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Forsmark site investigation

Interpretation of geophysical borehole measurements from KFM10A, KFM08C, HFM30, HFM31, HFM33, HFM34, HFM35 and HFM38

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Abstract

This report presents the compilation and interpretations of geophysical logging data from the cored boreholes KFM10A and KFM08C and the percussion drilled boreholes HFM30, HFM31, HFM33, HFM34, HFM35 and HFM38.

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 geological single-hole interpretation.

Noise levels greatly exceed the recommended levels for several methods in KFM08C. This may have had a significant negative effect on the interpretations presented in this report, especially regarding the possibilities of resolving low amplitude or high frequency anomalies.

The rocks in the vicinities of KFM10A, KFM08C, HFM35 and HFM38 are dominated by silicate density < 2,680 kg/m^3 and natural gamma radiation in the range 15–35 μR/h. The data correspond to those of granite rock, and in some sections leucocratic granite indicated by greatly decreased density in combination with increased natural gamma radiation. In the cored boreholes the magnetic susceptibility is mainly in the range 0.005–0.015 SI and in the percussion drilled boreholes there are long sections with significantly decreased magnetization.

The physical properties in the boreholes HFM30, HFM31, HFM33 and HFM34 display fairly large variations, which most likely correspond to variations in lithology. Especially in HFM31 there is a heterogeneous distribution of indicated diorite/gabbro rocks and leucocratic granite.

The fracture frequency estimations indicate fairly low fracturing in all the investigated boreholes except for HFM35 in which increased fracture frequency is indicated along two long intervals.

Possible deformation zones are indicated in KFM10A at c 85–145 m, c 300–350 m, 425–440 m and 480–490 m; in KFM08C at 453–550 m and c 675–705 m; in HFM30 at c 158–198 m; in HFM31 at c 27–49 m and c 95–110 m; in HFM33 no deformation zones are indicated; in HFM34 at c 81–133 m; in HFM35 at c 22–37 m, 48–52 m, 88–93 m, 114–123 m, 143–145 m and 167–174 m; and in HFM38 at c 20–50 m.

Sammanfattning

Föreliggande rapport presenterar en sammanställning och tolkning av geofysiska borrhålsmätningar från kärnborrhålen KFM10A och KFM08C samt hammarborrhålen HFM30, HFM31, HFM33, HFM34, HFM35 and HFM38.

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 den geologiska enhålstolkningen.

I KFM08C övertiger brusnivåerna i data hos flertalet loggar kraftigt de rekommenderade brusnivåerna. Detta kan ha haft en signifikant negativ påverkan på tolkningen som presenteras för borrhålet, speciellt beträffande möjligheten att identifiera svaga eller högfrekventa anomalier.

Berggrunden i närheten av KFM10A, KFM08C, HFM35 och HFM38 domineras av silikatdensitet < 2 680 kg/m^3 och en naturlig gammastrålning i intervallet 15–35 μR/h. Data indikerar förekomst av granit samt i vissa sektioner med avvikande låg densitet i kombination med förhöjd gammastrålning möjlig förekomst av leucokratisk granit. I de två kärnborrhålen är den magnetiska susceptibiliteten generellt inom intervallet 0,005–0,015 SI. I HFM35 och HFM38 förekommer långa sektioner med mycket låg magnetisering.

De fysikaliska egenskaperna hos bergarterna i borrhålen HFM30, HFM31, HFM33 och HFM34 uppvisar stora variationer. Särskilt i HFM31 förekommer flertalet blandade sektioner med indikerad diorit/gabbro och leucokratisk granit.

De uppskattningar av sprickfrekvens som presenteras för de undersökta borrhålen indikerar generellt relativt låg sprickfrekvens, utom för HFM35 där förhöjd sprickfrekvens indikeras längs två långa sektioner.

Förekomst av möjliga deformationszoner indikeras i KFM10A längs ca 85–145 m, 300–350 m, 425–440 m och 480–490 m; i KFM08C längs 453–550 m och ca 675–705 m; i HFM30 längs ca 158–198 m; i HFM31 längs ca 27–49 m och ca 95–110 m; i HFM33 finns inga möjliga deformationszoner indikerade; i HFM34 längs ca 81–133 m; i HFM35 längs ca 22–37 m, 48–52 m, 88–93 m, 114–123 m, 143–145 m och 167–174 m; och i HFM38 längs ca 20–50 m.

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 Oskarshamn. This document reports the results gained from the interpretation of geophysical borehole logging data from the cored boreholes KFM10A and KFM08C and the percussion drilled boreholes HFM30, HFM31, HFM33, HFM34, HFM35 and HFM38 in Forsmark (Figure 1-1).

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 2006 by Rambøll /1/.

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

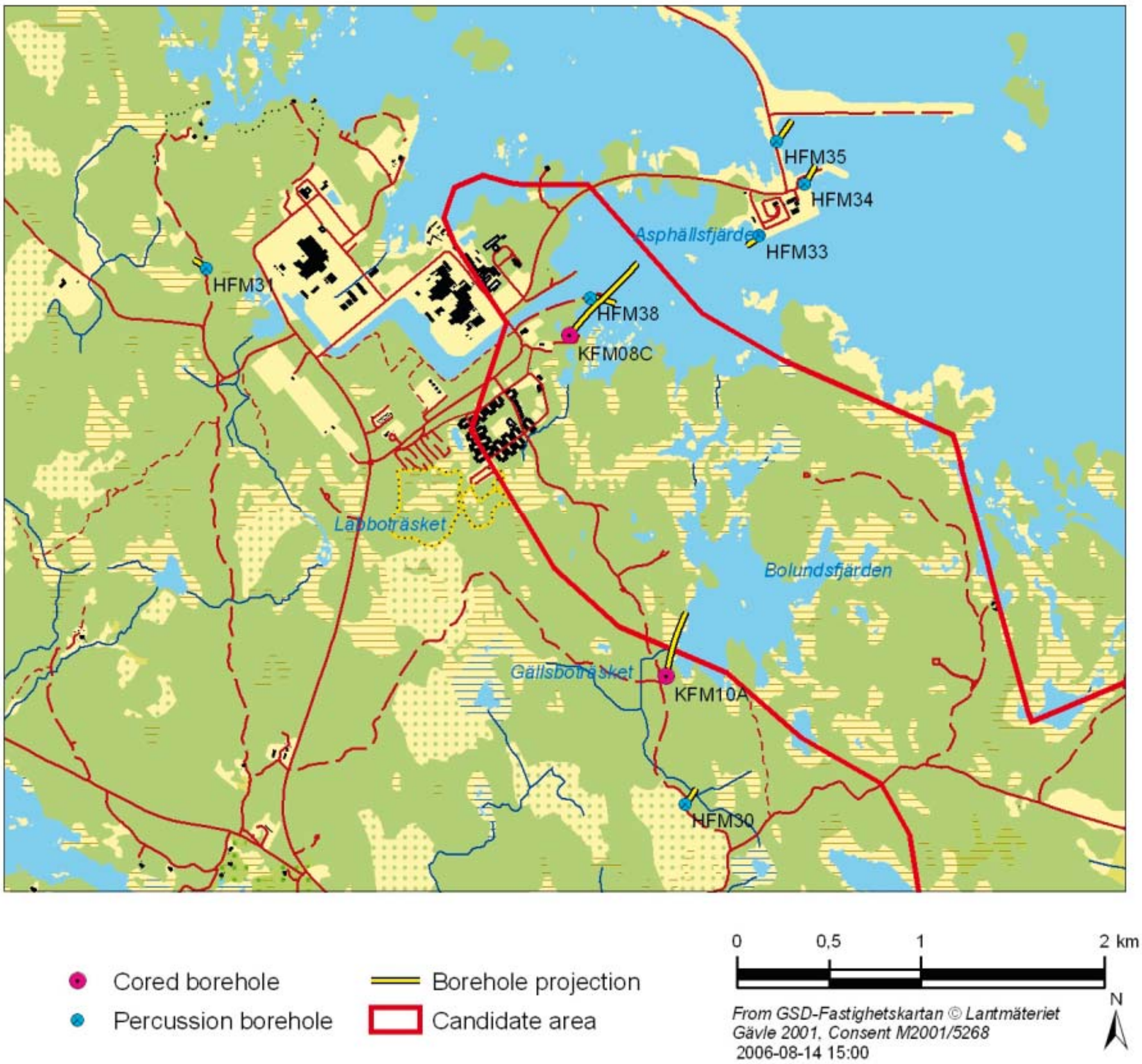

Figure 1-1. *Map showing the location of the investigated boreholes.*

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

Activity plan	Number	Version
Tolkning av geofysiska borrhålsdata från KFM10A, KFM08C, HFM30, HFM31, HFM33, HFM34, HFM35 och HFM38.	AP PF 400-06-074	1.0
Method descriptions	**Number**	**Version**
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.

4 Execution

4.1 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 KLX20A /2/. The magnetic susceptibility logging data are calibrated with respect to a combination of petrophysical data from the boreholes KFM01A and KFM02A /3 and 4/.

2. Interpretation 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 sections indicating a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to /6/. 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 /7/; $\sigma = a\,\sigma_w^k\,\varphi^m + \sigma_s$ 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 values of the coefficients used for both core drilled boreholes are a = 10, k = 0.37 and m = 1.7.

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 (°C) and ρ = resistivity (Ωm).

The salinity is only calculated for cored boreholes.

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 4-1) 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 4-1.

5. Report evaluating the results.

4.2 Preparations and data handling

The logging data were delivered as Microsoft Excel files via email from SKB during the time period 2006-06-30 to 2007-01-30. 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.

Table 4-1. 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	KFM10A	2.3	2.0	2.0	0.4	1.5	5.0	5.0	–
Weight	KFM10A	4.0	2.56	4.0	2.0	2.56	0.24	1.75	–
Threshold	KFM08C	1.0	2.0	2.0	0.5	0.5	3.0	6.0	–
Weight	KFM08C	4.0	2.56	4.0	2.0	2.56	0.24	1.75	–
Threshold	HFM30	1.5	1.5	1.5	0.5	–	3.5	4.0	–
Weight	HFM30	4.0	2.56	4.0	2.0	–	0.24	1.75	–
Threshold	HFM31	1.5	1.5	1.5	0.5	1.0	5.0	4.0	–
Weight	HFM31	4.0	2.56	4.0	2.0	2.56	0.24	1.75	–
Threshold	HFM33	1.5	1.5	1.4	0.5	–	4.0	4.0	–
Weight	HFM33	4.0	2.56	4.0	2.0	–	0.24	1.75	–
Threshold	HFM34	1.5	1.5	1.5	0.5	–	5.0	4.0	–
Weight	HFM34	4.0	2.56	4.0	2.0	–	0.24	1.75	–
Threshold	HFM35	2.0	1.0	1.0	0.5	–	5.0	7.0	–
Weight	HFM35	4.0	2.56	4.0	2.0	–	0.24	1.75	–
Threshold	HFM38	1.5	1.75	1.5	0.6	–	5.0	5.0	–
Weight	HFM38	4.0	2.56	4.0	2.0	–	0.24	1.75	–

- 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.

4.3 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.

4.4 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. In HFM30 SPR data were collected only in the section c 20–34 m, these data were therefore excluded in the borehole interpretation. No SPR data were delivered for HFM33, HFM34, HFM35 or HFM38.

5 Results

5.1 Quality controll of the logging data

Noise levels of the raw data for each logging method are presented in Table 5-1. For all boreholes the natural gamma radiation data have noise levels clearly above the recommended value of 0.3 µR/h. The density and natural gamma radiation data collected in KFM08C and HFM38 show very high noise levels. The high noise levels may have a significant effect on the quality of the interpretations, especially regarding the possibility of resolving the cause of high frequency anomalies. Also the noise levels of the magnetic susceptibility and long normal resistivity logs are above the recommended levels for several boreholes. However, these noise levels are most likely low enough to allow a meaningful interpretation of the data. To reduce the influence of the noise, all logs were average 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.

Table 5-1. Noise levels in the investigated geophysical logging data (the table continues on the next page).

Logging method	KFM10A	KFM08C	HFM30	HFM31	Recommended max noise level
Density (kg/m^3)	11	30	12	13	3–5
Magnetic susceptibility (SI)	2×10^{-4}	3×10^{-4}	0.9×10^{-4}	3×10^{-4}	1×10^{-4}
Natural gamma radiation (µR/h)	1.2	3.3	1.0	1.2	0.3
Long normal resistivity (%)	0.2	0.8	1.5	1.0	2.0
Short normal resistivity (%)	0.1	0.3	0.4	0.2	2.0
Fluid resistivity (%)	0.03	0.2	0.04	0.06	2
Fluid temperature (°C)	3×10^{-4}	0.001	3×10^{-4}	0.008	0.01
Lateral resistivity (%)	Not used	Not used	Not used	Not used	2
Single point resistance (%)	0.2	1.0	1.8	0.8	No data
Caliper (meter)	2×10^{-5}	3×10^{-5}	2×10^{-4}	1×10^{-4}	0.0005
Focused resistivity 300 (%)	10	5	15	19	No data
Focused resistivity 140 (%)	4	2	9	5	No data
Sonic (m/s)	8	31	17	10	20

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

Logging method	HFM33	HFM34	HFM35	HFM38	Recommended max noise level
Density (kg/m^3)	14	15	7	31	3 – 5
Magnetic susceptibility (SI)	2×10^{-4}	3×10^{-4}	1×10^{-4}	3×10^{-4}	1×10^{-4}
Natural gamma radiation (μR/h)	1.0	0.9	1.3	2.6	0.3
Long normal resistivity (%)	4.0	4.0	0.6	5.4	2.0
Short normal resistivity (%)	0.7	0.5	0.1	0.7	2.0
Fluid resistivity (%)	0.05	0.03	0.03	0.1	2
Fluid temperature (°C)	4×10^{-4}	0.005	4×10^{-4}	8×10^{-4}	0.01
Lateral resistivity (%)	Not used	Not used	Not used	Not used	2
Single point resistance (%)	No data	No data		No data	No data
Caliper (meter)	2×10^{-4}	3×10^{-4}	2×10^{-4}	1×10^{-4}	0.0005
Focused resistivity 300 (%)	11	10	6	5	No data
Focused resistivity 140 (%)	5	9	6	6	No data
Sonic (m/s)	14	21	17	6	20

5.2 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 meter sections.
- Classification of estimated fracture frequency (0 to 3, 3 to 6 and > 6 fractures/m).

5.2.1 Interpretation of KFM10A

The results of the generalized logging data and fracture estimations of KFM10A are presented in Figure 5-1 below, and in a more detailed scale in Appendix 1. The distribution of silicate density classes with borehole length is presented in Table 5-2.

The rocks in the vicinity of KFM10A are dominated by silicate density < 2,680 kg/m^3, natural gamma radiation in the interval 20–36 μR/h and magnetic susceptibility of c 0.004–0.010 SI. The combination of physical properties indicates the occurrence of granite rock.

Along the entire section c 84–120 m there is a general increase in the natural gamma radiation level (40–50 μR/h), in combination with decreased density (2,540–2,640 kg/m^3) and decreased magnetic susceptibility (0.0007–0.0014 SI). Along this section there is a clear indication of a possible deformation zone. The bulk resistivity is significantly decreased, there are several caliper anomalies and the P-wave velocity is also decreased. It is therefore also possible that the increased natural gamma radiation is related to mineral alteration caused by the deformation.

The section c 260–270 m is characterized by increased occurrences of short sections (< 5 m) with increased density (2,800–2,980 kg/m^3). A majority of these anomalies coincide with decreased magnetic susceptibility and decreased natural gamma radiation, which indicates amphibolite. Some of the indicated amphibolite dykes occur in direct vicinity to positive natural gamma radiation anomalies, which suggests that some mafic and felsic dykes are spatially related.

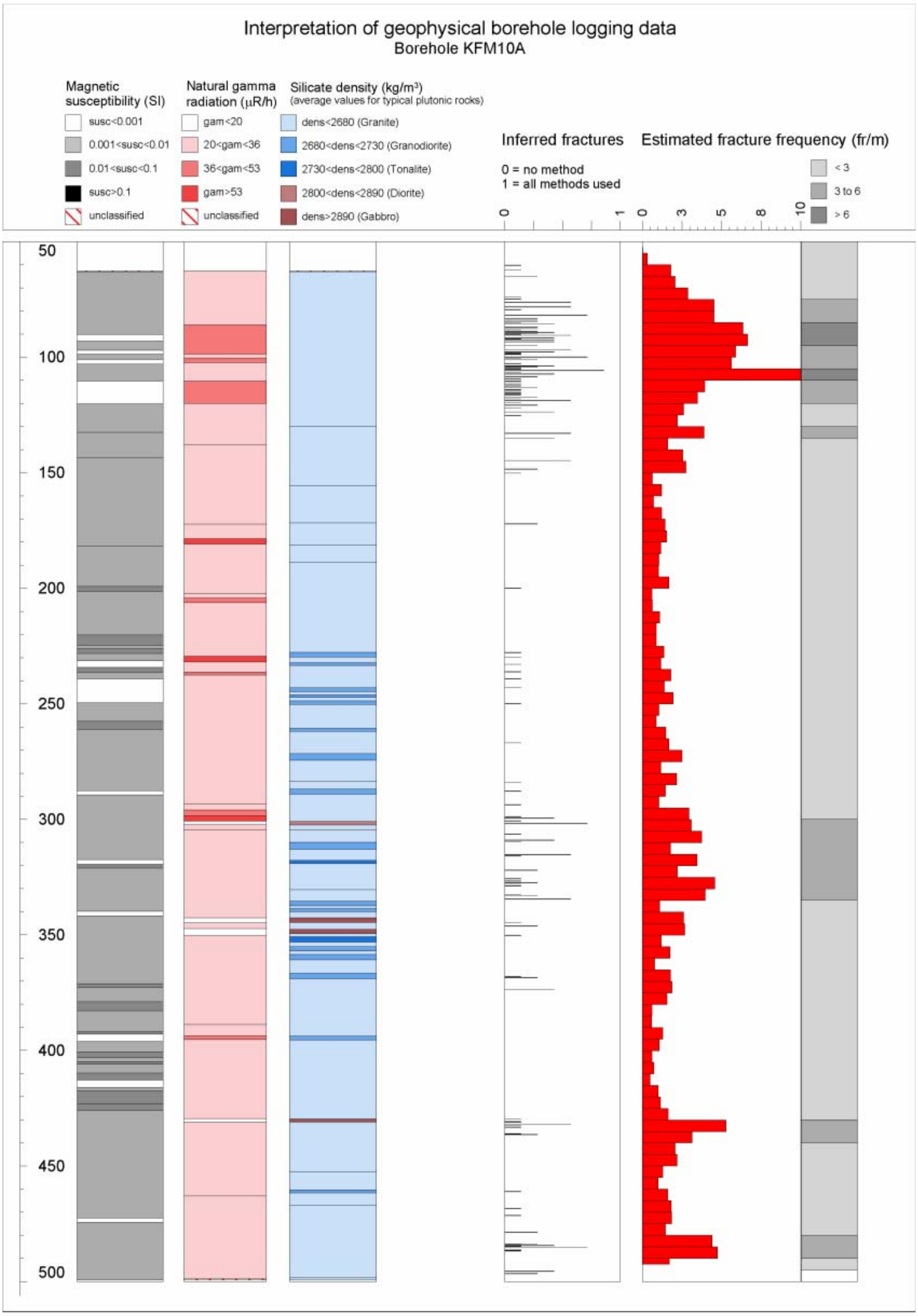

Figure 5-1. Generalized geophysical logs of KFM10A.

In the upper part of KFM10A, section c 85–260 m, there is a relatively larger occurrence of thin positive natural gamma radiation anomalies compared to remaining sections of the borehole. This suggests more frequent occurrences of felsic dykes along this part of the borehole.

Table 5-2. Distribution of silicate density classes with borehole length in KFM10A.

Silicate density interval (kg/m³)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	339	77
2,680 < dens < 2,730 (granodiorite)	67	15
2,730 < dens < 2,800 (tonalite)	17	4
2,800 < dens < 2,890 (diorite)	7	2
dens > 2,890 (gabbro)	7	2

The magnetic susceptibility is partly increased along the interval c 370–430 m and the fracture logs indicate anomalously low (decreased) fracture frequency in this section. Increased magnetic susceptibility in combination with increased natural gamma radiation occurs in the section c 230–232 m, which most likely indicates a pegmatite dyke enriched in magnetite.

The fracture frequency estimated for KFM10A is generally low. Sections with increased fracturing occur at c 85–145 m, c 300–350 m, 425–440 m and 480–490 m. The section 85–145 m is characterized by significantly decreased bulk resistivity, decreased P-wave velocity, decreased magnetic susceptibility and several distinct caliper anomalies, which all in all suggests strong brittle deformation and mineral alteration.

The section c 300–350 m is mainly characterized by an increased number of low resistivity anomalies, which indicates an increased occurrence of single fractures but no severe deformation. Along the entire interval c 425–440 m the bulk resistivity is decreased and there are several caliper anomalies. However, at c 432 m there is a sharp anomaly showing decreased P-wave velocity in combination with greatly decreased resistivity, which may indicate the core of this possible deformation zone.

The possible deformation zone at c 480–490 m is characterized be decreased resistivity, decreased P-wave velocity and decreased magnetic susceptibility mainly in the interval c 483–486 m.

Apart from the four possible deformation zones indicated by the estimated fracture frequency log, there are two other sections that may crosscut deformed or altered rock. At c 229–250 m (mainly 229–240 m) the caliper data show a major anomaly, which indicates a possible cavity. The magnetic susceptibility is greatly decreased along large parts of this interval and the density is also partly decreased. Also note the increased susceptibility at c 230–232 m commented above.

The section c 340–347 m is characterized by decreased bulk resistivity and partly decreased P-wave velocity, which may indicate the occurrence of a minor deformation zone.

The apparent porosity log (black curve in Figure 5-2) averages at c 0.65%, which is considered normal for crystalline rock in this area. There is a major positive porosity anomaly in the section c 84–126 m, which coincides with an indicated deformation zone. Partly increased apparent porosity also occurs along the other possible deformation zones.

Two significant anomalies in the vertical temperature log are identified. One is centered at c 100 m, clearly related to the major possible deformation zone indicated at c 85–145 m, and the other temperature anomaly occurs at c 435 m, which is also spatially related with a possible deformation zone. These two temperature anomalies most likely indicate water bearing fractures.

The estimated fluid water salinity is fairly constant at c 10,600 ppm NaCl along the entire borehole. The salinity level shows a slight decrease along the possible deformation zone indicated at c 84–126 m.

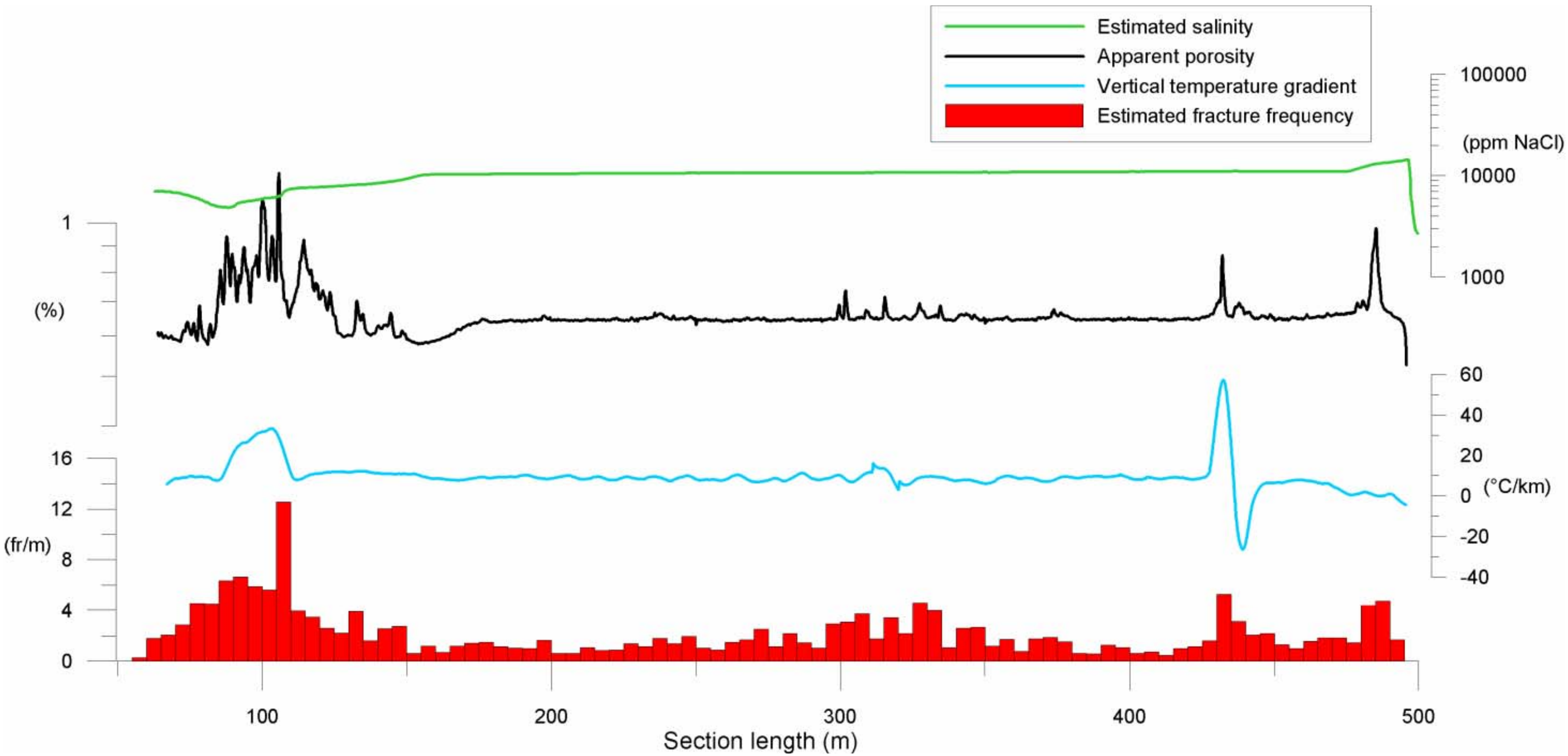

Figure 5-2. *Estimated salinity, apparent porosity, vertical temperature gradient and estimated fracture frequency of KFM10A.*

5.2.2 Interpretation of KFM08C

The results of the generalized logging data and fracture estimations of KFM08C are presented in Figure 5-3 below, and in a more detailed scale in Appendix 2. The distribution of silicate density classes with borehole length is presented in Table 5-3.

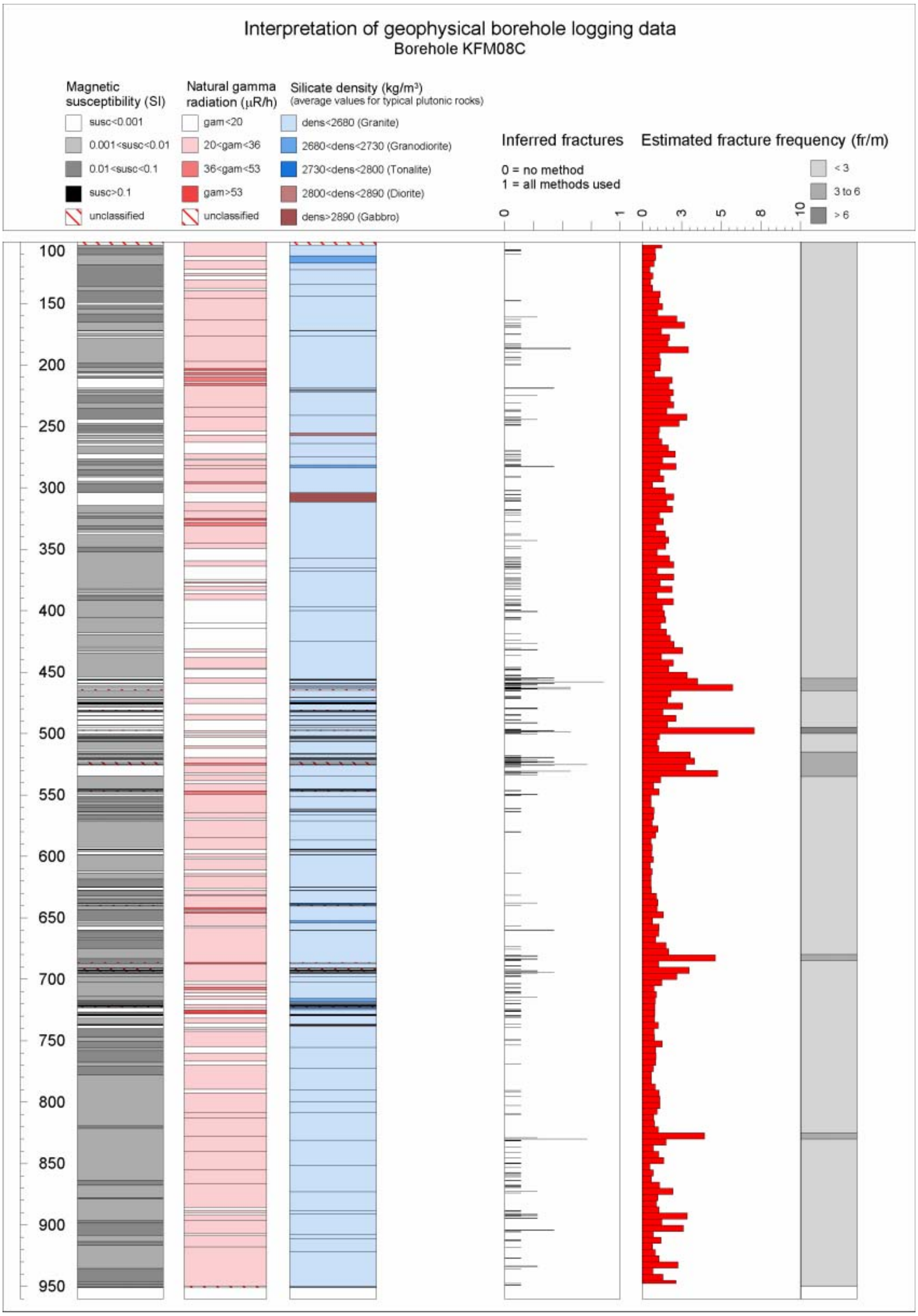

Figure 5-3. Generalized geophysical logs of KFM08C.

Table 5-3. Distribution of silicate density classes with borehole length in KFM08C.

Silicate density interval (kg/m³)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	704	85
2,680 < dens < 2,730 (granodiorite)	96	12
2,730 < dens < 2,800 (tonalite)	12	1
2,800 < dens < 2,890 (diorite)	5	1
dens > 2,890 (gabbro)	9	1

The rocks in the vicinity of KFM08C are completely dominated by silicate density < 2,680 kg/m³ (Table 5-2 and Figure 5-3). The density log is almost constant along the entire borehole and displays only minor variations. The natural gamma radiation is generally in the interval 15–30 μR/h and the magnetic susceptibility is mainly in the interval 0.009–0.015 SI. In the generalized logs in Figure 5-3 these data seem to display fairly large variations, but the main reason for this appearance is that the data levels are close to the boundary between two classes (20 μR/h and 0.01 SI, respectively). However, sections with significantly decreased magnetic susceptibility occur fairly abundantly in the borehole, and these are generally spatially related with either positive radiation anomalies (indicating pegmatite or fine-grained granite) or with positive density anomalies that indicate amphibolites. One exception from this is the fairly long interval c 453–534 m. The decreased magnetization in this section is most likely related to mineral alteration caused by rock deformation (see the possible deformation zones described below).

In the interval c 304–311 m the density is c 3,000–3,050 kg/m³ and the magnetic susceptibility as well as the natural gamma radiation is significantly decreased. The combination of physical properties is typical for amphibolite. Short sections (< 5 m) with increased density, in combination with decreased magnetic susceptibility and natural gamma radiation, occur along the entire borehole length. Some of the indicated amphibolite dykes occur in direct vicinity to positive natural gamma radiation anomalies, which suggests that some mafic and felsic dykes are spatially related.

The fracture frequency estimated for KFM08C is generally low. A significant possible deformation zone is indicated in the geophysical data at c 453–550 m. The section is characterized by several low resistivity anomalies, decreased magnetic susceptibility, partly decreased P-wave velocity and numerous caliper anomalies. The most intensely deformed parts are indicated at c 455–460 m, 496–500 m and 517–534 m. Anomalies in the vertical temperature gradient data in Figure 5-4 suggest that parts of this possible deformation zone are water bearing.

A possible deformation zone is also indicated in the section c 675–705 m. This interval is mainly characterized by decreased resistivity, but in the lower part there is also decreased magnetic susceptibility and two short intervals with decreased P-wave velocity.

Two significant single fractures (short intervals with sharp high amplitude anomalies) are identified at c 639 m and 830 m. The former constitutes a significant sonic anomaly (decreased P-wave velocity) in combination with a distinct anomaly in the vertical temperature gradient data (Figure 5-4). The lower fracture, which is mainly indicated by decreased resistivity, is also clearly visible in the temperature gradient data. The temperature anomalies suggests that both these fractures are water bearing.

The estimated apparent porosity shown in Figure 5-4 (black curve) indicates an average porosity of 0.60–0.65%, which is normal for crystalline rock in this area with low fracture frequency. The section with increased porosity correlate well with the possible deformations described above.

The estimated salinity (green curve in Figure 5-4) is almost constant at c 6,500 ppm NaCl along the entire borehole length.

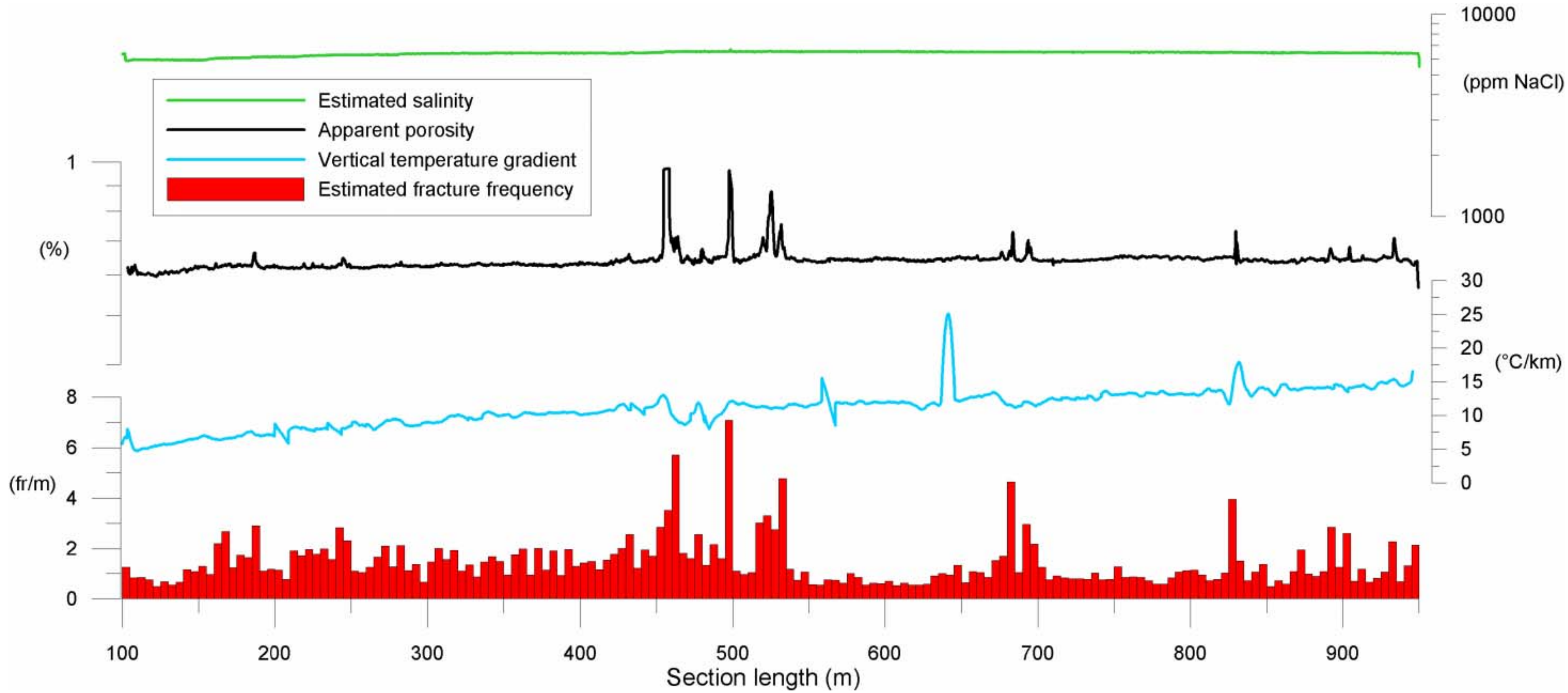

Figure 5-4. *Estimated salinity, apparent porosity, vertical temperature gradient and estimated fracture frequency of KFM08C.*

5.2.3 Interpretation of HFM30

The results of the generalized logging data and fracture estimations of HFM30 are presented in Figure 5-5 below.

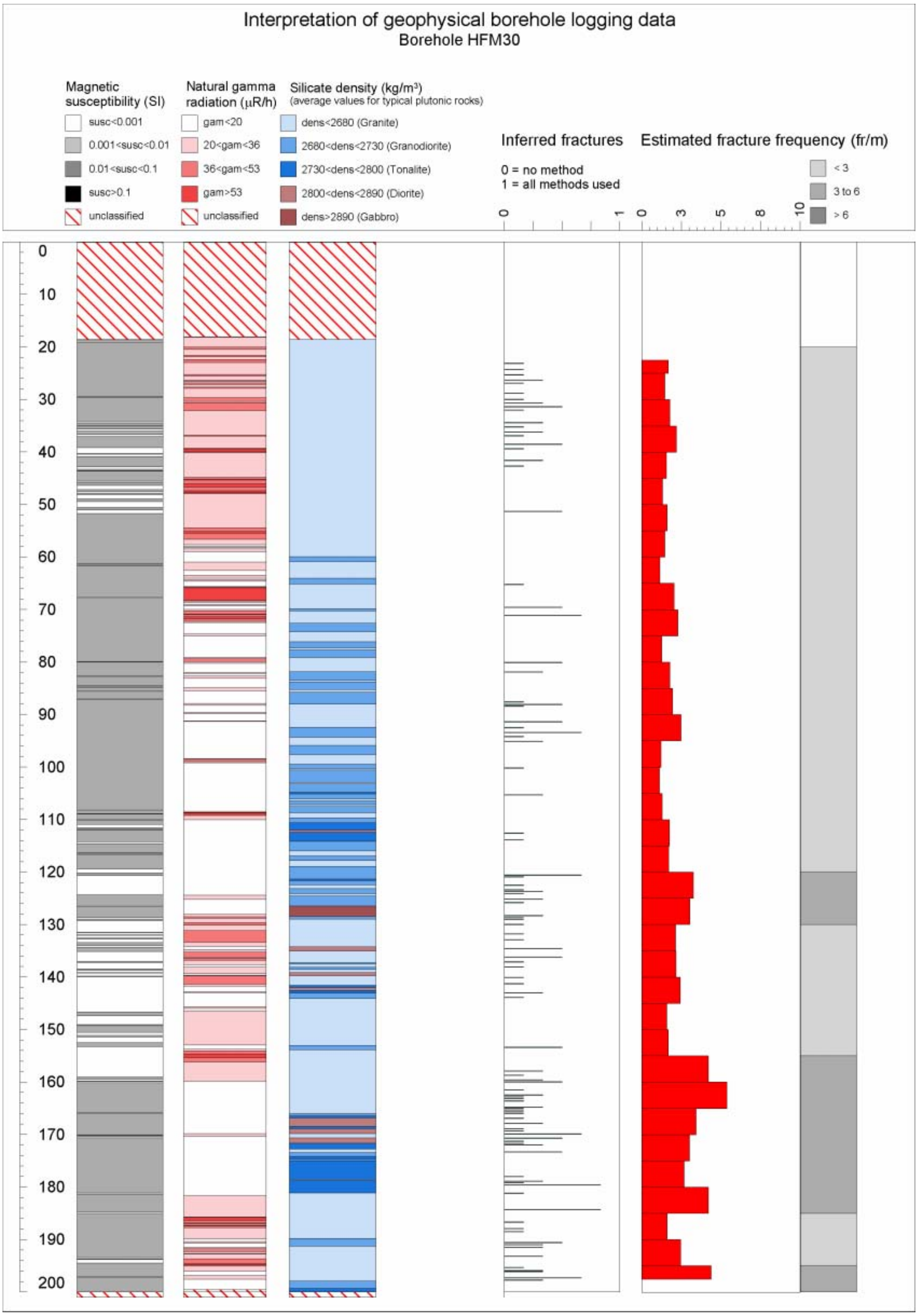

Figure 5-5. Generalized geophysical logs of HFM30.

Large parts of the sections c 18–52 m and 129–165 m of HFM30 have silicate density < 2,680 kg/m^3 and natural gamma radiation in the interval 20–36 µR/h. In these sections the magnetic susceptibility is decreased, generally in the range 0.0007–0.0015 SI. The rock in the vicinity of the intervals is most likely some kind of low magnetic granite, possibly leucocratic granite.

Along the sections c 52–129 m and 165–180 m the silicate density is generally 2,680–2,730 kg/m^3, and in short sections it is also higher. The natural gamma radiation is decreased (< 20 µR/h) and the magnetic susceptibility is increased (0.0030–0.0080 SI) along these intervals. This combination of physical properties indicates rock with mainly granodioritic mineral composition, with relatively higher magnetite content as compared to the more low density sections described above.

At c 127 m and along the interval 167–172 m the wet density is greater than 2,800 kg/m^3, which indicates the occurrences of amphibolites. Approximately 10 short sections (< 5 m) with increased natural gamma radiation occur in scattered places along the entire borehole length, and these most likely correspond to pegmatite or fine-grained granite dykes.

The estimated fracture frequency is low along the section c 20–120 m. At c 120 m there is a short interval with slightly increased fracturing. In the interval c 158–198 m the geophysical data indicate the occurrence of a major possible deformation zone. The entire section is characterized by a large number of caliper anomalies, decreased resistivity and decreased P-wave velocity. The most intensely deformed part is indicated to occur in the interval 159–166 m.

A special comment on the resistivity logs is that in the section c 20–120 m there is fairly high and constant resistivity. At c 120 m, and down to the bottom of the borehole, there is a stepwise decrease in resistivity. The decrease could possibly be related to rock alteration and/or deformation. However, there is also a spatial relation between this change in resistivity and the variations in the density, natural gamma radiation and magnetic susceptibility logs, which may suggest that it is related to a change in lithology.

5.2.4 Interpretation of HFM31

The results of the generalized logging data and fracture estimations of HFM31 are presented in Figure 5-6 below.

It is an anomalously heterogeneous distribution of physical properties in HFM31. The density, natural gamma radiation and magnetic susceptibility data display large variations along the entire borehole. There is a mixture of two different petrophysical signatures, either low density (2,540–2,600 kg/m^3), high natural gamma radiation (60–100 µR/h) and low magnetic susceptibility (0.001–0.002 SI) or high density (2,850–2,950 kg/m^3), low natural gamma radiation (c 10 µR/h) and high magnetic susceptibility (0.015–0.060 SI). The former signature most likely indicates the occurrences of fine-grained granite or leucocratic granite and the latter most likely indicates the occurrences of diorite/gabbro rock.

In the section c 100–110 m there are some intervals with intermediate densities of c 2,650–2,700 kg/m^3, which indicates rock with more “normal” granitic mineral composition, as compared to the very low density values in the other parts of the borehole.

The fracture frequency estimated for HFM31 is fairly low and there are only a few sections with slightly increased fracturing as indicated in Figure 5-6. However, when looking at the primary data there is decreased resistivity, caliper anomalies and partly decreased P-wave velocity in the section c 27–49 m. The rock in the vicinity of this part of the borehole has most likely suffered from brittle deformation. A similar indication of increased fracturing is also indicated along the interval c 95–110 m.

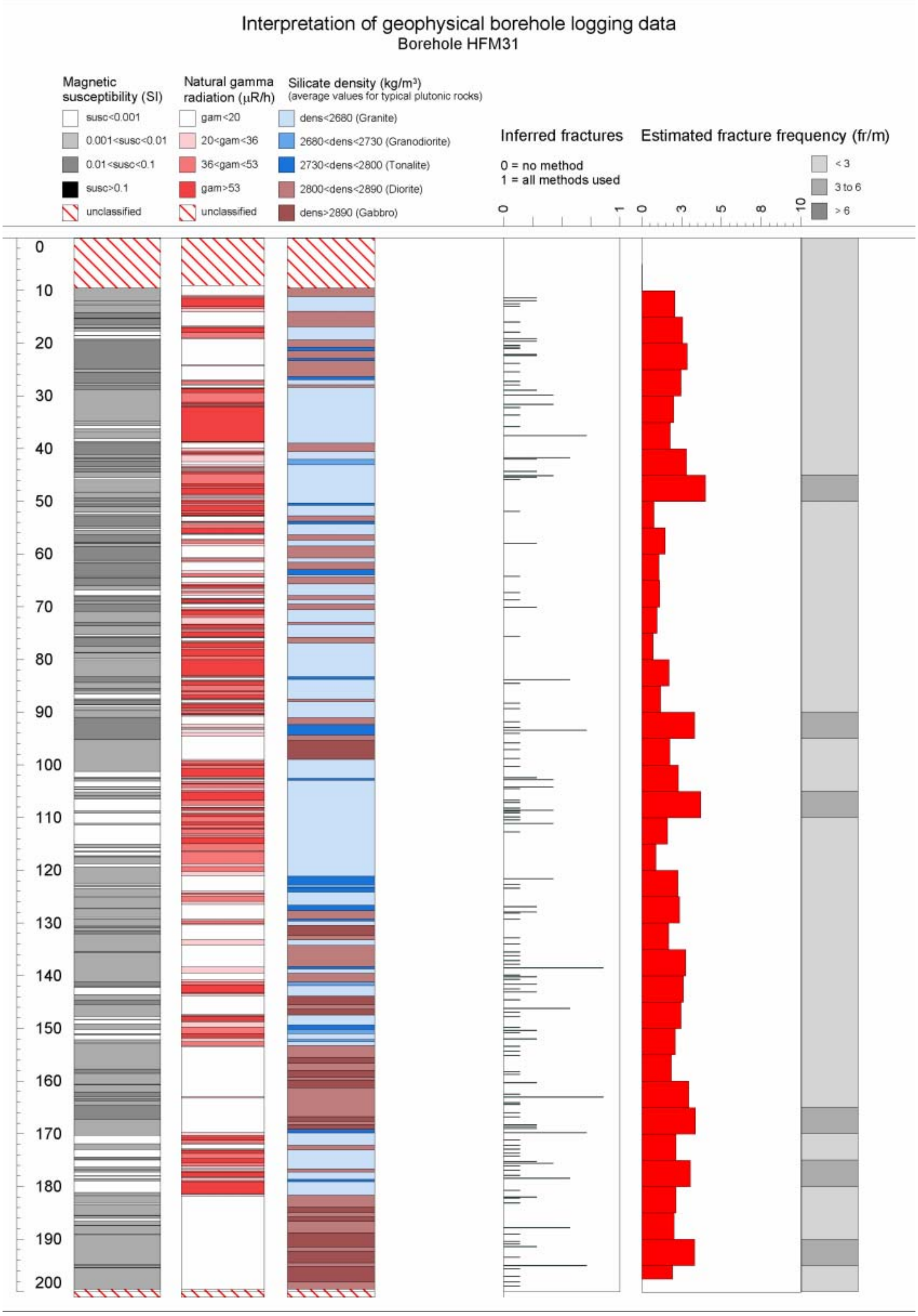

Figure 5-6. Generalized geophysical logs of HFM31.

5.2.5 Interpretation of HFM33

The results of the generalized logging data and fracture estimations of HFM33 are presented in Figure 5-7 below.

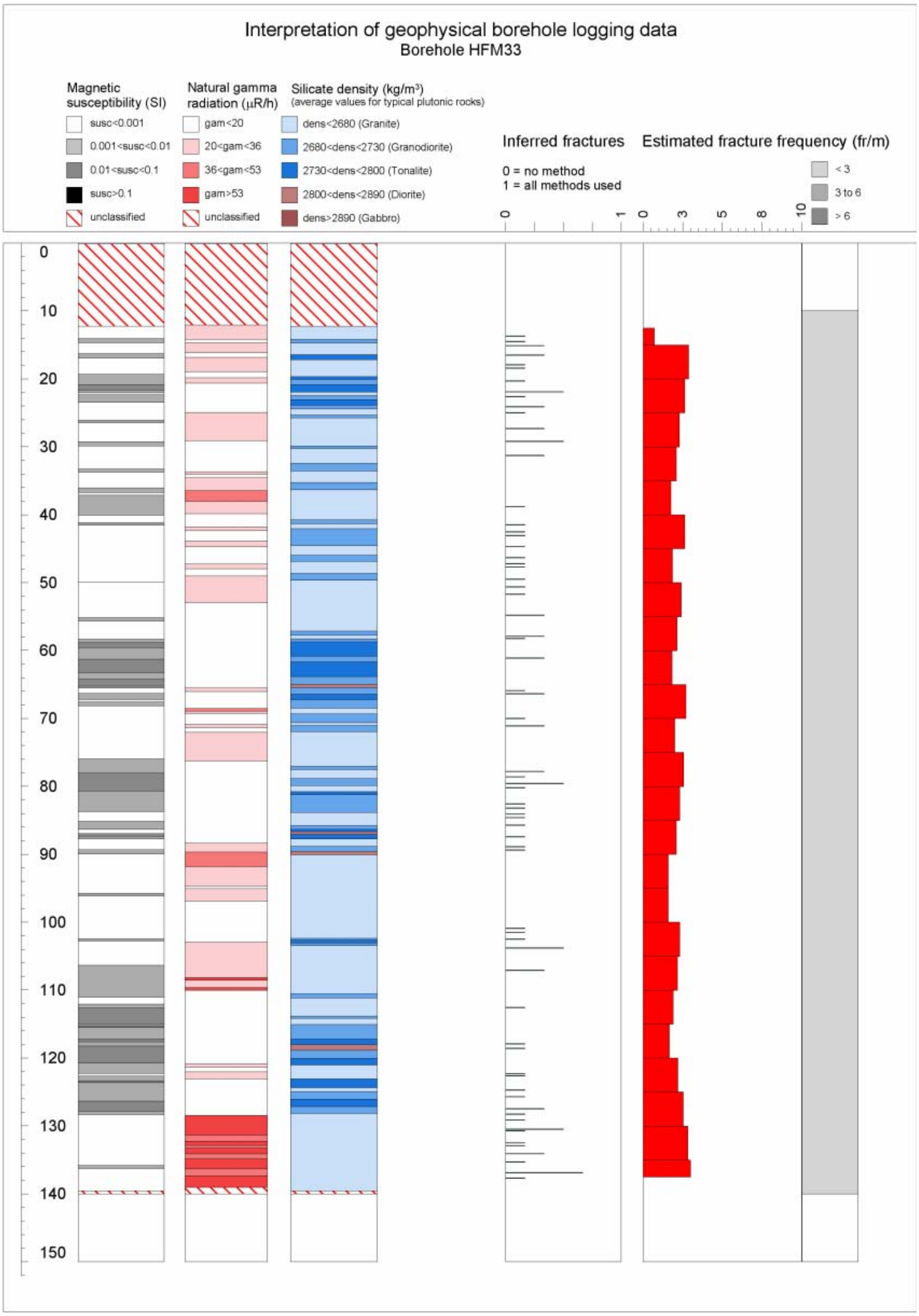

Figure 5-7. Generalized geophysical logs of HFM33.

A majority of the rocks in the vicinity of HFM33 are dominated by silicate density < 2,680 kg/m^3; the wet density is generally in the range 2,650–2,700 kg/m^3. Along these sections the natural gamma radiation mainly varies within the range 15–25 μR/h (varying up and down between two classes with the boundary at 20 μR/h) and the magnetic susceptibility is < 0.001 SI. The data corresponds to that of low magnetic granite rock.

In the sections c 26–40 m and 129–140 m the density is significantly decreased (2,550–2,630 kg/m^3) and the natural gamma radiation is increased (35–120 μR/h), which most likely indicates the occurrences of leucocratic granite.

C 5–10 m long sections with increased density, mainly in the range 2,750–2,850 kg/m^3 occur along the entire borehole section. Along these sections the magnetic susceptibility is mainly 0.005–0.035 SI and the natural gamma radiation is generally < 20 μR/h. The combination of physical properties indicates the occurrences of granodiorite or tonalite rock.

The estimated fracture frequency is low along the entire borehole length. No deformation zones are identified.

5.2.6 Interpretation of HFM34

The results of the generalized logging data and fracture estimations of HFM34 are presented in Figure 5-8 below.

The section c 12–72 m is characterized by silicate density in the range 2,680–2,800 kg/m^3, magnetic susceptibility of 0.010–0.030 SI and natural gamma radiation in the range 5–15 μR/h. The combination of physical properties indicates rock with granodioritic or tonalitic mineral composition and with a fairly high content of magnetite.

In the remaining part of HFM34, section c 72–199 m, the rock in the vicinity of the borehole has decreased magnetization; the susceptibility is 0.0015 SI or less.

The sections c 105–125 m, 135–144 m and 183–193 m have density < 2,600 kg/m^3. In the section c 135–144 m the density is < 2,565 kg/m^3, which is anomalously low, and in combination with increased natural gamma radiation of 70–100 μR/h, this indicates the occurrence of leucocratic granite.

The sections 86–96 m, 125–135 m and 144–183 m are characterized by density of 2,670–2,730 kg/m^3 and natural gamma radiation of 15–25 μR/h, which most likely corresponds to granite-granodiorite rock.

The estimated fracture frequency for HFM34, presented in Figure 5-8, is low and there are no indications of possible deformation zones. However, in the raw data there is a clear indication of a possible deformation zone along the section c 81–133 m. This part of the borehole is characterized by partly decreased resistivity, numerous caliper anomalies and partly decreased P-wave velocity.

5.2.7 Interpretation of HFM35

The results of the generalized logging data and fracture estimations of HFM35 are presented in Figure 5-9 below.

The rocks in the vicinity of HFM35 are completely dominated by silicate density < 2,680 kg/m^3. The lowest densities (< 2,600 kg/m^3) occur in the section c 60–120 m, and in this interval the natural gamma radiation is increased, averaging at c 40–80 μR/h. Apart from this interval the natural gamma radiation is mainly 20–36 μR/h. The low density sections may correspond to leucocratic granite.

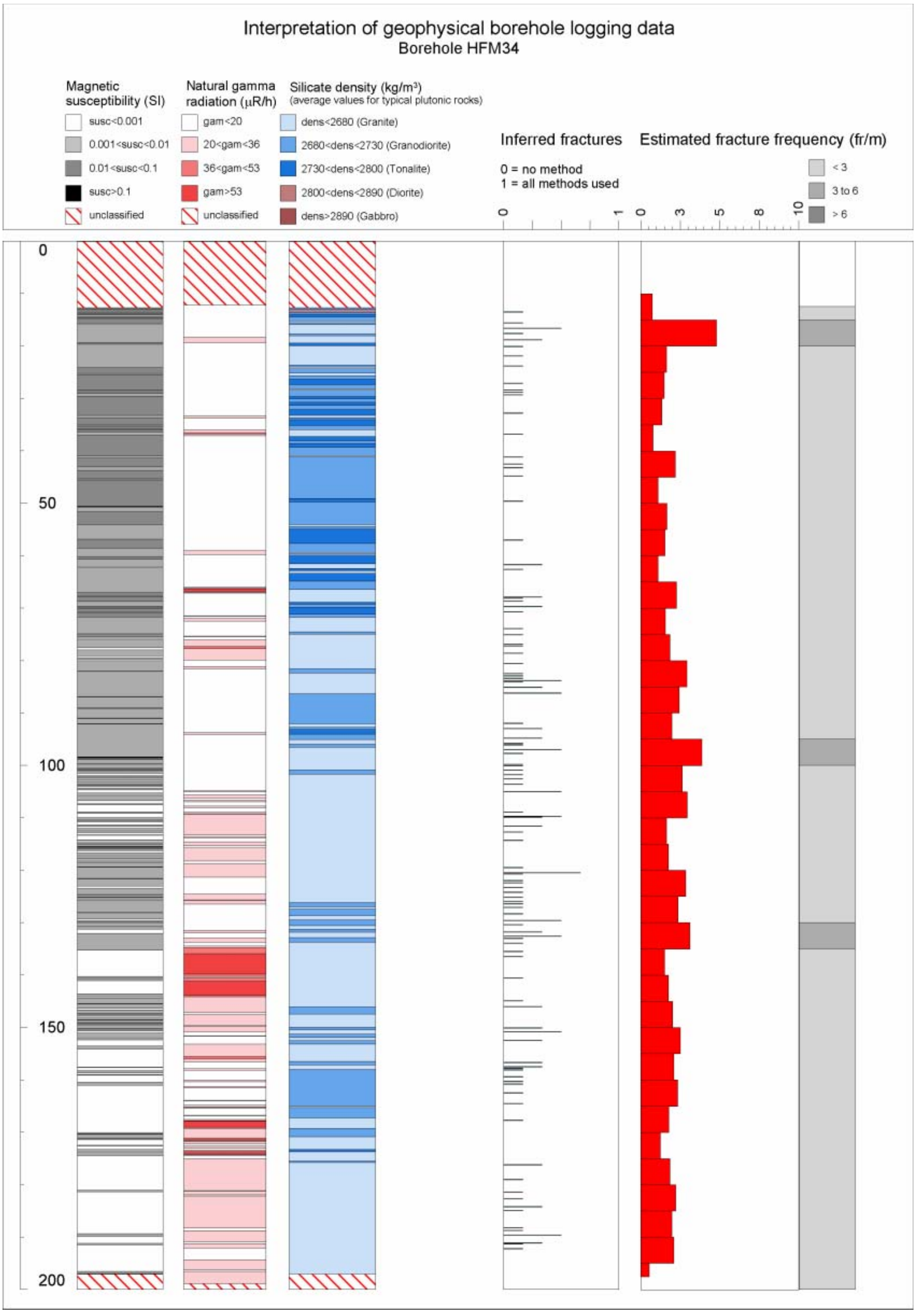

Figure 5-8. Generalized geophysical logs of HFM34.

Figure 5-9. Generalized geophysical logs of HFM35.

Short sections (< 5 m) with increased density, in combination with decreased magnetic susceptibility and natural gamma radiation, occur in 6 sections in the borehole. Some of these indicated amphibolite dykes occur in direct vicinity to positive natural gamma radiation anomalies, which suggests that some mafic and felsic dykes are spatially related.

The magnetic susceptibility is generally < 0.0010 SI in the section c 12–144 m. In the section c144–199 m the magnetic susceptibility varies greatly within the range 0.0006–0.0060 SI. In general, the rocks along the entire borehole have decreased magnetization.

The fracture frequency estimated for HFM35 is low or moderate. However, in the sections c 22–37 m, 48–52 m, 88–93 m, 114–123 m, 143–145 m and 167–174 m there are clear signs of partly strong brittle deformation, which is indicated by decreased bulk resistivity, decreased P-wave velocity and caliper anomalies.

5.2.8 Interpretation of HFM38

The results of the generalized logging data and fracture estimations of HFM38 are presented in Figure 5-10 below.

The silicate density is fairly constant along the entire borehole, with an average of c 2,620 kg/m^3. The natural gamma radiation is also fairly constant, with minor variations in the range c 15–25 μR/h. The large variations in natural gamma radiation indicated in Figure 5-10 are mainly caused by the level varying up and down across the boundary of 20 μR/h between two classes.

In the intervals c 125–128 m and 136–145 m there are significant positive density anomalies in combination with decreased natural gamma radiation and decreased magnetic susceptibility. This combination of physical properties is typical for amphibolites. Both sections are surrounded by positive natural gamma radiation anomalies, most likely indicating the occurrences of felsic dykes, which suggests that mafic and felsic dykes are spatially related.

The estimated fracture frequency is mainly low. In the section c 20–50 m there is a possible deformation, mainly indicated by decreased resistivity, decreased magnetic susceptibility and a number of caliper anomalies. The most intensely deformed interval occurs in the section c 28.5–31.5 m, along which the P-wave velocity is also partly decreased.

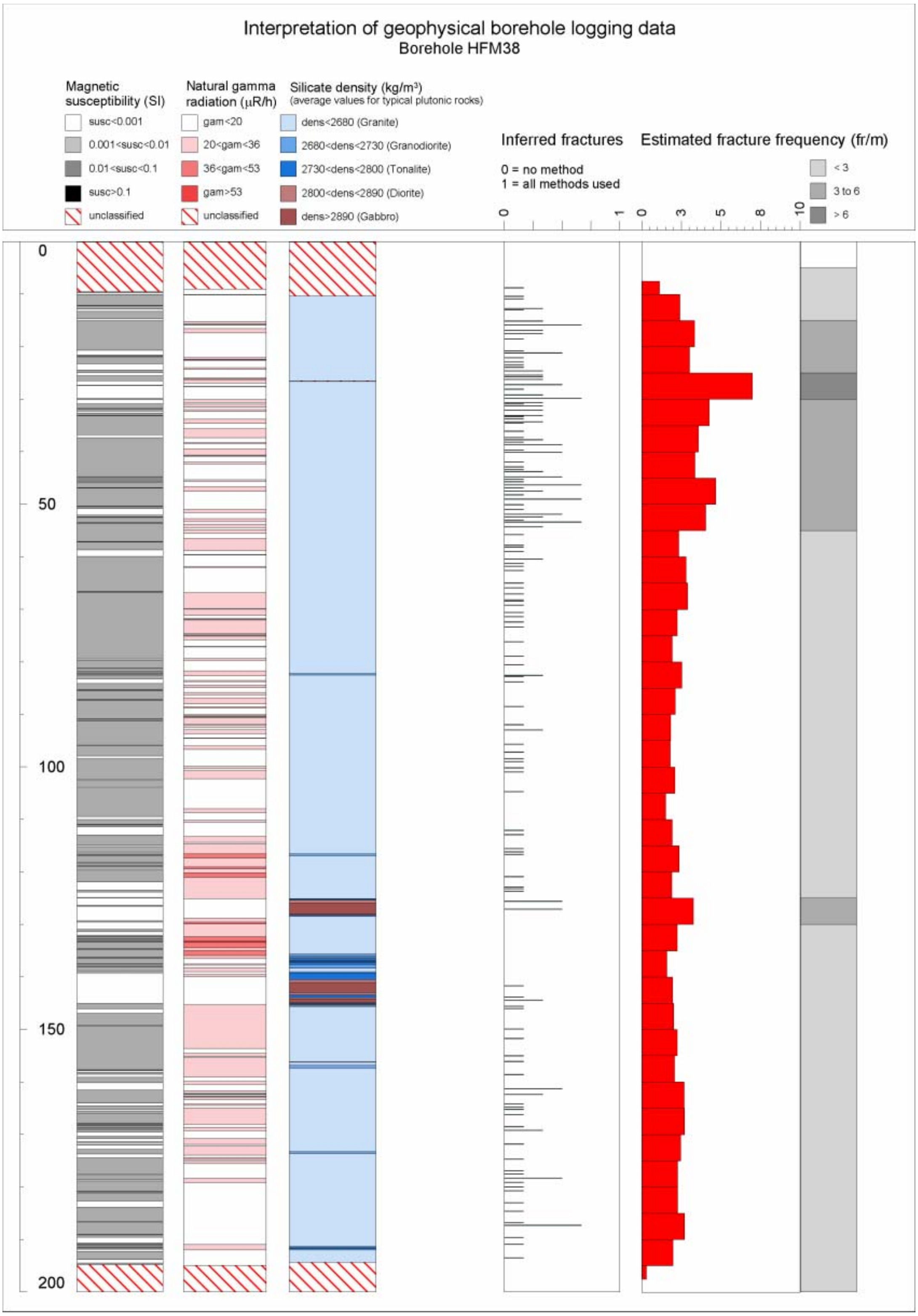

Figure 5-10. Generalized geophysical logs of HFM38.

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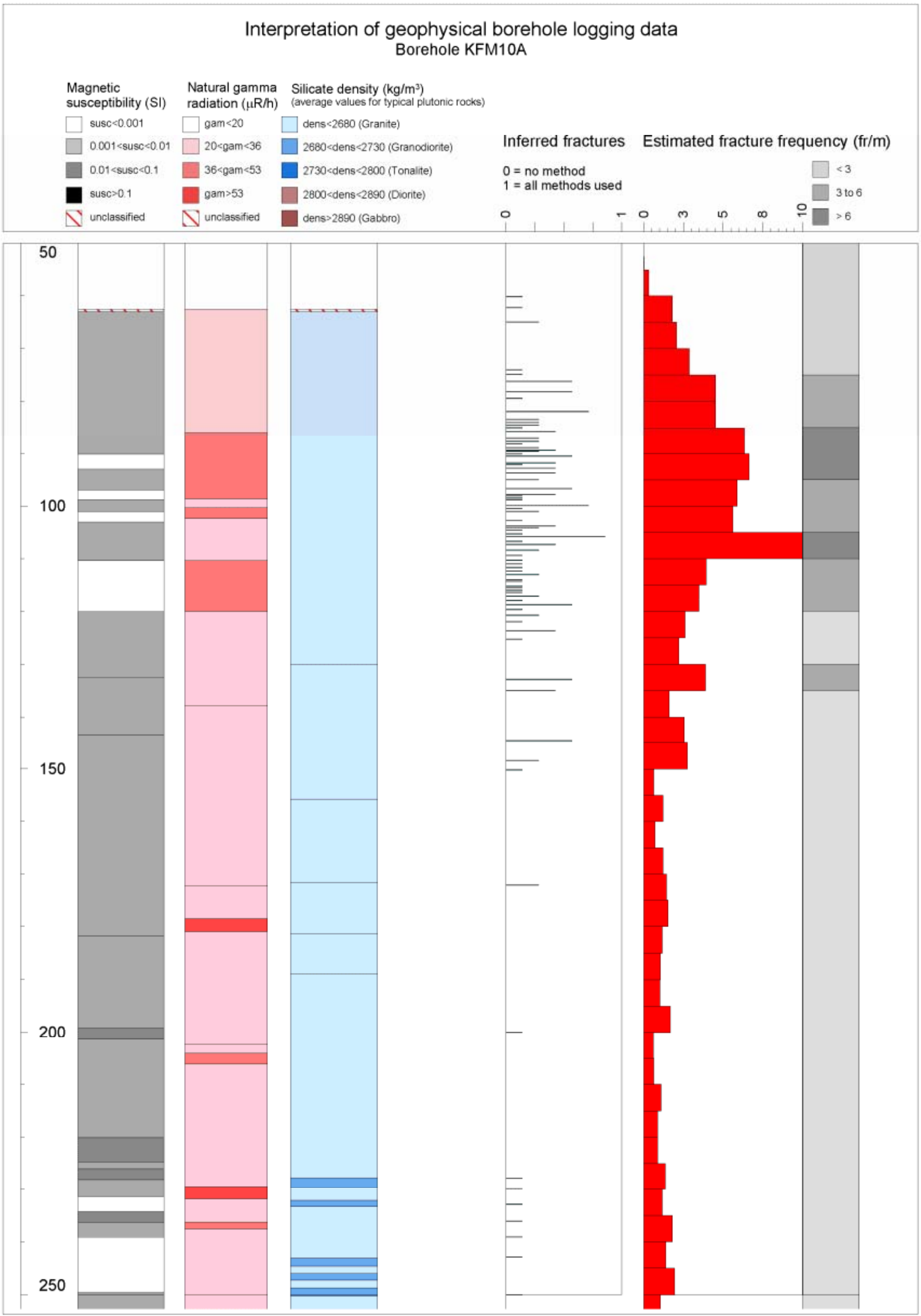
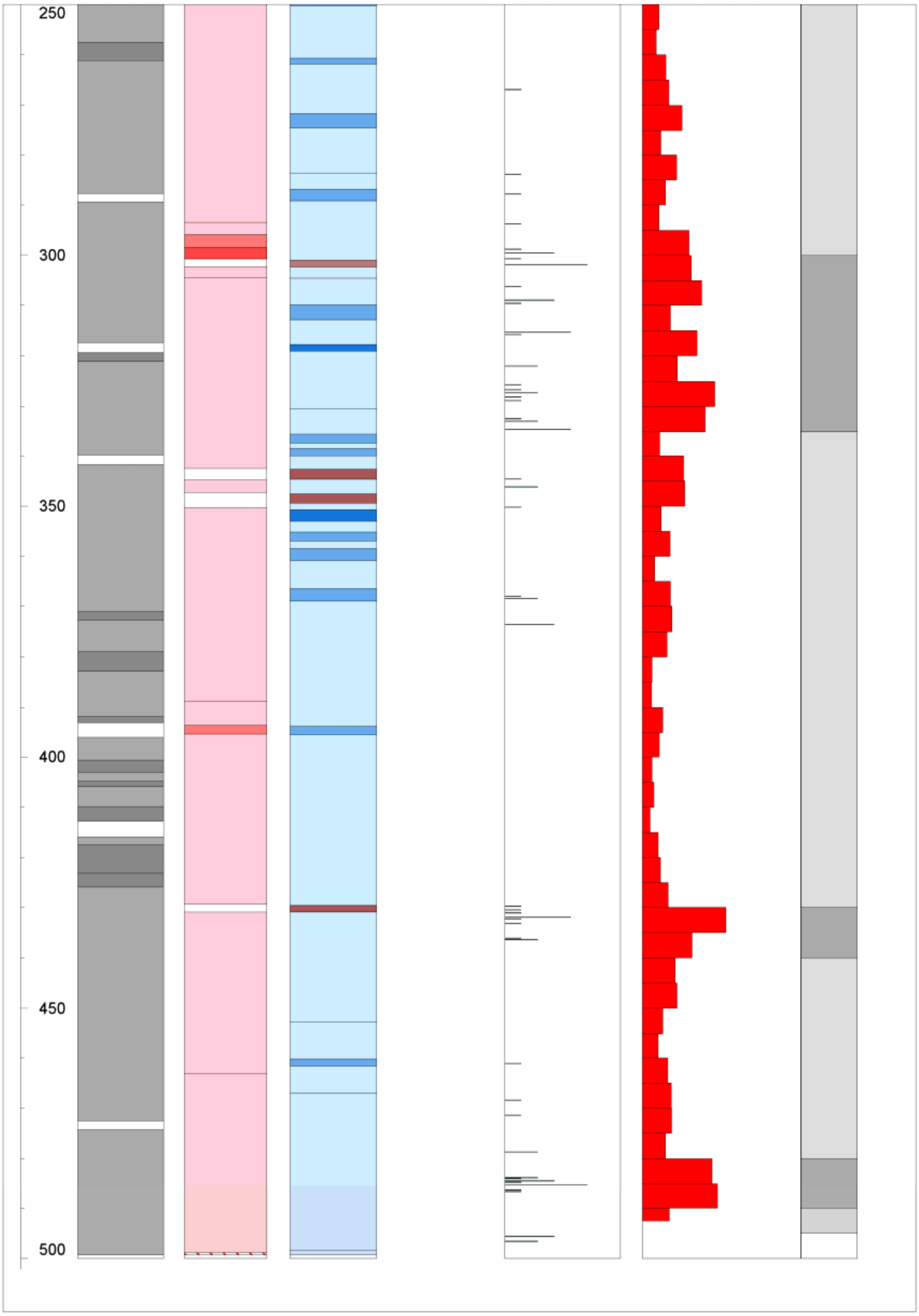
Generalized geophysical loggings of KFM010A

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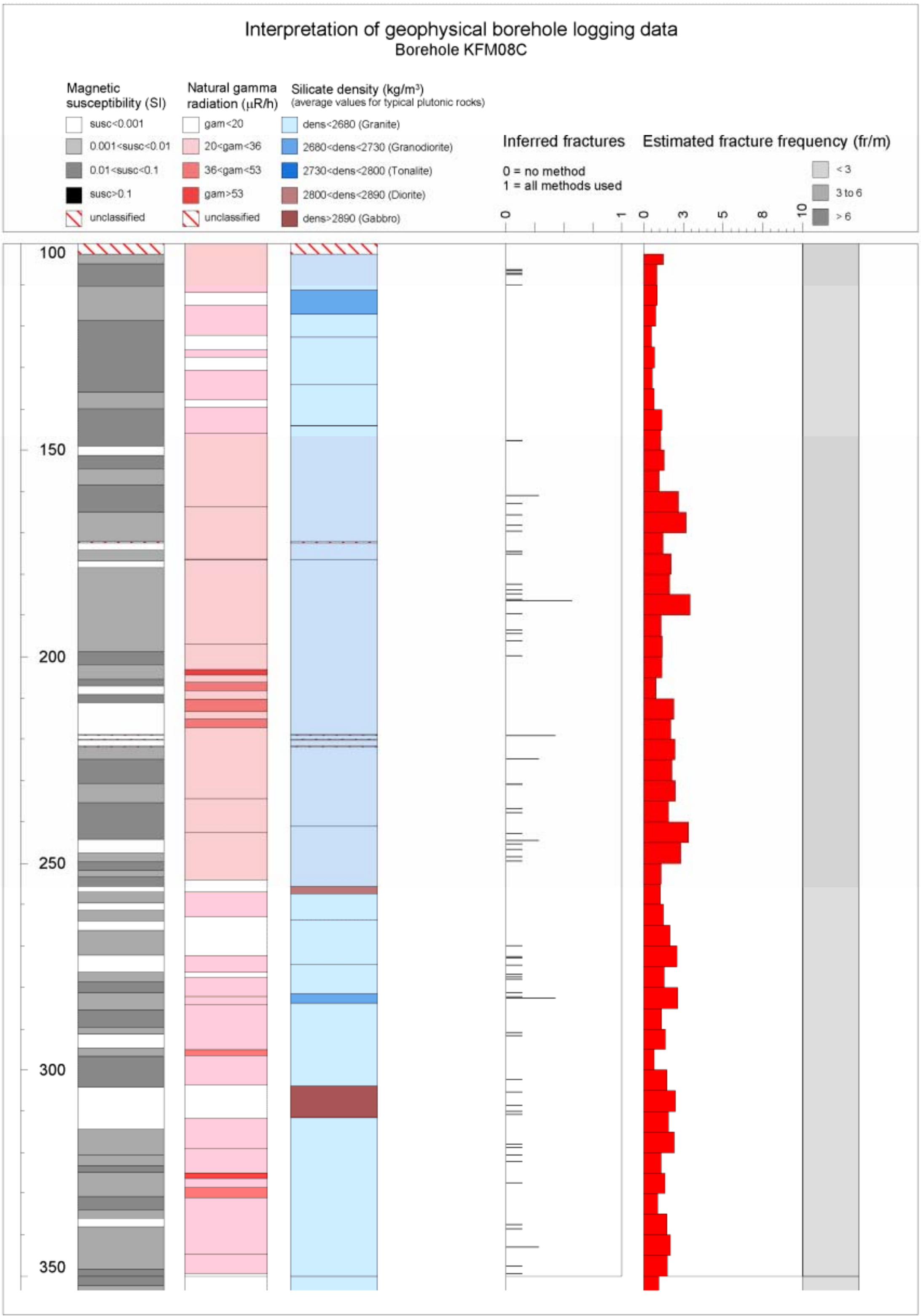

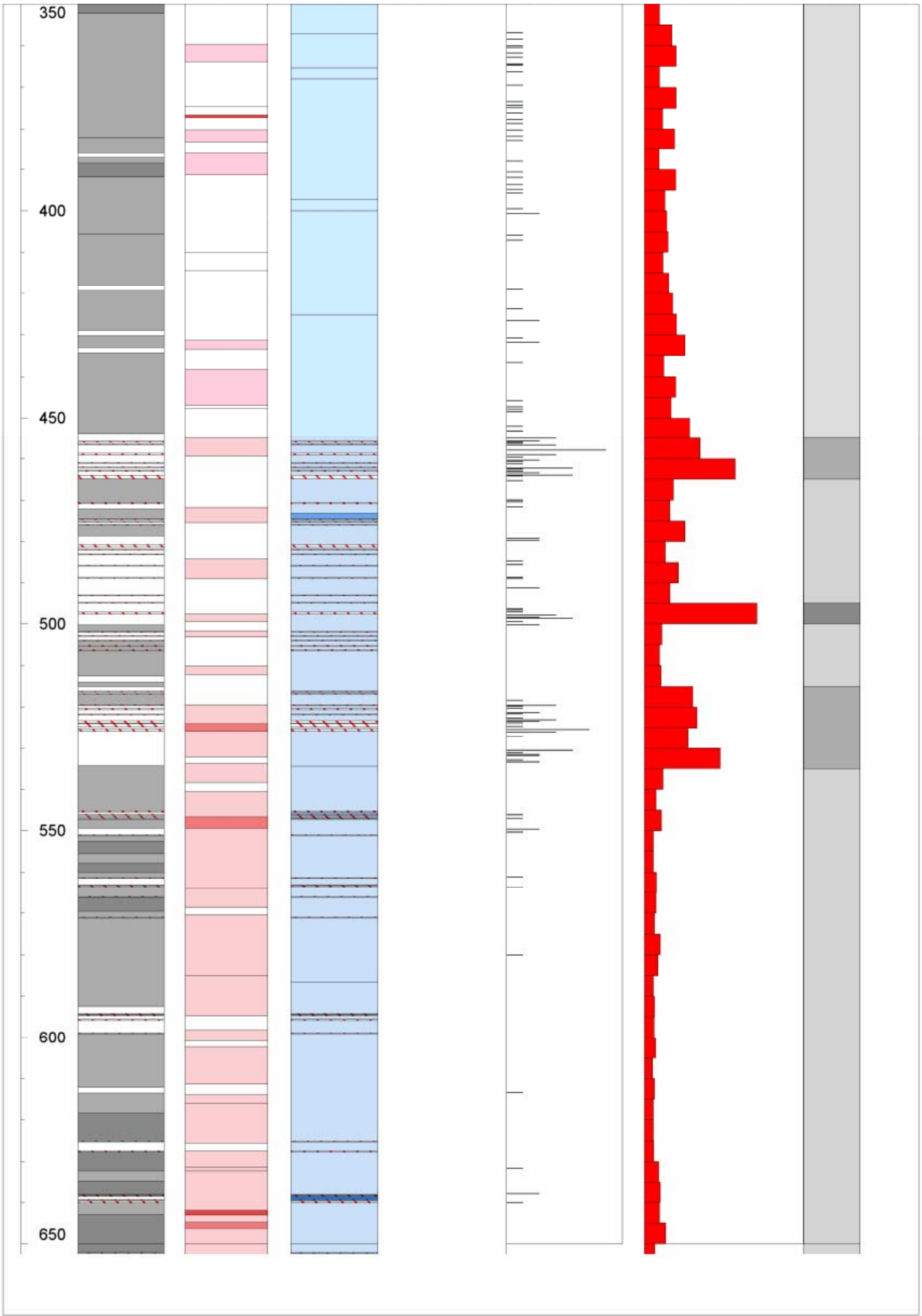
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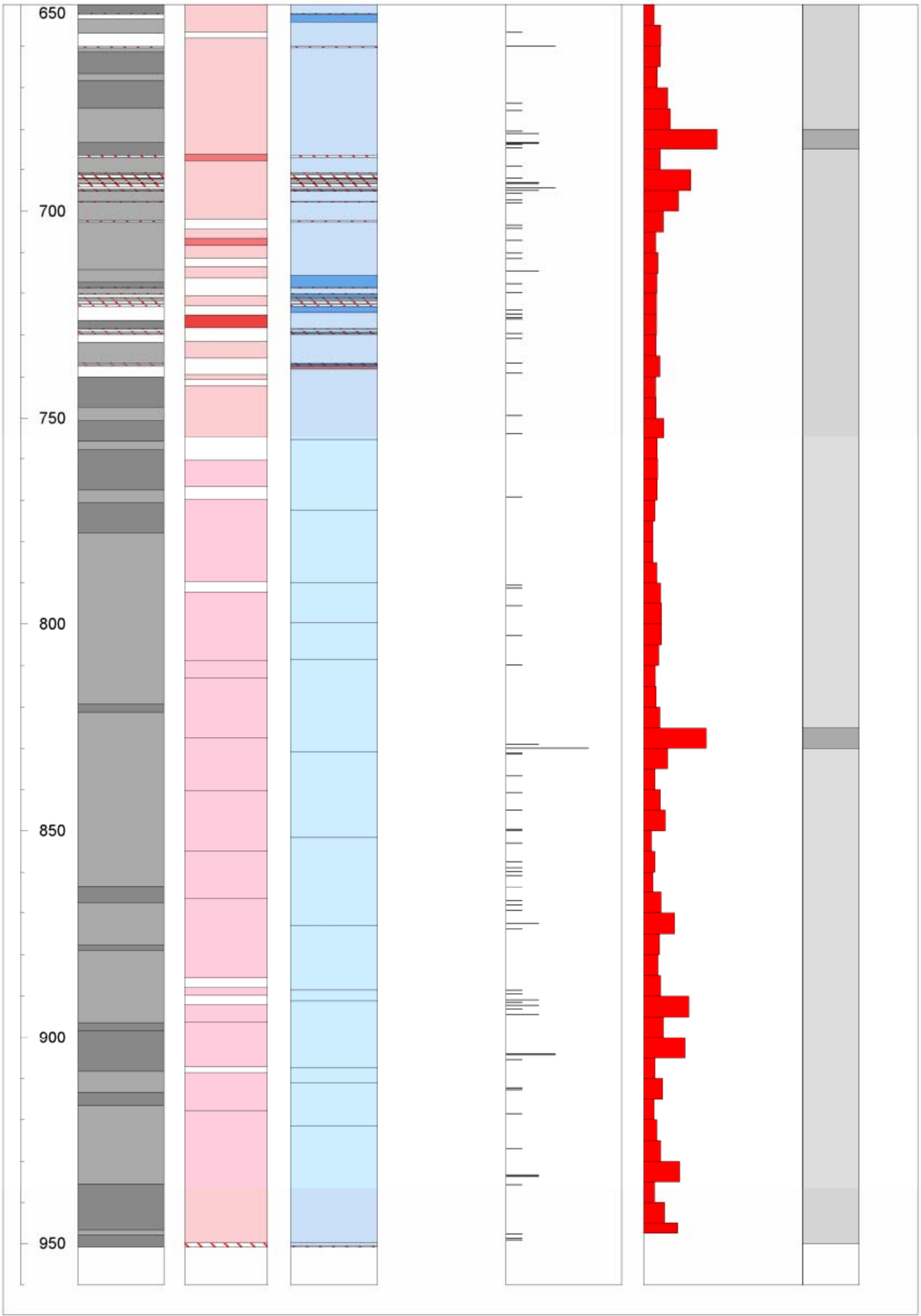
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