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# Forsmark site investigation

# Interpretation of geophysical borehole measurements from KFM08A and KFM08B

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October 2005

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*Keywords:* Borehole, Logging, Geophysics, Geology, Bedrock, Fractures, Forsmark, AP PF 400-05-022.

# Abstract

This report presents the compilation and interpretations of geophysical logging data from the cored boreholes KFM08A and KFM08B.

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 rocks in the vicinities of both boreholes KFM08A and KFM08B are completely dominated by silicate density indicating a mineral composition that corresponds to granite rock (< 2,680 $kg/m^3$). Subordinate short sections of rocks with higher densities occur commonly in the boreholes. 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. 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 basic and acid dykes are spatially related.

The natural gamma radiation is mainly in the interval 20–36 µR/h. Short sections with positive radiation anomalies occur fairly frequent in both investigated boreholes, and these most likely indicate the presence of pegmatite or fine-grained granite dykes. Sections with low natural gamma radiation, without the "normal" increase in density related to amphibolites, are identified in KFM08A. Along these sections there is generally low magnetic susceptibility (< 0.001 SI), which may indicate that the rocks have suffered from alteration and/or fracturing.

The indicated fracture frequency in KFM08A is mainly low. There is partly increased fracturing indicated in the sections c 100–500 m and c 900–1,000 m. Four sections of significantly increased fracturing are indicated at 185–200 m, 480–485 m, 685–690 m and 910–925 m. These sections are characterized by numerous low resistivity anomalies, intervals with low P-wave velocity and caliper anomalies. The low resistivity anomalies generally coincide with a decrease in the magnetic susceptibility.

The indicated fracture frequency in KFM08B is mainly low. At c 35 m length there is a short section of indicated high fracture frequency, which coincides with a positive natural gamma radiation anomaly and low magnetic susceptibility that probably corresponds to a pegmatite dyke.

# Sammanfattning


Föreliggande rapport presenterar en sammanställning och tolkning av geofysiska borrhålsmätningar från kärnborrhålen KFM08A och KFM08B.

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.

Resultaten av undersökningarna visar att bergrunden i närheten av båda de undersökta borrhålen domineras av en silikatdensitet som indikerar en mineralsammansättning motsvarande den för granit (< 2 680 kg/m$^3$). Korta sektioner av bergarter med relativt hög densitet är vanligt förekommande i borrhålen. De högsta densiteterna, de som indikerar diorit till gabbro, sammanfaller i regel med låg naturlig gammastrålning och låg magnetisk susceptibilitet, vilket är en indikation på förekomst av amfibolitgångar. Många av de indikerade amfibolitgångarna ligger nära positiva anomalier i den naturliga gammastrålningen som troligen indikerar förekomst av pegmatit eller finkornig granit. Detta antyder att basiska och felsiska gångar har ett rumsligt samband.

Den naturliga gammastrålningen ligger oftast i intervallet 20–36 μR/h. Korta sektioner med hög naturlig gammastrålning, som troligen indikerar förekomst av pegmatit eller finkornig granit, förekommer i båda borrhålen. I KFM08A finns även några sektioner med låg naturlig gammastrålning (< 20 μR/h) som inte sammanfaller med den ”normala” förhöjningen i densitet kopplad till amfibolitgångar. Längs dessa sektioner är den magnetiska susceptibiliteten oftast låg, < 0,001 SI. Den låga naturliga gammastrålningen i kombination med låg susceptibilitet kan vara en indikation på att berget längs dessa sektioner är omvandlat eller har en högre sprickfrekvens.

Den uppskattade sprickfrekvensen i KFM08A är generellt låg. Det finns indikationer på bitvis förhöjd sprickfrekvens främst längs sektionerna ca 100–500 m och ca 900–1 000 m. Längs fyra sektioner finns indikationer på kraftigt förhöjd sprickighet, och dessa är ca 185–200 m, 480–485 m, 685–690 m och 910–925 m. Sektionerna karaktäriseras av flertalet lågresistiva anomalier, intervall med låg P-vågshastighet samt caliperanomalier. Områden med låg resistivitet sammanfaller ofta med låg magnetisk susceptibilitet.

Den uppskattade sprickfrekvensen i KFM08B är generellt låg. Vid ca 35 m finns en kort sektion med indikerad hög sprickfrekvens som dessutom sammanfaller med en positiv naturlig gammastrålningsanomali samt sänkt magnetisk susceptibilitet, vilket troligen indikerar förekomst av en pegmatitgång eller finkornig granitgång.

# 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 KFM08A and KFM08B 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 vertical temperature gradient, estimated salinity and apparent porosity are also presented for the boreholes. The logging measurements were conducted in 2005 by Rambøll.

The interpretation presented in this report is performed by GeoVista AB in accordance with the instructions and guidelines from SKB (activity plan AP PF 400-05-022 incl addendum and method description MD 221.003, see Table 1-1).

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

| Activity plan | Number | Version |
|---|---|---|
| Tolkning av geofysiska borrhålsdata från KFM07A (102–1,000 m) och KFM08B (0–200 m) samt tillägg avseende KFM08A. | AP PF 400-05-022 | 1.0 |
| Method descriptions | Number | Version |
| Metodbeskrivning för tolkning av geofysiska borrhålsdata. | SKB MD 221.003 | 2.0 |

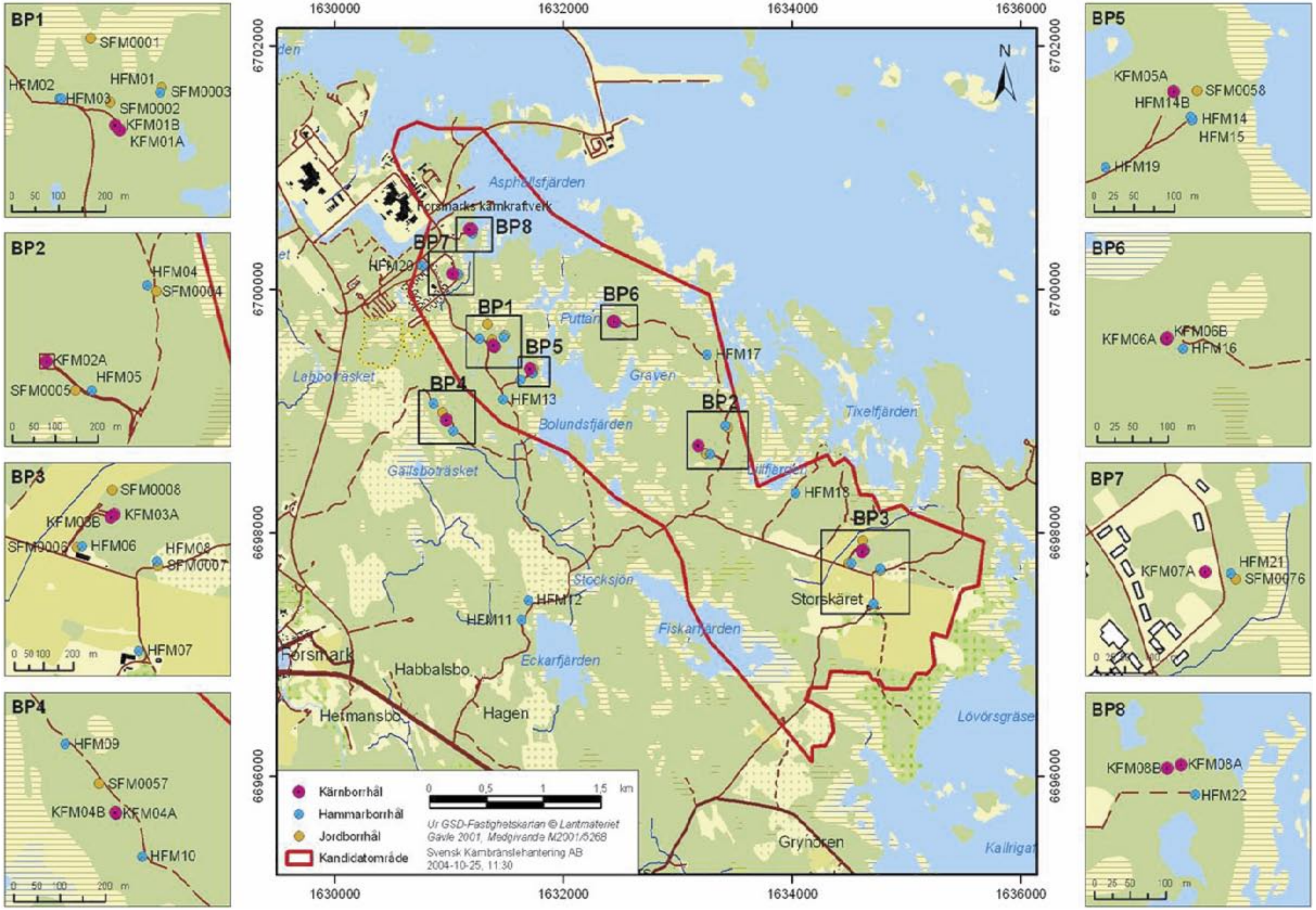


*Figure 1-1. Map showing the location of the investigated boreholes KFM08A and KFM08B.*

# 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.

The vertical temperature gradient, an estimation of the salinity and the apparent porosity are presented for the cored boreholes. These parameters indicate the presence of water bearing fractures, 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 and magnetic susceptibility logging data are calibrated with respect to petrophysical data. The logging data were calibrated by use of a combination of petrophysical data from the boreholes KFM01A and KFM02A /1, 2/.

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

The silicate density is calculated with reference to /3/ and the data are then divided into 5 sections **indicating** a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to /4/. 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" (< 20 μR/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 /5/; $\sigma = a\,\sigma_w^k\,\varphi^m + \sigma_s$ where σ = bulk conductivity (S/m), $\sigma_w$ = pore water conductivity (S/m), φ = volume fraction of pore space, $\sigma_s$ = 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 4-1.

**Table 4-1. 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 |
|---|---|---|---|---|
| KFM08A | 1.1 | 10 | 0.37 | 1.7 |
| KFM08B | 2.9 | 10 | 0.37 | 1.7 |

The vertical temperature gradient (in degrees/km) is calculated from the fluid temperature logging for 9 m sections according to the following equation /6/:

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

where $z$ = depth co-ordinate (m), $t$ = fluid temperature (°C) and $\varphi$ = borehole inclination (°). 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 $\rho$ = resistivity (Ωm).

The vertical temperature gradient and salinity are 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 4-2) 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 4-2.

**Table 4-2. 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 | KFM08A | 2.0 | 2.0 | 2.0 | 0.4 | 1.5 | 5.0 | 5.0 | – |
| Weight | KFM08A | 4.0 | 2.56 | 8.0 | 4.0 | 1.28 | 0.24 | 1.75 | – |
| Threshold | KFM08B | 1.0 | 1.0 | 1.0 | 0.4 | 1.0 | 3.0 | 2.0 | – |
| Weight | KFM08B | 4.0 | 2.56 | 8.0 | 4.0 | 1.28 | 0.24 | 1.75 | – |

**5.** Report evaluating the results.

## 4.2 Preparations and data handling

The logging data were delivered as Microsoft Excel files via email from Rambøll. 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.

## 4.3 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 vertical temperature gradient, salinity and apparent porosity help identifying water bearing fractures, 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. Apart from this, no nonconformities are reported.

# 5 Results

## 5.1 Quality controll of the logging data

### 5.1.1 Noise levels

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 log, the density log and the magnetic susceptibility log are slightly 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.

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

| Logging method | KFM08A | KFM08B | Recommended max noise level |
|---|---|---|---|
| Density ($kg/m^3$) | 14 | 12 | 3–5 |
| Magnetic susceptibility (SI) | $2\times10^{-4}$ | $1.4\times10^{-4}$ | $1\times10^{-4}$ |
| Natural gamma radiation (μR/h) | 0.8 | 0.6 | 0.3 |
| Long normal resistivity (%) | 0.3 | 0.2 | 2.0 |
| Short normal resistivity (%) | 0.2 | 0.1 | 2.0 |
| Fluid resistivity (%) | 0.02 | 0.01 | 2 |
| Fluid temperature (°C) | 0.0001 | 0.0003 | 0.01 |
| Lateral resistivity (%) | Not used | Not used | 2 |
| Single point resistance (%) | 0.5 | 0.2 | No data |
| Caliper (m) | $0.5\times10^{-4}$ | $0.5\times10^{-5}$ | 0.0005 |
| Focused resistivity 300 (%) | 8.4 | 12.4 | No data |
| Focused resistivity 140 (%) | 2.6 | 3.8 | No data |
| Sonic (m/s) | 4 | 3 | 20 |

## 5.2 Interpretation of the logging data

The presentation of interpretation products presented below, in the chapters 5.2.1 and 5.2.2 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 m sections.
- Classification of estimated fracture frequency (0 to 3, 3 to 6 and > 6 fractures/m).

### 5.2.1 Interpretation of KFM08A

The results of the generalized logging data and fracture estimations of KFM08A are presented in Figure 5-1 below, and in a more detailed scale in Appendix 1.

The rocks in the vicinity of KFM08A are completely dominated by silicate density indicating a mineral composition that corresponds to granite rock (< 2,680 kg/m$^3$), see Table 5-2 and Figure 5-1. Subordinate short sections of rocks with higher densities occur 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 occurrence 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 basic and acid dykes are spatially related.

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. Two significant positive radiation anomalies occur at c 668–676 m and 952–966 m. Sections with low natural gamma radiation, without the "normal" increase in density related to amphibolites, are also identified (e.g. at c 490 m). Along these sections there is generally low magnetic susceptibility (< 0.001 SI), which may indicate that the rocks have suffered from alteration and/or fracturing.

The magnetic susceptibility in section c 100–500 m is mainly in the interval 0.001–0.01 SI. Along the section c 500–750 m the magnetic susceptibility is higher, mainly in the interval 0.01–0.02 SI. In the lowermost c 250 m of KFM08A there are several long sections with low magnetic susceptibility (< 0.001 SI), possibly related to fracturing and/or alteration.

Partly increased fracturing is mainly indicated in the sections c 100–500 m and c 900–1,000 m. Four sections of significantly increased fracturing are indicated at 185–200 m, 480–485 m, 685–690 m and 910–925 m. These sections are characterized by numerous low resistivity anomalies, intervals with low P-wave velocity and caliper anomalies. The low resistivity anomalies generally coincide with a decrease in the magnetic susceptibility.

In the section c 500–900 m there are only few short indications of increased fracturing.

The estimated apparent porosity shown in Figure 5-2 (black line) is mainly in the interval 0.3–0.5%, which is reasonable in comparison to the petrophysical data from this area. Apparent porosity anomalies are few and mainly occur in the sections with indicated increased fracturing.

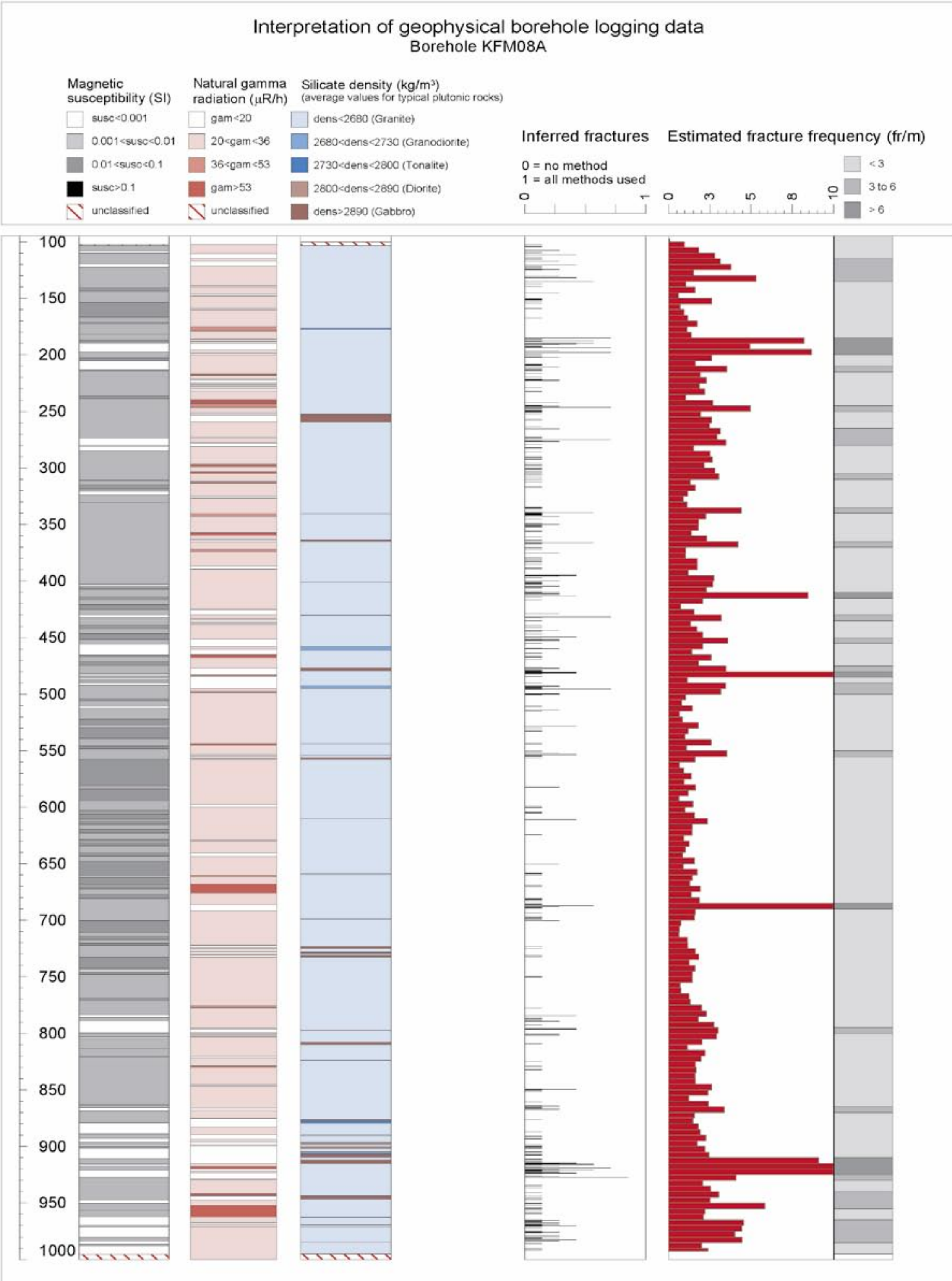


*Figure 5-1.* *Generalized geophysical logs of KFM08A.*

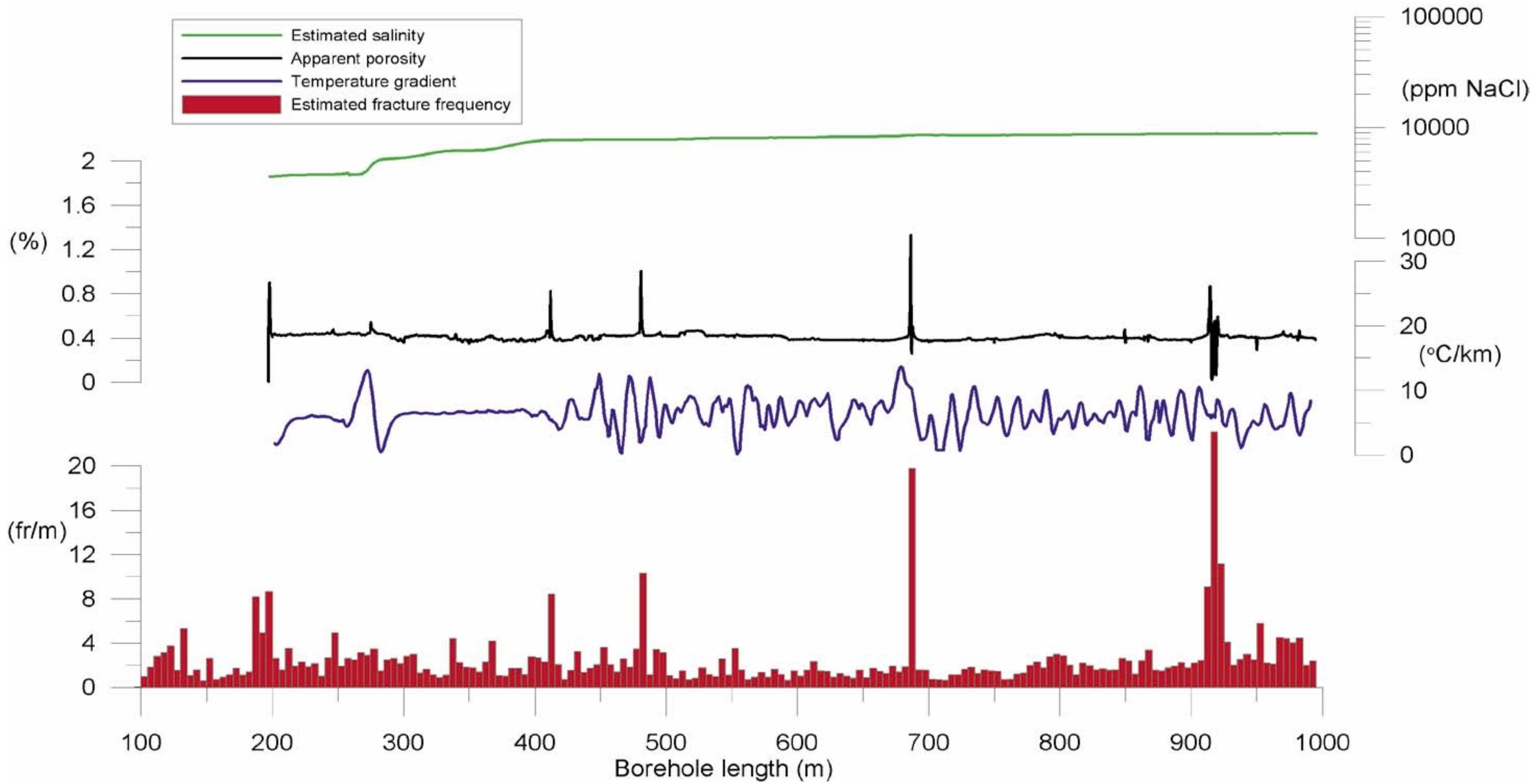


***Figure 5-2.*** *Estimated salinity, apparent porosity, vertical temperature gradient and estimated fracture frequency of KFM08A.*

**Table 5-2. Distribution of silicate density classes with borehole length of KFM08A.**

| Silicate density interval ($kg/m^3$) | Borehole length (m) | Relative borehole length (%) |
|---|---|---|
| dens < 2,680 (granite) | 787 | 88 |
| 2,680 < dens < 2,730 (granodiorite) | 35 | 4 |
| 2,730 < dens < 2,800 (tonalite) | 22 | 2.5 |
| 2,800 < dens < 2,890 (diorite) | 21 | 2.5 |
| dens > 2,890 (gabbro) | 27 | 3 |

The fluid temperature gradient log shows only one major anomaly (at c 278 m) in the uppermost 100–400 m of the borehole. Along the section 400–1,000 m there are numerous minor anomalies and a few significant anomalies at c 440–495 m and at c 685 m. The large anomalies coincide with sections of increased fracturing, which indicates that the increased fracturing is related to water bearing fractures.

### 5.2.2 Interpretation of KFM08B

The results of the generalized logging data and fracture estimations of KFM08B are presented in Figure 5-3 below.

The logging data of KFM08B remind a great deal of the data from KFM08A. The rocks in the vicinity of KFM08B 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 5-3. Subordinate short sections of rocks with higher densities occur along the entire borehole length, with a concentration to the lowermost c 30 m. 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 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. A fairly long section of increased natural gamma radiation is identified at c 145–160 m.

In the section 5–115 m the magnetic susceptibility is mainly in the interval 0.001–0.01 SI. Along the remaining part of the boreholes (section 115–200 m), there are large variations in the magnetic susceptibility, from 0.0001 SI up to c 0.03 SI, which indicates a more heterogeneous distribution of magnetite in the lower half of KFM08B as compared to the upper half .

The indicated fracture frequency is mainly low. At c 35 m length there is a short section of indicated high fracture frequency, which coincides with a positive natural gamma radiation anomaly and low magnetic susceptibility that probably corresponds to a pegmatite dyke. In the lowermost c 30 m of the borehole there is an indication of slightly increased fracture frequency.

The estimated apparent porosity shown in Figure 5-4 (black line) averages at c 0.6%, which corresponds well the petrophysical data from this area. Apparent porosity anomalies are few and they are low in amplitude, and mainly occur in the section c 5–35 m.

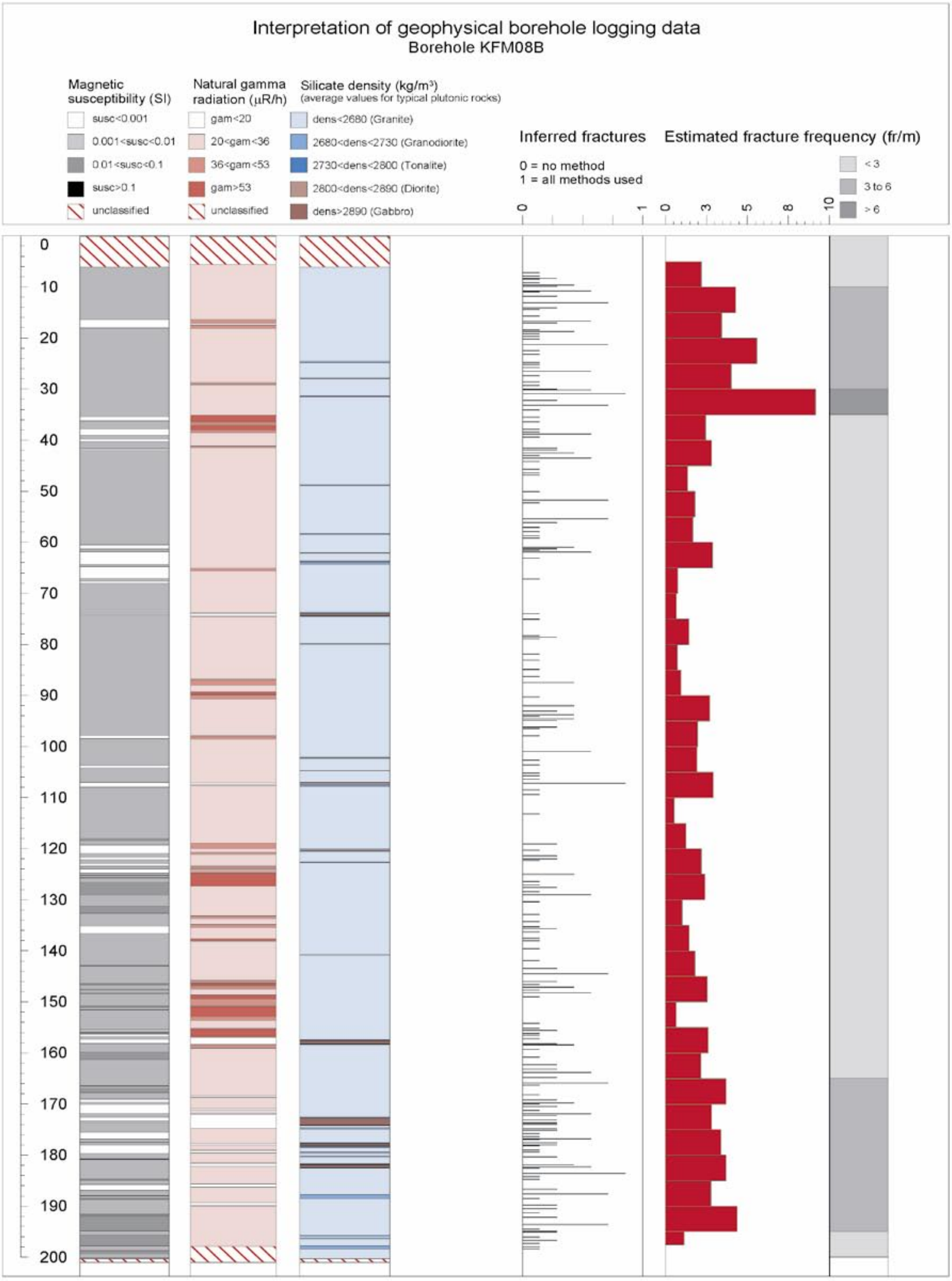


*Figure 5-3. Generalized geophysical logs of KFM08B.*

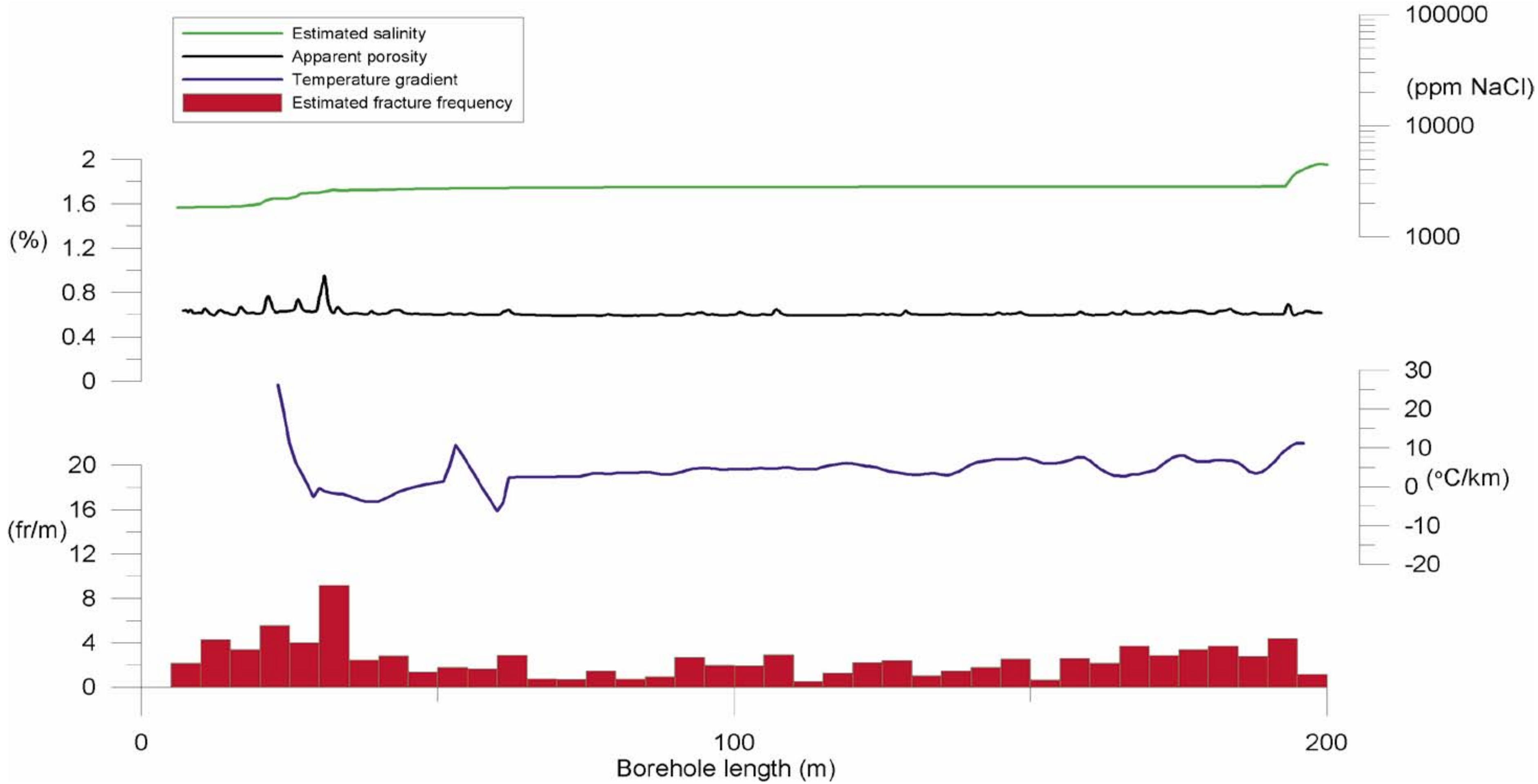


***Figure 5-4.*** *Estimated salinity, apparent porosity, vertical temperature gradient and estimated fracture frequency of KFM08B.*

The fluid temperature gradient log shows only one fairly small anomaly at c 35 m length. For the rest of the borehole there are no indications of temperature gradient anomalies.

**Table 5-3. Distribution of silicate density classes with borehole length of KFM08B.**

| Silicate density interval ($kg/m^3$) | Borehole length (m) | Relative borehole length (%) |
|---|---|---|
| dens < 2,680 (granite) | 182 | 94 |
| 2,680 < dens < 2,730 (granodiorite) | 6 | 3 |
| 2,730 < dens < 2,800 (tonalite) | 1 | 0.5 |
| 2,800 < dens < 2,890 (diorite) | 2 | 1 |
| dens > 2,890 (gabbro) | 3 | 1.5 |

# References

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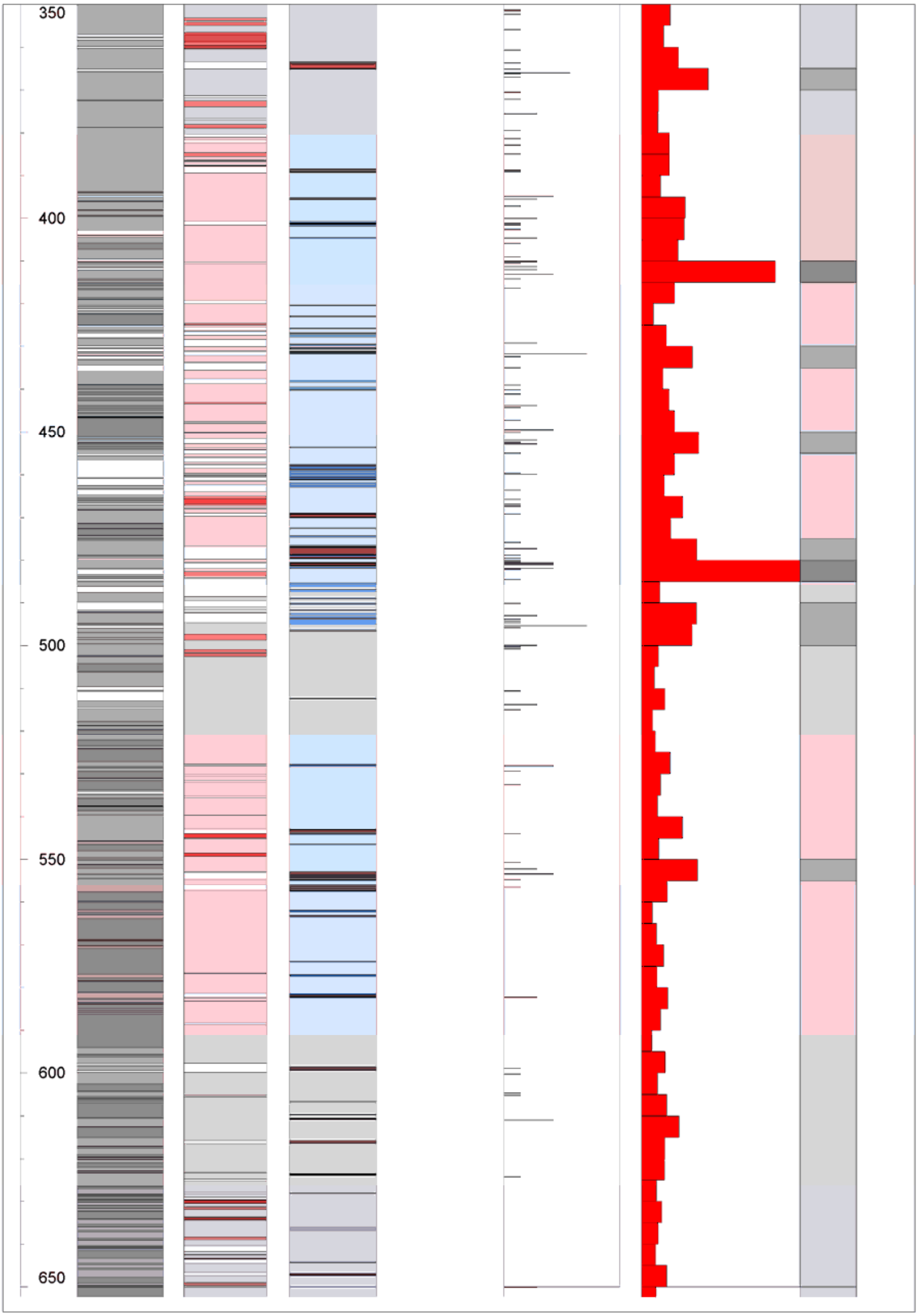
# Appendix 1

## Generalized geophysical loggings of KFM08A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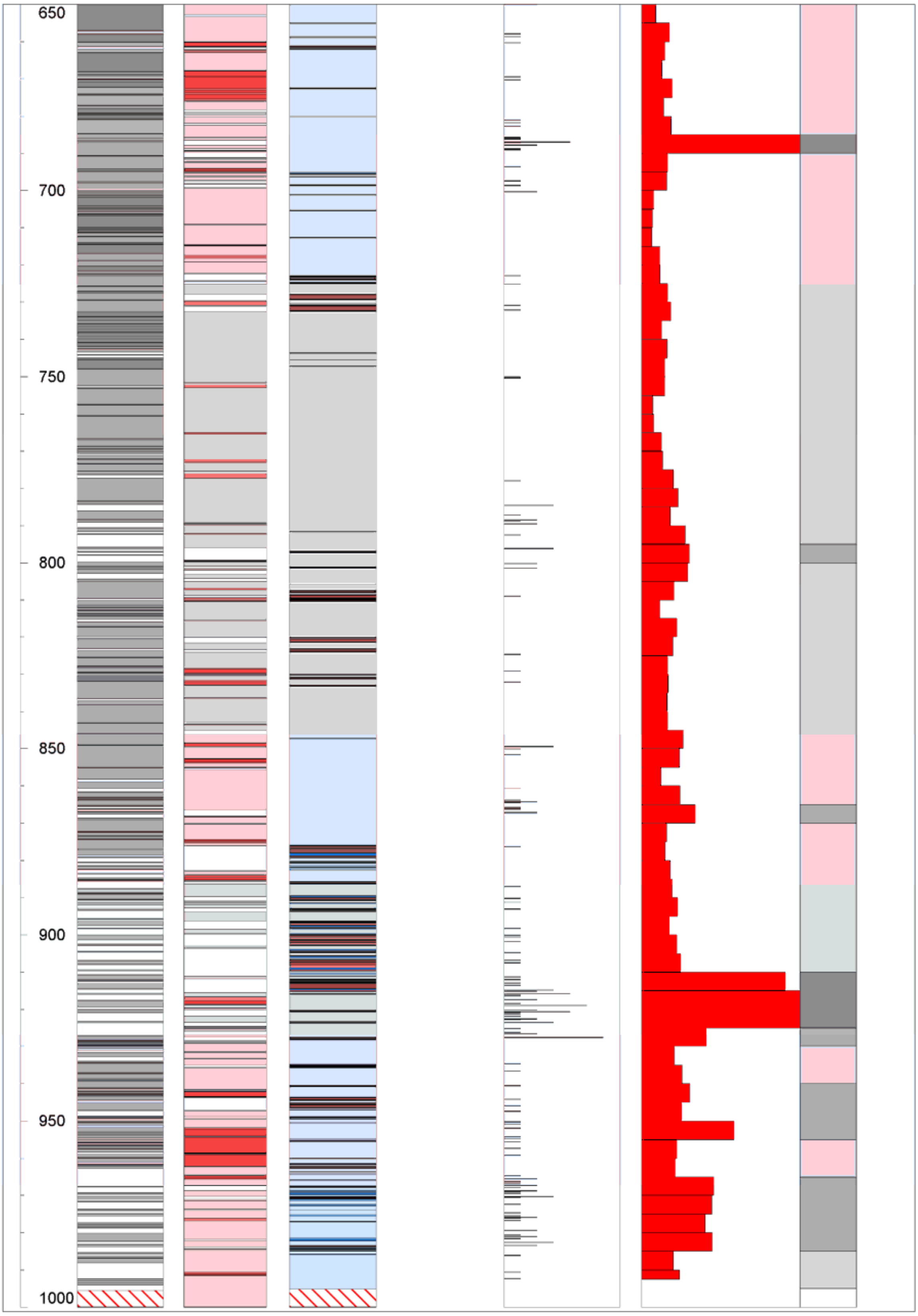
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