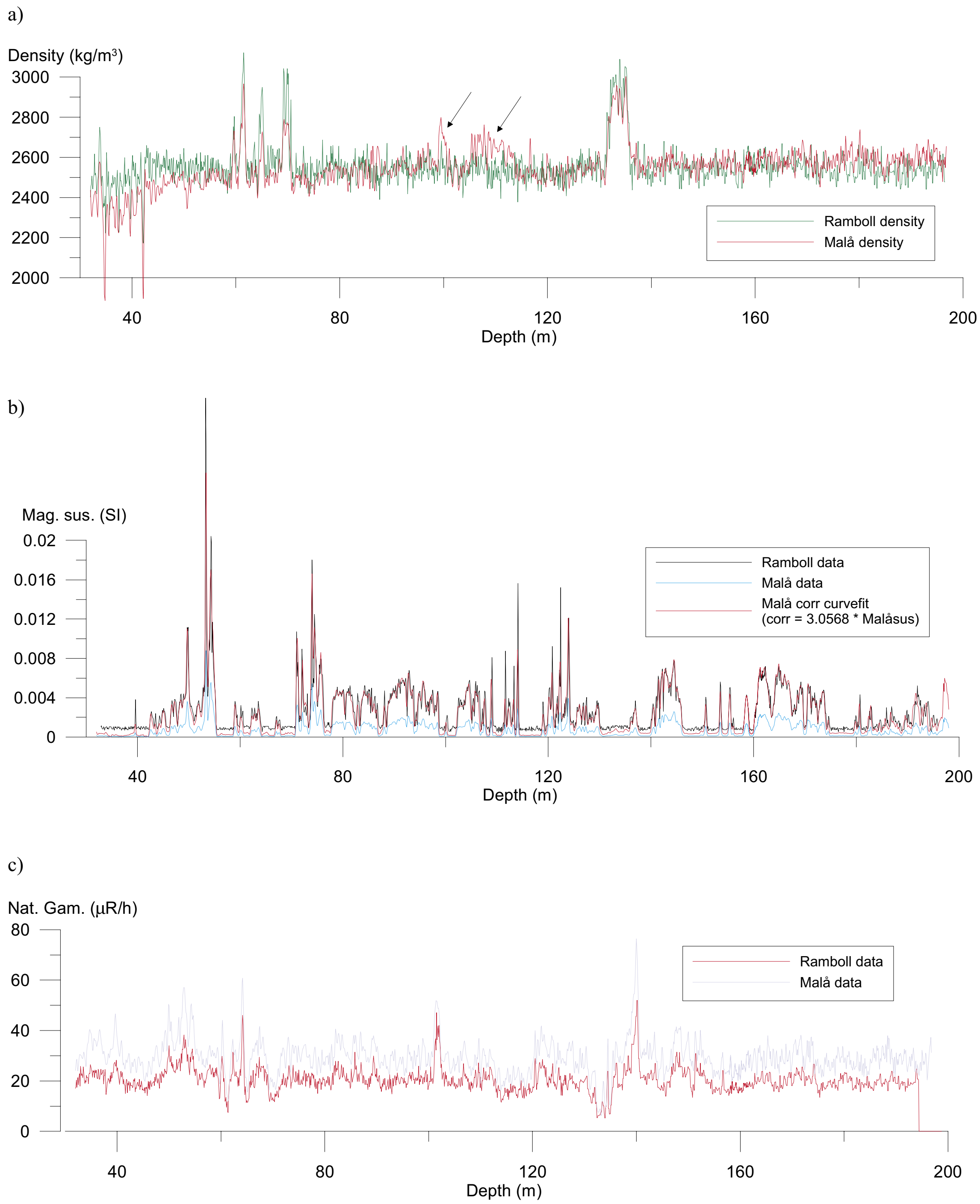


Figure 4-4. *Log data versus depth for HFM01. a) Density log. b) Magnetic susceptibility log. c) Natural gamma radiation log. See the text for explanation.*

4.3 Interpretation of the logging data

The presentation of interpretation products presented below, and in appendices 1 and 2, 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 (1 metre sections for KFM01A 0-100 m and HFM03)
- Classification of estimated fracture frequency (0 to 3, 3 to 6 and >6 fractures/m)

4.3.1 Interpretation of KFM01A (100-1000 m)

The results of the generalized data and fracture estimations for the borehole KFM01A are presented in Figure 4-6 below. The data are also presented in a larger scale in Appendix 1. The percussion drilled upper 100 metres were logged by Malå GeoScience whereas the core drilled deeper part of the hole was logged by Rambøll. This should be kept in mind if comparisons are made, although the generalized logs should be more or less independent on actual logging methods used. It should also be noted that the density log of Malå GeoScience has been difficult to calibrate.

Vertical temperature gradient and salinity
The median vertical temperature gradient in KFM01A (100-1000 m) is 11.5 ºC/km. The uppermost c. 500 m are calm with only a few anomalies at depths c. 180 m and 350 m (Figure 4-5). Below c. 700 m depth the pattern of the graph changes and there is a large number of high-frequency anomalies down to the bottom of the borehole. These anomalies may correspond to water bearing fractures. However, the repeatedly occurring wavelength of c. 10 m of many of the anomalies could indicate that some of them are noise related.

The estimated salinity is c. 8000 ppm NaCl at 100 m depth, and shows a slow but consistent decrease down to c. 2500 ppm NaCl at the bottom of the borehole (Figure 4-5). This is not in accordance with the expected result, as the salinity generally increases towards depth, and very different from the nearby borehole KFM01B (Section 4.3.3).

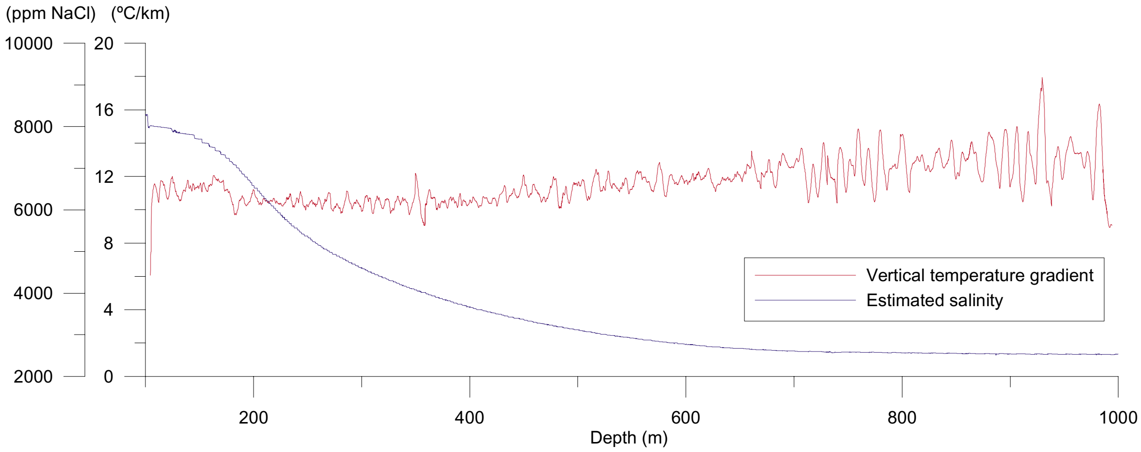


***Figure 4-5.** Vertical temperature gradient and estimated salinity for KFM01A (100-1000m).*

Correction of resistivity logs and calculation of apparent porosity

The median short normal resistivity prior to correction is 950 Ωm, and the median of the corrected short normal resistivity is 650 Ωm. These values are clearly lower than the resistivity measurements on core samples from KFM01A, which indicate that the median resistivity of the rock (taking into account the current fluid resistivity) is c. 2000-4000 Ωm. The median apparent porosity is c. 2 %, which is a large overestimation (approximately 10 times) of the rock porosity indicated by petrophysical data. The reason for this overestimation is the anomalously low resistivity data obtained by the logging.

Interpretation of rock types and fractures

Generalized geophysical logs and estimated fractures are presented in Figure 4-6. The rocks in the vicinity of the borehole are completely dominated by silicate densities that indicate a mineral composition corresponding to granite. Minor sections (generally shorter than 2 m) of high densities (>2800 kg/m^3) occur throughout the entire borehole. The majority of these sections most likely correspond to amphibolite dykes. The magnetic susceptibility and the natural gamma radiation logs show only small variations along the uppermost c. 250 m of the borehole (section 100-350 m). Between c. 450 m and 550 m depth there are several sections with low gamma radiation and very high frequency susceptibility variations (the latter not visible in Figure 4-6). Two c. 10 m wide low susceptibility and low natural gamma radiation sections occur at the depths 860 m and 980 m. Along some sections of the uppermost c. 150 m of the borehole, the estimated fracture frequency is slightly increased. For the remaining part, except one short section at 475 m depth, the fracture frequency is estimated to < 3 fr/m.

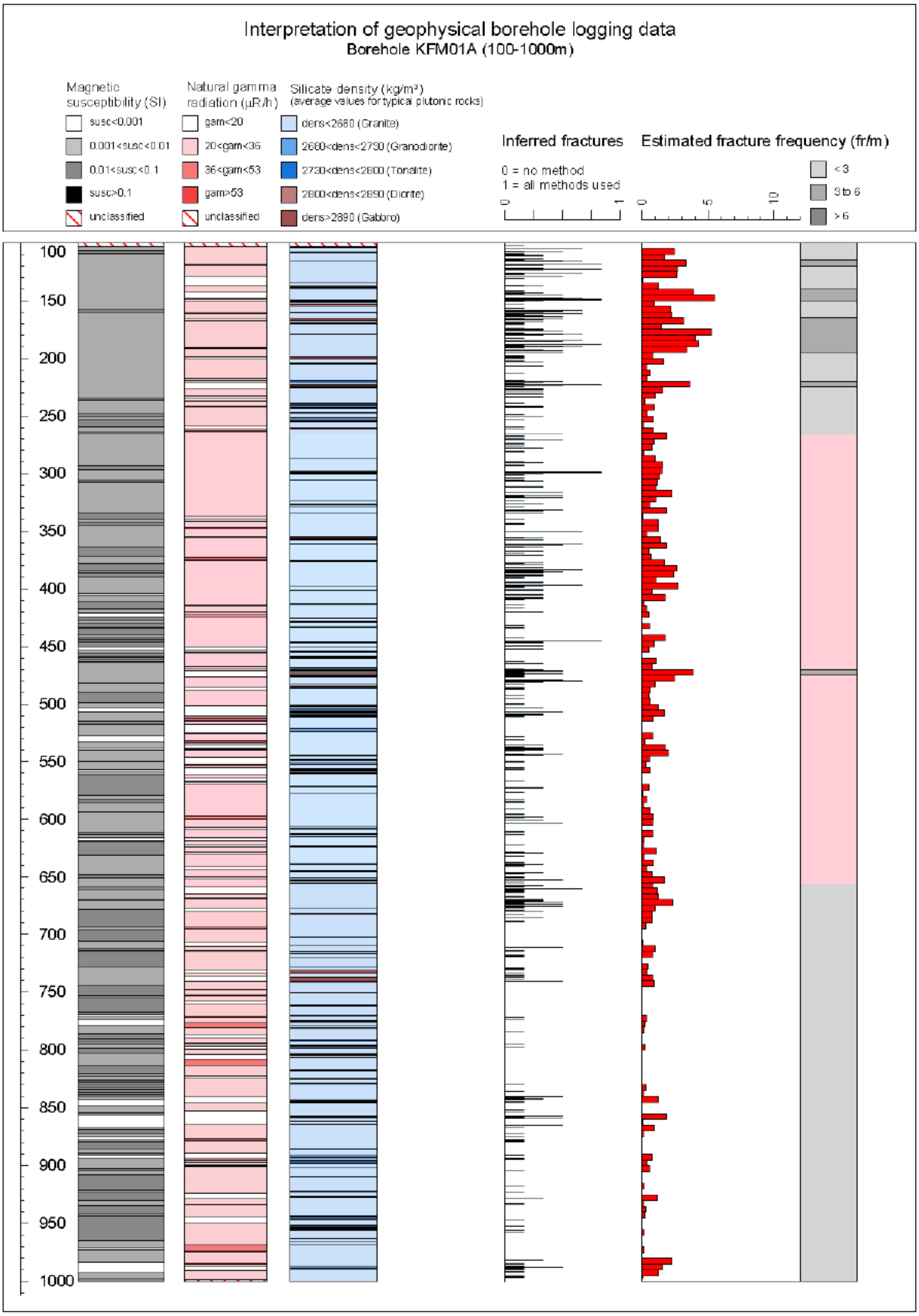


__Figure 4-6.__ Generalized geophysical logs for KFM01A (100-1000m).

4.3.2 Interpretation of KFM01A (0-100 m)

These percussion drilled uppermost section (0-100 m) of KFM01A was logged by Malå GeoScience, whereas the core drilled deeper part of the borehole was logged by Rambøll. This should be kept in mind if comparisons are made, although the generalized logs should be more or less independent on actual logging methods used. It should also be noted that the density log of Malå GeoScience has been difficult to calibrate. Reliable data only exist for the section 30-50 m. No integrated fracture frequency is presented due to the short length of the borehole.

Vertical temperature gradient and salinity

The fluid temperature and the fluid resistivity logs are very unstable and the data are most likely not reliable for interpretation. The borehole fluid was probably not in thermal nor chemical equilibrium with the surrounding rock volume at the time of the measurements.

Interpretation of rock types and fractures

The section 30-40 m is dominated by a silicate density that indicates a mineral composition corresponding to granite, whereas the section 40-50 m is dominated by granodioritic rock type densities. The magnetic susceptibility is fairly constant and the natural gamma radiation generally low. Increased fracturing is indicated at 36-40 m and 48 m depths.

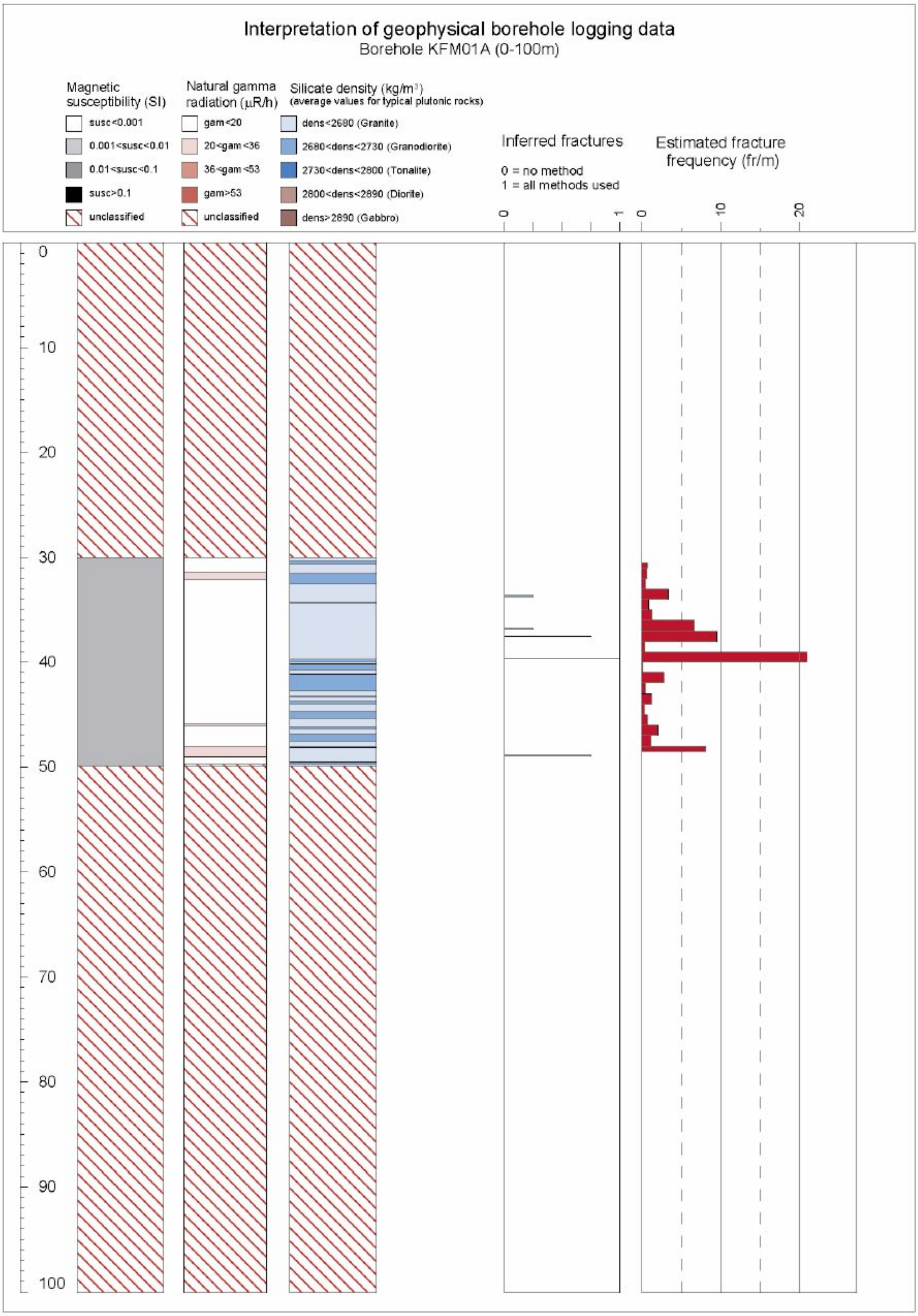


Figure 4-7. Generalized geophysical logs for KFM01A (0-100m).

4.3.3 Interpretation of KFM01B

The results of the generalized data and fracture estimations for the borehole KFM01B are presented in Figure 4-9 below. The data are also presented at a larger scale in Appendix 2.

Vertical temperature gradient and salinity

The median vertical temperature gradient is 9.1 ºC/km (when disregarding the extreme anomaly close to the top of the borehole, which is probably not related to a natural temperature variation). A large anomaly occurs at c. 40-60 m depth (Figure 4-8), and at this depth section the geophysical logs also indicate increased fracturing of the rock in the vicinity of the borehole (Figure 4-9). A few minor temperature gradient anomalies occur along the section c. 160-300 m and 425-475 m.

The estimated salinity is fairly constant at c. 6000 ppm NaCl from 100 m depth down to c. 390 m depth (Figure 4-8), except for a small step at 97 metres depth and local maxima at 200 metres depth. At 390 m depth there is a slow linear increase in salinity down to c. 430 m depth where the level rapidly increases to c. 13000 ppm NaCl. For the remaining part of the borehole the salinity level only shows minor variations.

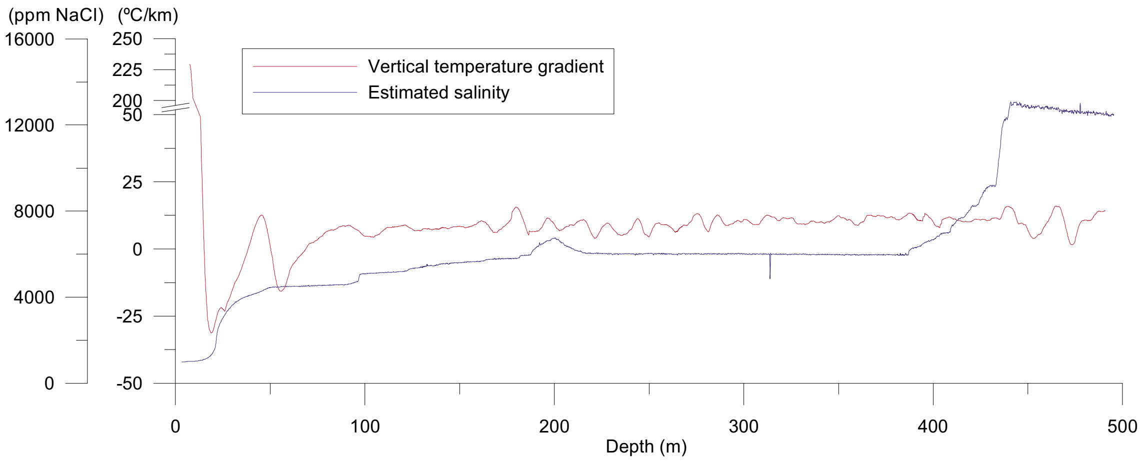


Figure 4-8. *Vertical temperature gradient and estimated salinity for KFM01B.*

Correction of resistivity logs and calculation of apparent porosity

The median short normal resistivity is 5500 Ωm prior to correction, and the median of the corrected short normal resistivity is 6800 Ωm. These resistivity values correspond fairly well to the data from the petrophysical measurements. The median apparent porosity is c. 0.26%, also in good accordance with petrophysical data.

Interpretation of rock types and fractures

The vast majority of the rocks in the vicinity of the borehole have a silicate density indicating a mineral composition that corresponds to granite. Thin high density rocks are sparsely scattered along the borehole. The magnetic susceptibility is generally lower for the uppermost c. 120 m, sections c. 190-210 m and c. 430-460 m. The natural gamma radiation shows a moderate level for the major part of the borehole. The uppermost low susceptibility section coincides with an increased fracture frequency. Partly increased fracturing is also found at c. 200 m depth and c. 430 m depth.

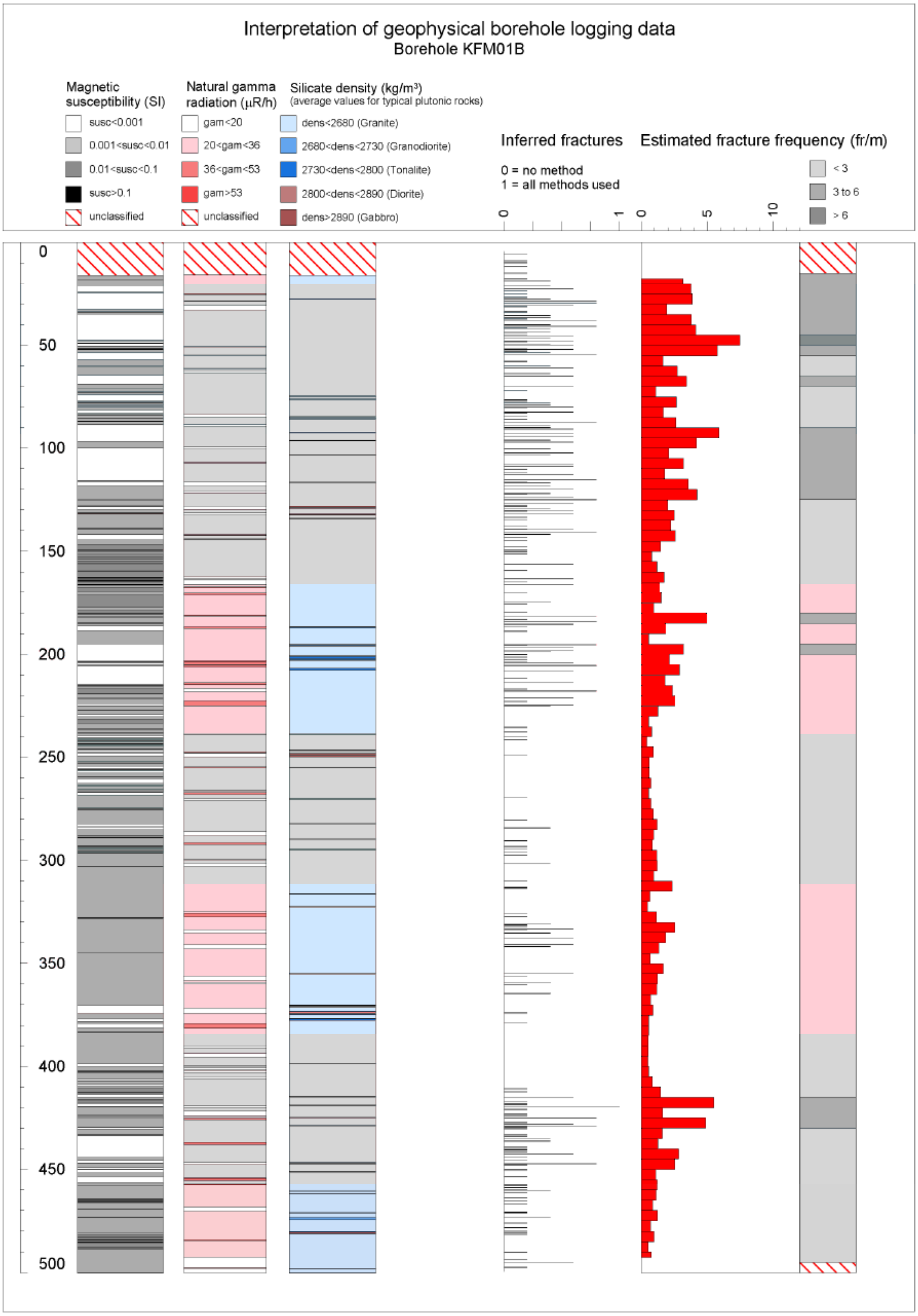


Figure 4-9. Generalized geophysical logs for KFM01B.

4.3.4 Interpretation of HFM01 (data from Rambøll)

Vertical temperature gradient and salinity

The median vertical temperature gradient of HFM01 is 9.5 ºC/km (Figure 4-10). One fairly large negative anomaly is located at 55-60 m depth and positive anomalies occur at 85 m, 123 m, 146 m and 158 m depth. The anomalies most likely correspond to water bearing fractures crosscutting the borehole. From 30 m down 86 m depth, the salinity of the borehole fluid shows moderate variations between c. 1000-2000 ppm NaCl. At 86 m depth there is a large and rapid increase in the salinity level up to c. 7000 ppm NaCl. At c. 123 m depth there is another increase in the salinity up to c. 8000 ppm NaCl. Observe that the salinity anomalies at 86 and 123 metres coincide with temperature gradient anomalies, which supports the interpretation of water bearing fractures at these depths. However, there is no increased fracturing indicated at these depths.

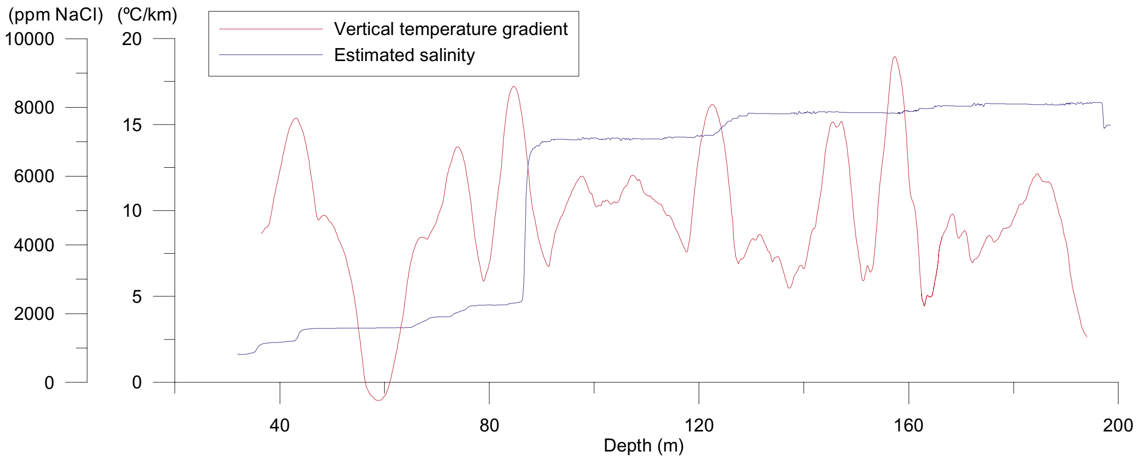


Figure 4-10. *Vertical temperature gradient and estimated salinity for HFM01.*

Interpretation of rock types and fractures

The vicinity of the borehole is completely dominated by a rock type (or types) with a silicate density that corresponds to granite (Figure 4-11). Three minor high density sections occur between 60 and 70 m depth and a c. 5 m long section with high silicate density is located at c 133 m depth. The magnetic susceptibility is fairly constant along the entire borehole, varying between 0.001 SI and 0.01 SI, whereas the natural gamma radiation shows repeated fluctuations. Increased fracturing is indicated at 35-70 m depth.

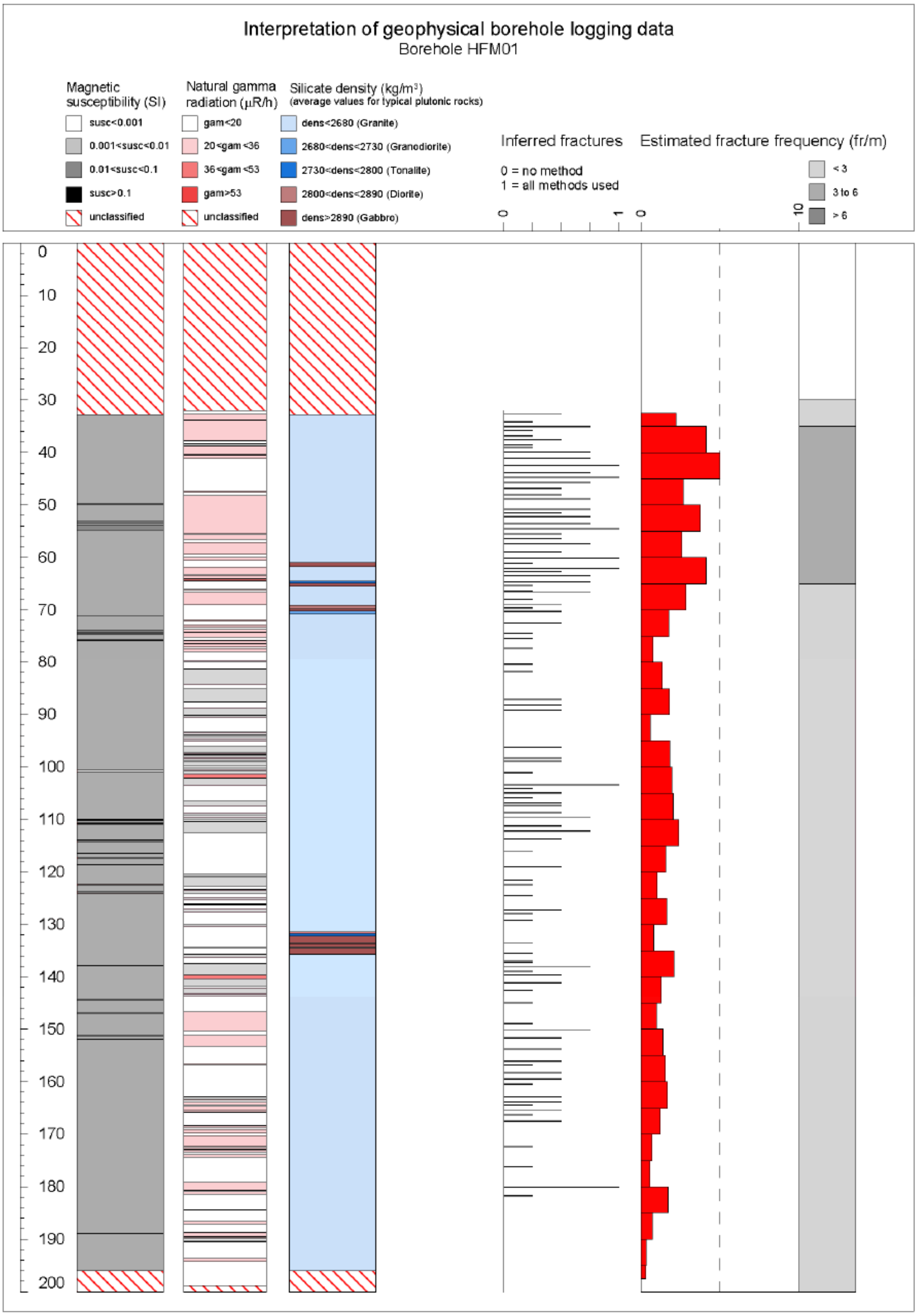


__Figure 4-11.__ Generalized geophysical logs for HFM01.

4.3.5 Interpretation of HFM02 (data from Rambøll)

Vertical temperature gradient and salinity

The median vertical temperature gradient of HFM02 is 8.1 ºC/km. One large anomaly occurs at c. 21 m depth (Figure 4-12). The borehole fluid salinity is c. 300 ppm NaCl at 25-43 m depth. Between 43 m and 47 m depth the salinity increases to c. 3000 ppm NaCl, and this level is kept constant down to 78 m depth where there is a second increase up to c. 6200 ppm NaCl. At third increase to 7400 ppm NaCl occurs at 88 m depth.

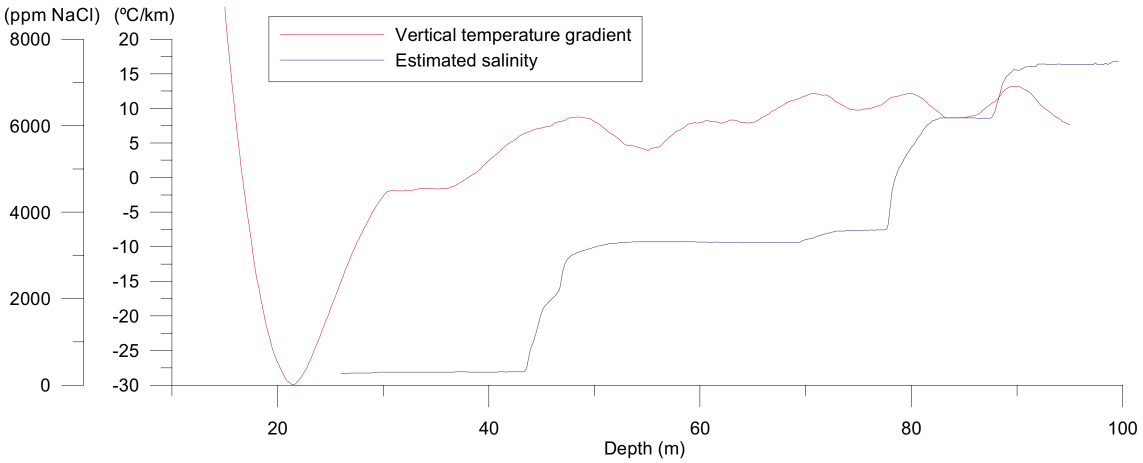


Figure 4-12. *Vertical temperature gradient and estimated salinity for HFM02.*

Interpretation of rock types and fractures

The rocks in the vicinity of the borehole are completely dominated by a silicate density that corresponds to granite (Figure 4-13). Minor high density sections mainly occur between 85 m and 100 m depth. The magnetic susceptibility is fairly constant along the entire borehole, apart from two low magnetic sections (possibly related to alteration) at c. 45 m and 75 m depth. The natural gamma radiation shows repeated fluctuations between low and moderate levels. At c. 85 m depth there is a short section of high natural gamma radiation. Increased fracturing is indicated at 40-45 m depth.

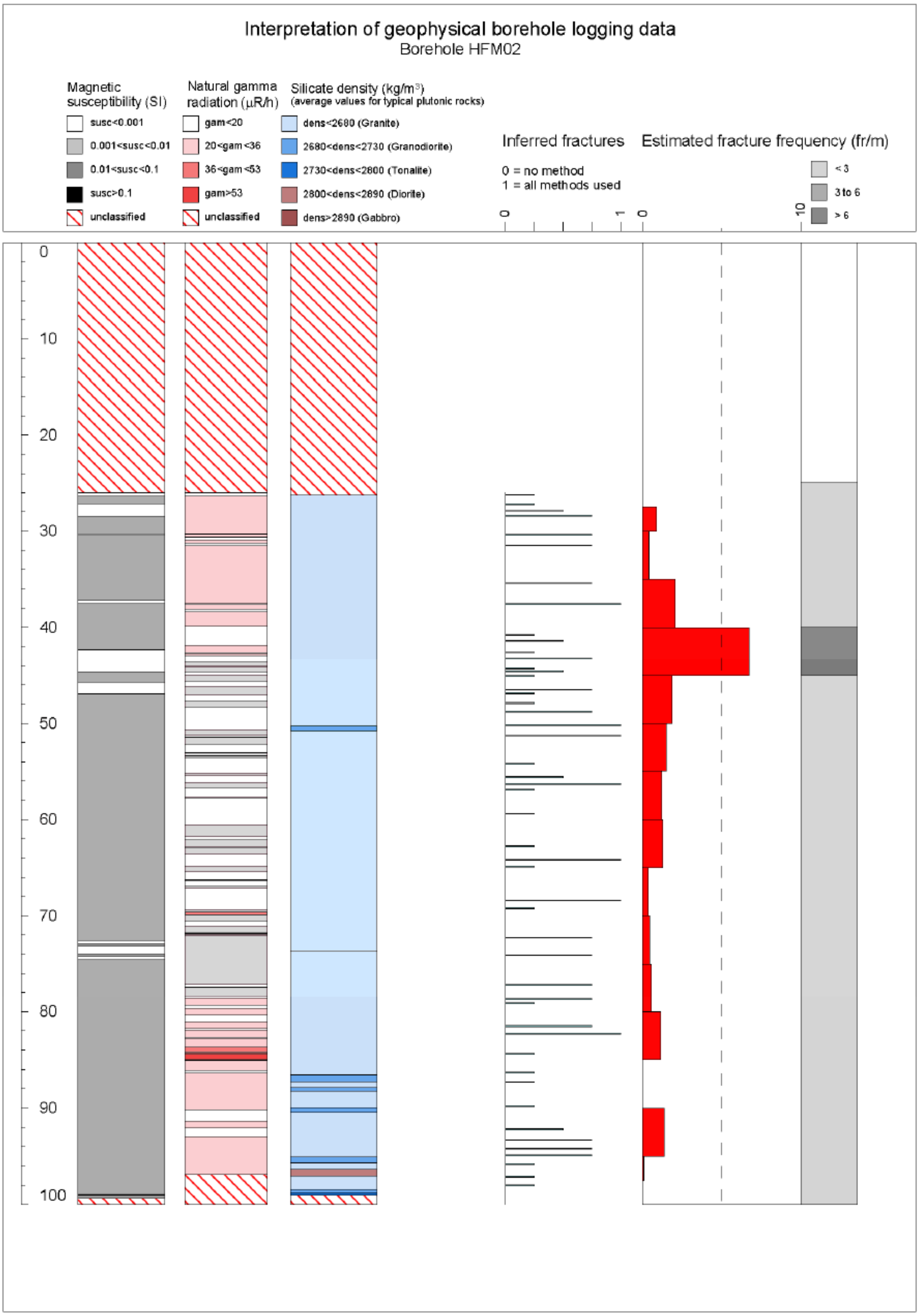


Figure 4-13. Generalized geophysical logs for HFM02.

4.3.6 Interpretation of HFM03 (data from Malå GeoScience)

No integrated fracture frequency is presented due to the short length of the borehole.

Vertical temperature gradient and salinity

The fluid temperature data do not seem to show natural variations, therefore no calculations of the vertical temperature gradient or the salinity were performed.

Interpretation of rock types and fractures

The rocks in the vicinity of the borehole are completely dominated by a silicate density that corresponds to granite composition (Figure 4-14). The magnetic susceptibility is fairly constant along the borehole, apart from a low magnetic section (possibly related to alteration) at 14-16 m depth. The natural gamma radiation is generally low. Increased fracturing is indicated at 15 m and 21 m depth.

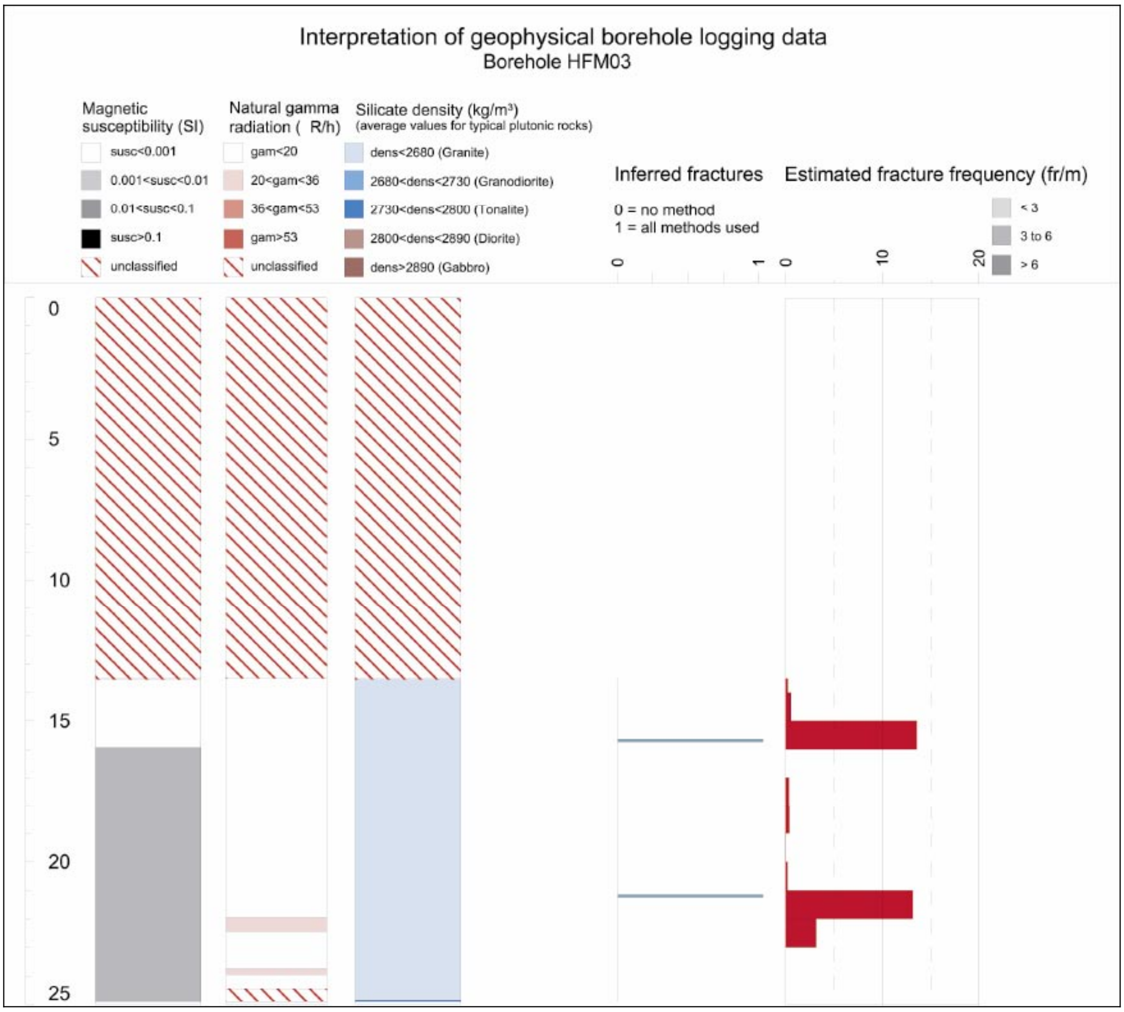


Figure 4-14. *Generalized geophysical logs for HFM03.*

5 Conclusions and discussion

The rocks in the vicinity of the interpreted boreholes are dominated by a mineral composition that corresponds to granite, and partly also granodiorite (Figure 5-1). The geophysical logging data indicate frequent occurrences of both high-density rocks (probably amphibolite and tonalite) and high radiation rocks (pegmatite or fine-grained granite) often as thin veins. The fracture frequency is in general low in all boreholes. However, the top c. 120 m of KFM01B, section 100-220 m of KFM01A and section c. 35-65 m of HFM01 clearly show an increased fracturing. Distinct geophysical anomalies, including temperature gradient, infer the presence of water bearing fractures.

The comparison of logging data (density, magnetic susceptibility and natural gamma radiation) between the two contractors Malå GeoScience and Rambøll, measured in HFM01 and HFM02, indicates a number of deviations, of which some are significant. In HFM01, there are two distinct positive anomalies in the Malå GS density log data that do not occur in the Rambøll log, and no corresponding high density rocks are indicated in the Boremap data. These kinds of erroneous data could transfer into faulty rock classifications of the boreholes. However, it must again be pointed out that the density logging tool of Malå GeoScience is not up to the standards required for these types of loggings, and this has been pointed out by the contractor before the surveys. The natural gamma radiation logs and the magnetic susceptibility correlate nicely, but show different levels. The magnetic susceptibility measured by Malå GeoScience is generally c. 3 times lower than what is measured by Rambøll. Comparisons made between Rambøll's susceptibility log in cored boreholes and petrophysical data indicate that their instrument underestimates the magnetic susceptibility by c. 30-50 %. The level difference of the natural gamma radiation is more or less constant in HFM01 and HFM02, where the Malå GS log shows c. 50 % higher values than the Rambøll log. However, the Rambøll natural gamma log has given very consistent background levels in a large number of boreholes in the Forsmark area and in the Simpevarp area whereas the logging tool of Malå GS tends to show more scattered background levels.

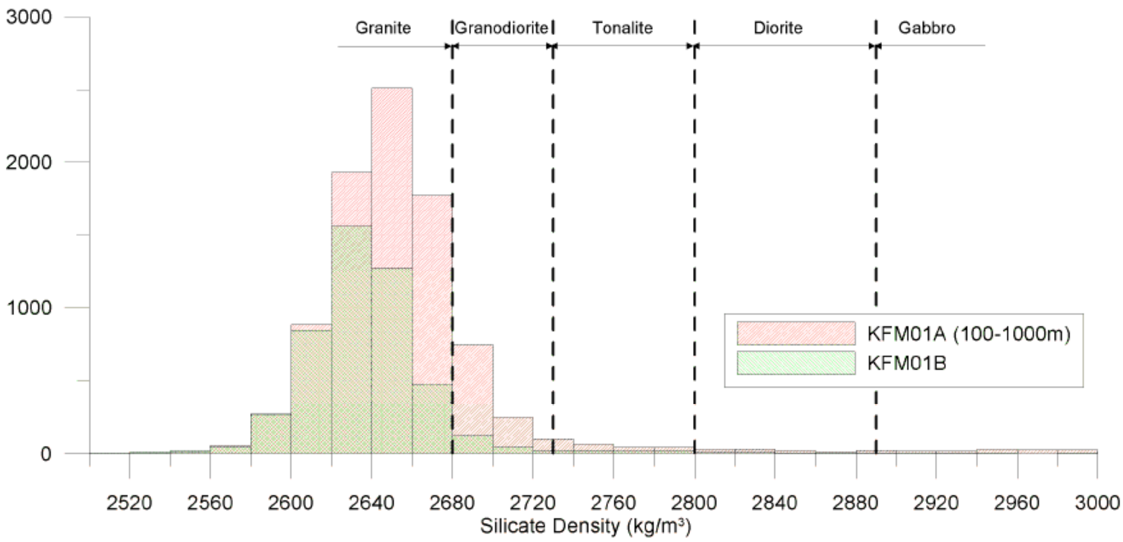


Figure 5-1. *Histograms of the silicate density for KFM01A (100-1000m) and KFM01B. The hatched lines show intervals that indicate rock types inferred from the silicate density.*

A related matter that also has been up to discussion is the question whether log data from cored boreholes are comparable to data from percussion drilled boreholes, since percussion drilled boreholes have a wider inner diameter and a more coarse surface of the borehole wall. In Table 5-1, a comparison between Rambøll's natural gamma log, density log and magnetic susceptibility log of KFM01A (cored borehole) and HFM02 (percussion drilled borehole) is presented. Equivalent sections of medium grained foliated granite-granodiorite in the two boreholes were selected by use of the boremap classification data. Average values of the density, magnetic susceptibility and natural gamma radiation data were calculated for each section respectively, and also for the two boreholes respectively. As indicated by the data in Table 5-1 there are no significant differences related to the different borehole types in the data between the cored and percussion drilled boreholes logged by Rambøll.

Table 5-1. Logging data measured by Rambøll from the percussion drilled borehole HFM02 and the cored borehole KFM01A. See the text for explanation.

HFM02 Section (m)	**No of data points**	**Gamma-gamma Density (kg/m^3)**	**Log. Magnetic Susceptibility (10^{-5} SI±decades)**	**Natural gamma radiation (μR/h)**
28-34	60	2551±56	2.382±0.314	23.6±2.9
86-93	70	2626±44	2.591±0.095	21.3±2.7
	Average	2589	2.487	22.4
KFM01A Section (m)	**No of data points**	**Gamma-gamma Density (kg/m^3)**	**Log. Magnetic Susceptibility (10^{-5} SI±decades)**	**Natural gamma radiation (μR/h)**
111-116	50	2606±51	2.232±0.358	21.5±1.8
209-214	50	2593±46	2.605±0.089	24.1±1.6
333-338	50	2610±46	2.876±0.052	21.2±2.0
	Average	2603	2.571	22.3

6 Data delivery

The following data have been delivered to SKB: Resampled, filtered and calibrated data, calculated silicate density, salinity and temperature gradient, generalized logs and logs of inferred fractures and estimated fracture frequency. Apparent porosity and corrected resistivity for KFM01A (100-1000 m) and KFM01B. The generalized logs have also been delivered as WellCAD-files.

The reference to SICADA is Field notes Forsmark 335 and 344.

7 References

/1/ **Gustafsson C, Nilsson P, 2003.** Geophysical Radar and BIPS logging in borehole HFM01, HFM02, HFM03 and the percussion drilled part of KFM01A. SKB P-03-39. Svensk Kärnbränslehantering AB.

/2/ **Nielsen U T, Ringgaard J, 2004.** Geophysical Borehole logging. Borehole KFM01A, HFM01 and HFM02. P-03-103. Svensk Kärnbränslehantering AB.

/3/ **Thunehed H, 2003.** Interpretation of borehole geophysical measurements in KFM02A, KFM03A, KFM03B and HFM04 to HFM08. SKB P-04-98.

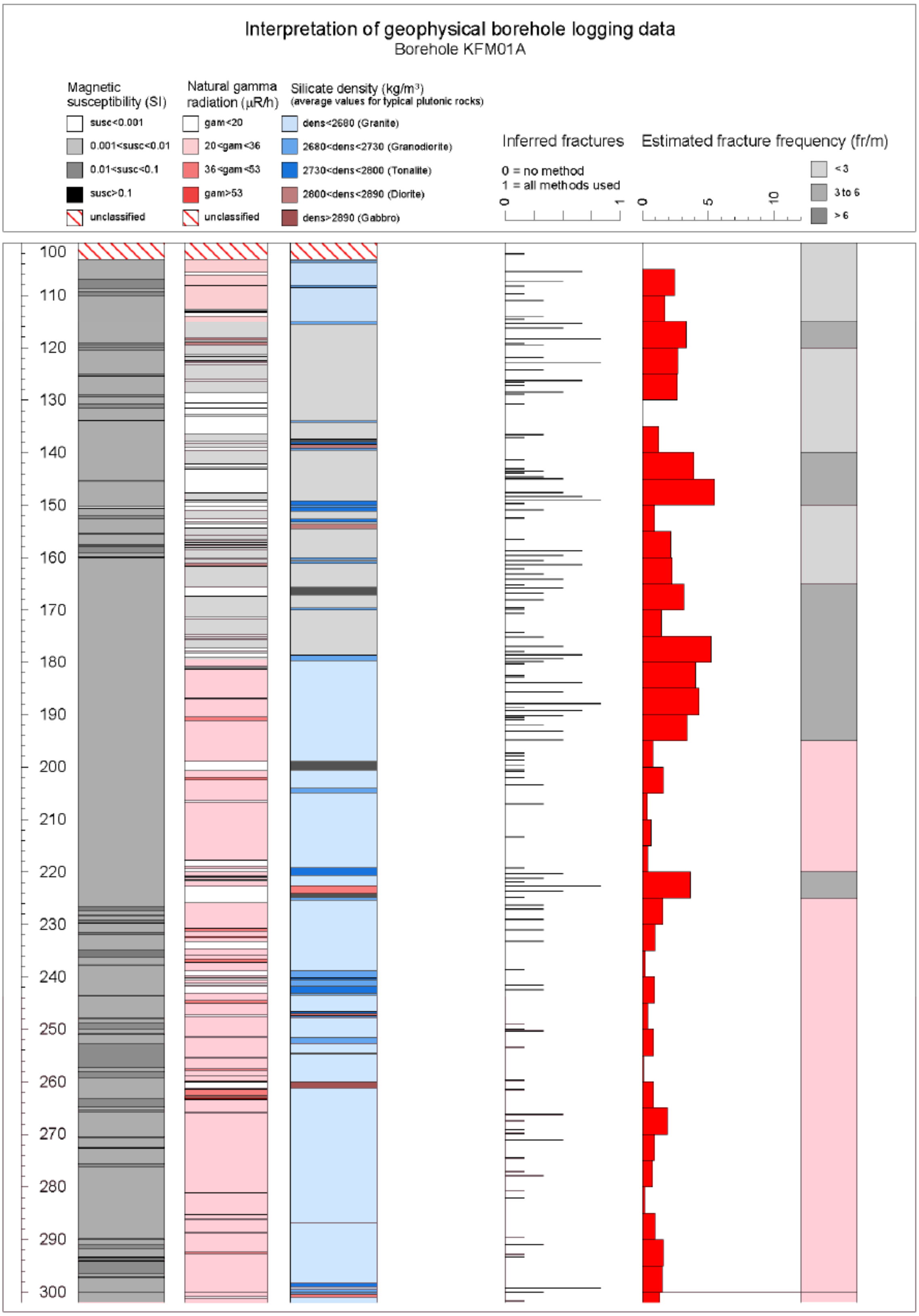
/4/ **Sehlstedt S, 1988.** Description of geophysical data on the SKB data base GEOTAB. SKB TR 88-05, Svensk Kärnbränslehantering AB.

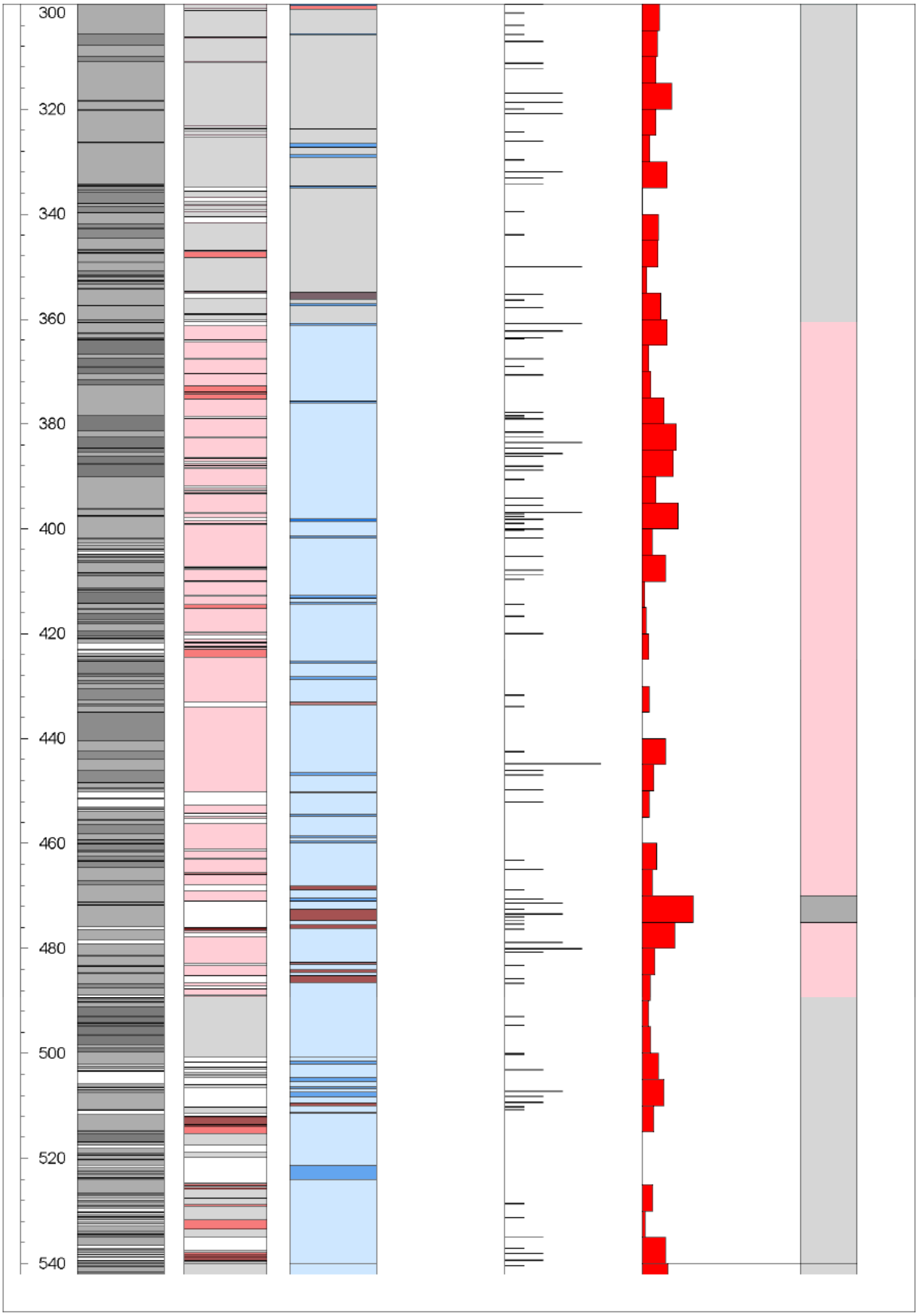
/5/ **Henkel H, 1991.** Petrophysical properties (density and magnetization) of rock from the northern part of the Baltic Shield. Tectonophysics 192, 1 – 19.

/6/ **Puranen R, 1989.** Susceptibilities, iron and magnetite content of precambrian rocks in Finland. Geological survey of Finland, Report of investigations 90, 45 pp.

Appendix 1

Generalized geophysical logs for the borehole KFM01A (100-1000m)

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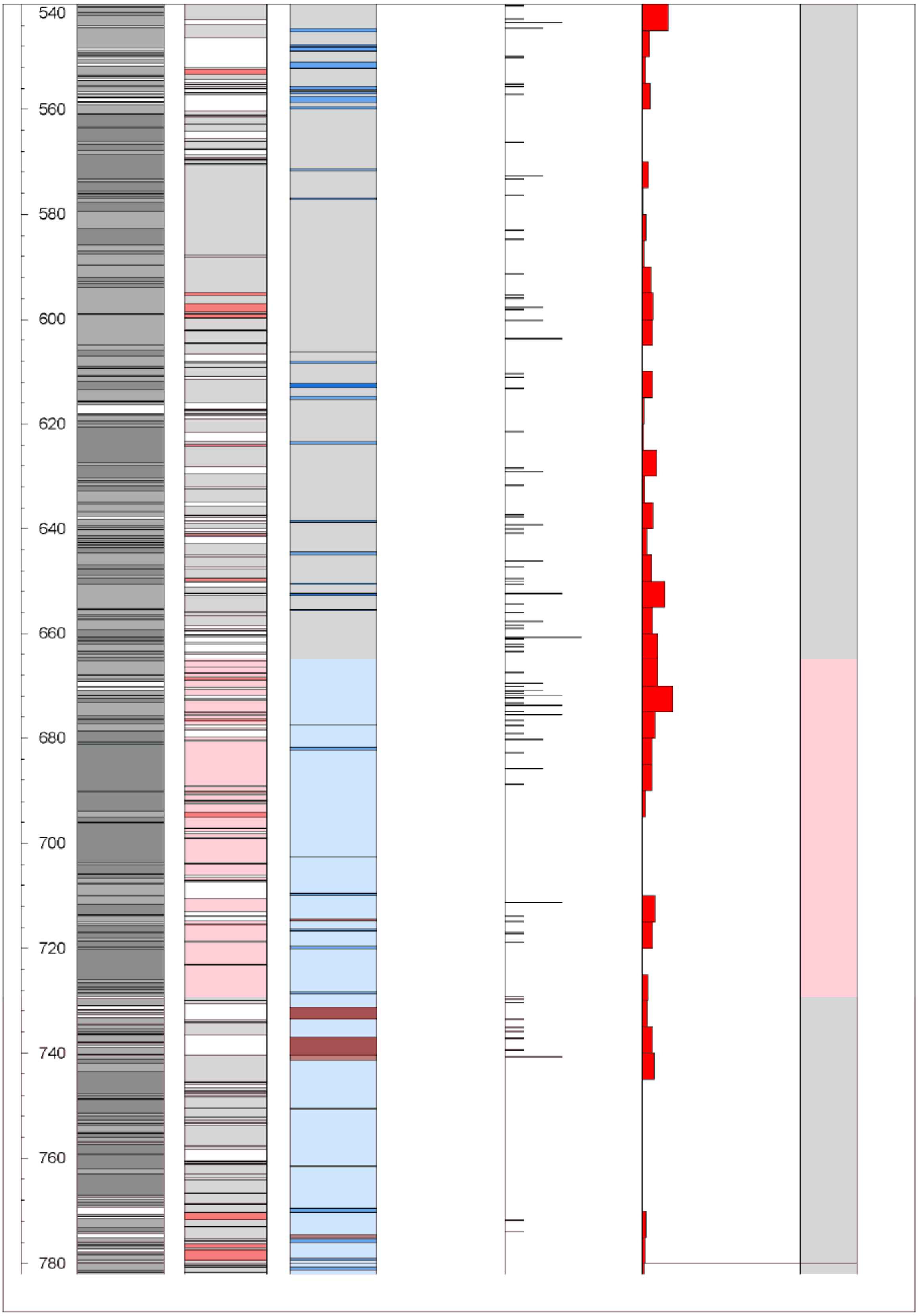
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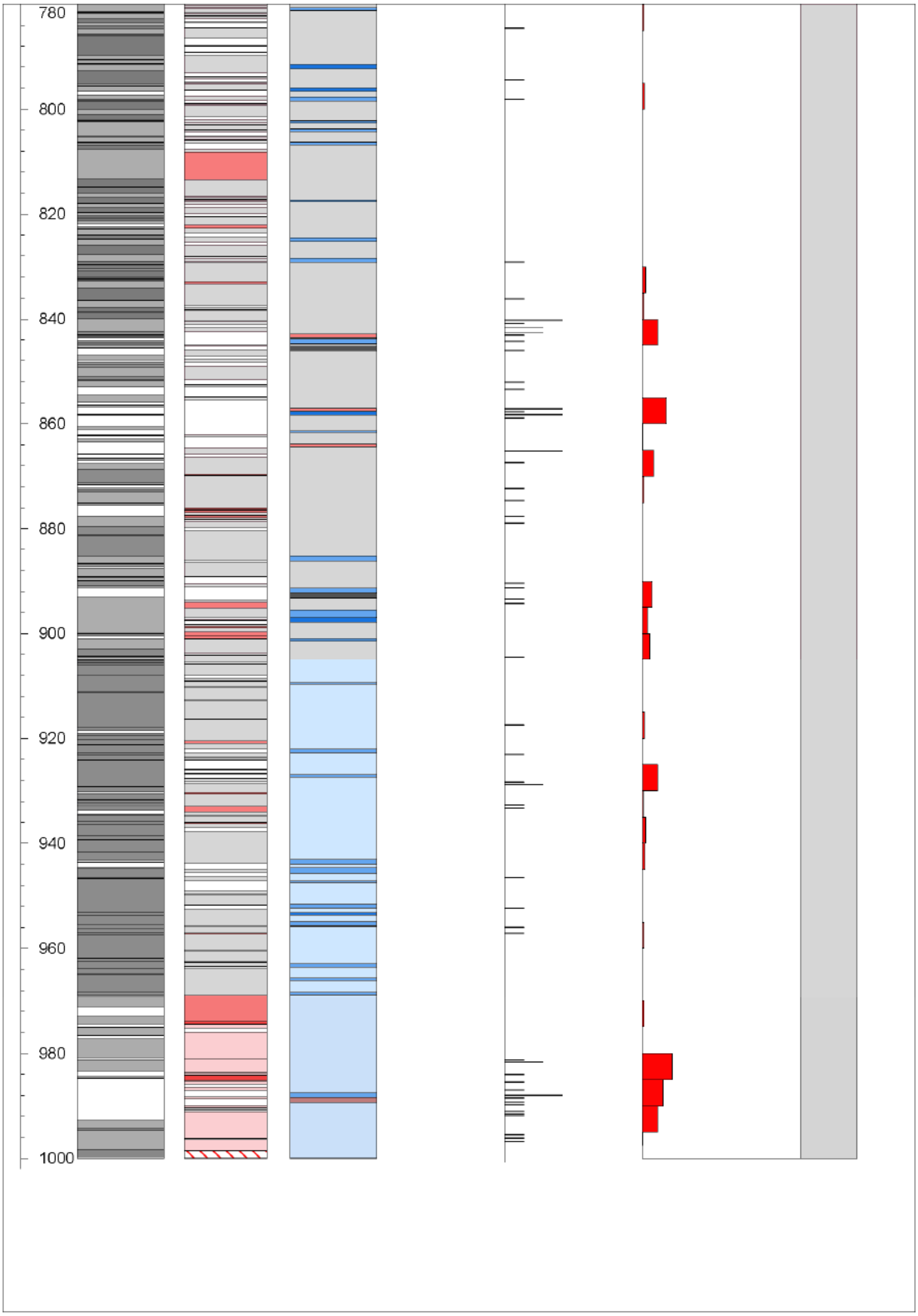
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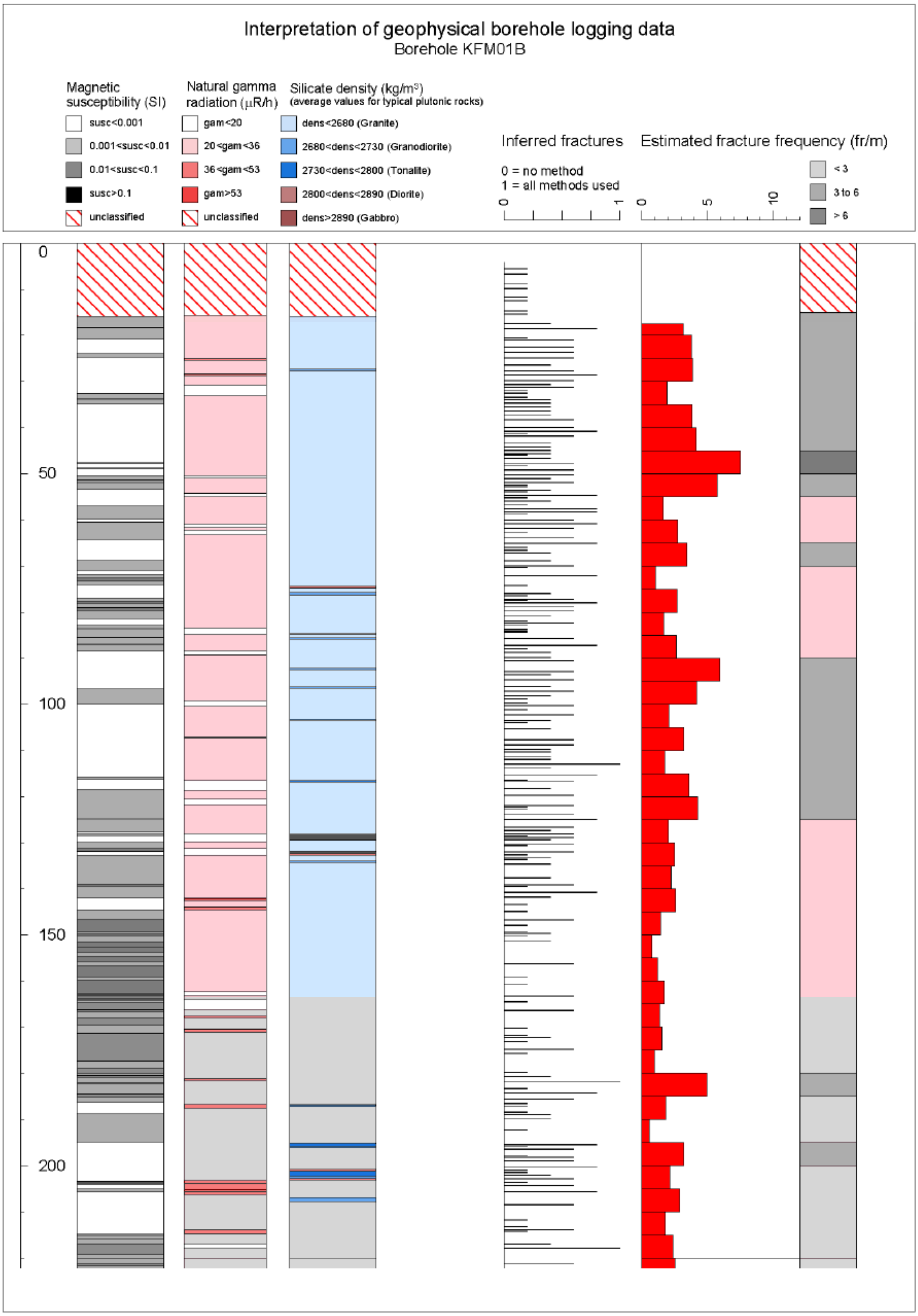
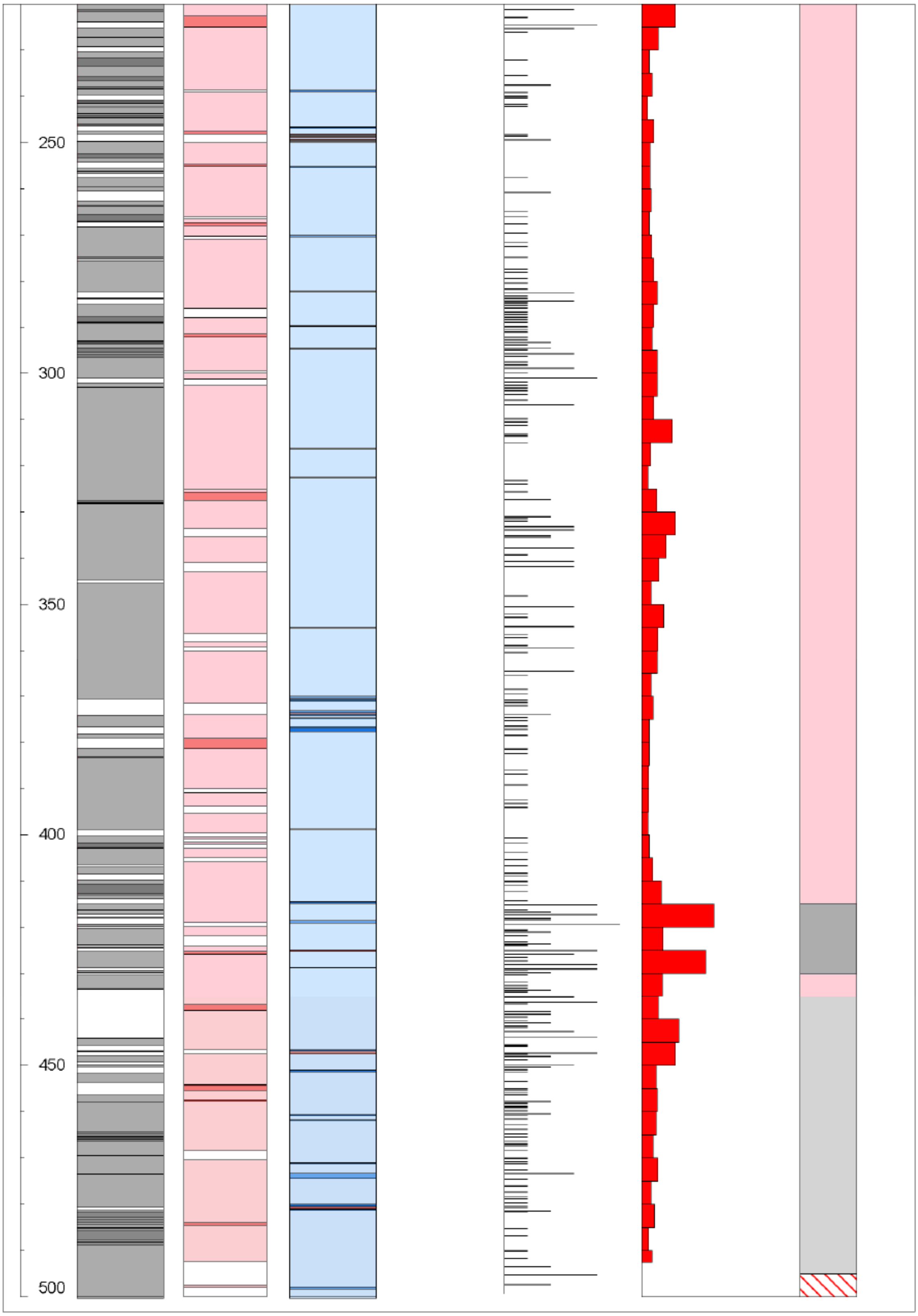
Appendix 2

Generalized geophysical logs for the borehole KFM01B

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