P-04-154

# Forsmark site investigation

# Interpretation of borehole geophysical measurements in KFM05A, HFM14, HFM15 and HFM19

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August 2004

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ISSN 1651-4416
SKB P-04-154

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*Keywords:* Borehole, Logging, Geophysics, Geology, Bedrock, Fractures, Salinity, Temperature gradient, AP PF 400-03-90, AP PF 400-04-49, Field note no Forsmark 344; 395.

# Abstract

This report presents the compilation and interpretation of geophysical logging data from the cored borehole KFM05A and the percussion drilled boreholes HFM14, HFM15 and HFM19.

The main objective of these investigations is to provide supportive information to the geological core mapping and to the so called single-hole interpretation.

The bedrock in the vicinity of KFM05A is dominated by rock types with a silicate density and thus a mineral composition that corresponds to granite. A c. 10 m wide section between 350 and 360 m has a silicate density corresponding to diorite and gabbro. Most of the rock has, for the area, normal values of magnetic susceptibility and natural gamma radiation. Several sections below 350 m depth do however show low magnetic susceptibility. This might be due to rock alteration.

The geophysical logs indicate that the fracture frequency along KFM05A is generally quite low. An exception is between 110 and 180 m depth. Narrow sections with increased fracturing are also inferred at 260, 425, 610, 715 and 975 m depth. The deeper part of the borehole can be subdivided into parts with virtually no significant fracture related geophysical anomalies and parts with some inferred fracturing. There is no clear relation between fracturing and low magnetic susceptibility.

The rocks at HFM14, HFM15 and HFM19 appear to have roughly the same petrophysical properties as the nearby KFM05A. Some narrow but possibly water bearing fracture zones are inferred in all three boreholes.

# Sammanfattning

Denna rapport presenterar tolkningen av geofysiska loggningsdata från kärnborrhålet KFM05A och hammarborrhålen HFM14, HFM15 och HFM19.

Det huvudsakliga syftet med detta arbete är att ta fram stödjande underlag till kärnkarteringen och till enhålstolkningen av de aktuella borrhålen.

Berggrunden vid KFM05A domineras av bergarter med en silikatdensitet och därmed en mineralsammansättning som motsvarar granit. Mellan 350 och 360 m förekommer bergarter med en silikatdensitet motsvarande diorit och gabbro. Berggrunden uppvisar huvudsakligen för området normala värden för magnetisk susceptibilitet och naturlig gammastrålning. Ett antal sektioner under 350 m djup har dock låg magnetisk susceptibilitet. Detta kan vara en effekt av omvandling.

De geofysiska loggarna indikerar att sprickfrekvensen i KFM05A generellt sett är mycket låg. Ett undantag är mellan 110 och 180 m. Smala sektioner med indikerad förhöjd sprickighet förekommer på 260, 425, 610, 715 och 975 m. Den djupare delen av borrhålet kan delas upp i relativt väl avgränsade delar av dels partier med knappast några sprickrelaterade geofysiska anomalier, dels partier med viss indikerad sprickighet. Ingen tydlig relation mellan sprickighet och magnetisk susceptibilitet kan ses.

Berggrunden vid HFM14, HFM15 och HFM19 uppvisar ungefär samma petrofysiska egenskaper som i det närbelägna KFM05A. Smala men troligen vattenförande sprickzoner har indikerats i alla tre borrhålen.

# 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 borehole KFM05A and the percussion drilled boreholes HFM14, HFM15 and HFM19 at Forsmark. The location of the boreholes are shown in Figure 1-1 (drill site 5).

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 measurements were conducted by Rambøll.

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 plans AP PF 400-03-90 and AP PF 400-04-49 (SKB internal controlling documents).

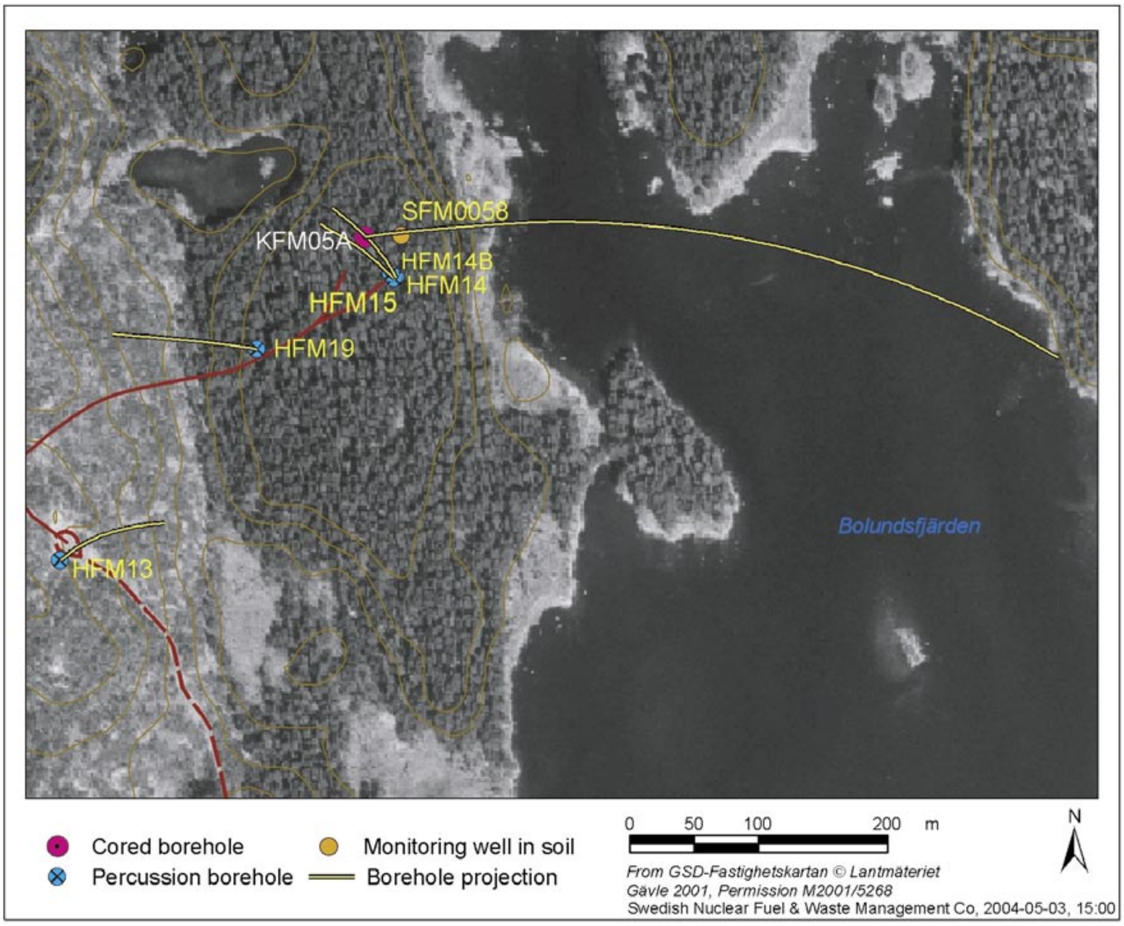



***Figure 1-1.** Forsmark site investigation. Drill site 5.*

# 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 boreholes are calculated by interpreting data from the resistivity logs, the single point resistance (SPR), caliper and sonic logs.

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

# 3 Execution

The software used for the interpretation are WellCad v3.2 (ALT) and Strater v1.0 (Golden Software) 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 /1/.

## 3.1 Logging data

The logging data were retrieved from SICADA. The data sets used for interpretation are:

*Density (gamma-gamma)*
*Magnetic susceptibility*
*Natural gamma radiation*
*Focused resistivity (300 cm and 140 cm)*
*Short and long normal resistivity*
*Sonic*
*Caliper mean (HFM14/15)*
*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.

## 3.2 Interpretation of the logging data

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

***1) Preparation 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 (except fluid temperature) have been average filtered (3 or 5 points). The fluid temperature log was filtered with a 17 point triangular average filter. 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 m sections according to the following equation /2/:

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

where $z$ = depth co-ordinate (m), $t$ = fluid temperature (ºC) 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).

***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 /3/ and the data are then divided into 5 intervals indicating a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to /4/. The intervals 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 "low", "medium", "high" or "very high" radiation, where 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*** (classification based on analyses focused resistivity, short normal, SPR, caliper and sonic logs).

The position of large fractures is estimated by applying a second derivative filter 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 m 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 holes 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 program *fract_det*, and weights used for estimating position of fractures and calculation of estimated fracture frequency, respectively.**

| | Borehole | Sonic | Focused res. 300 | Focused res. 140 | Short normal | Long normal | SPR | Caliper |
|---|---|---|---|---|---|---|---|---|
| Threshold | KFM05A | 1.0 | 1.5 | 1.5 | 2.5 | 3.5 | 1.0 | not used |
| Weight | KFM05A | 4.0 | 4.0 | 2.56 | 1.75 | 0.48 | 2.56 | not used |
| Threshold | HFM14/15 | 0.4 | 0.6 | 0.6 | 2.5 | not used | not used | 0.7 |
| Weight | HFM14/15 | 1 | 1 | 1 | 1 | not used | not used | 1 |
| Threshold | HFM19 | 0.4 | 1.0 | 1.0 | 2.5 | not used | 0.7 | not used |
| Weight | HFM19 | 1 | 1 | 1 | 1 | not used | 1 | not used |

# 4 Results

## 4.1 Control of the logging 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. 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. In KFM05A, the noise level of the fluid temperature log is higher than the recommended level in spite of the fact that temperature anomalies usually have long wave-length in comparison to the sampling distance. It should be noted that the noise levels calculated in this way will be a function of the length and type of filter used.

A qualitative inspection was performed on the logs. The data were checked for spikes and/or other obviously incorrect data points.

**Table 4-1. Noise levels in geophysical logging data.**

| Logging method | KFM05A | HFM14 | HFM15 | HFM19 | Recommended max noise level |
|---|---|---|---|---|---|
| Density ($kg/m^3$) | 20 | 9 | 10 | 32 | 3–5 |
| Magnetic susceptibility (SI) | $2.0 \cdot 10^{-4}$ | $1.2 \cdot 10^{-4}$ | $0.9 \cdot 10^{-4}$ | $1.4 \cdot 10^{-4}$ | $1 \cdot 10^{-4}$ |
| Natural gamma radiation (μR/h) | 0.8 | 0.4 | 0.4 | 0.6 | 0.3 |
| Fluid temperature (°C) | 0.02 | 0.0012 | 0.0016 | 0.003 | 0.01 |
| Caliper (mm) | | 0.20 | 0.19 | | 0.5 |
| Focused resistivity 300 (%) | 6.9 | 11.2 | 10.6 | 13.6 | – |
| Focused resistivity 140 (%) | 1.2 | 6.8 | 7.7 | 8.2 | – |
| Short normal resistivity (%) | 0.04 | 0.90 | 0.55 | 0.31 | 2.0 |
| SPR (%) | 0.09 | | | 0.47 | – |
| Sonic (m/s) | 8 | 41 | 43 | 29 | 20 |

## 4.2 Interpretation of the logging data

A complete presentation of all processed logs and interpretation products is given below. The interpretation logs presented in the figures are:

- Classification of silicate density.
- Classification of natural gamma radiation.
- Classification of magnetic susceptibility.
- Position of inferred fractures (= 0 no method, = 1 fracture inferred from all methods).
- Estimated fracture frequency in 5 m sections.
- Classification of estimated fracture frequency (0 to 3, 3 to 6 and > 6 fractures/m).

### 4.2.1 Interpretation of KFM05A

***Vertical temperature gradient and salinity***

The median vertical temperature gradient in KFM05A is 8.7°C/km (Figure 4-1). The temperature data is somewhat noisy and anomalies of rather short wave-length can be seen, especially in the interval from 600 to 800 m. A few anomalies with a shape more typical of water-bearing fractures can be seen at depths of around 154, 213 and 275 m. The exact location of the possible corresponding fracture might be difficult to determine. A residual temperature where a gradient of 8.7°C/km has been subtracted is also shown.

The estimated salinity varies between 7,700 and 12,500 ppm NaCl (Figure 4-1). There are no major breaks or anomalies in the estimated salinity curve that indicates water flow. A small anomaly can however be seen at a depth of around 270 m. It should be noted that borehole temperature and salinity might be affected by non-equilibrium with the surrounding rock at the time of logging. It should also be noted that the high salinity values corresponds to low fluid resistivity values, making effects of possible calibration errors large.

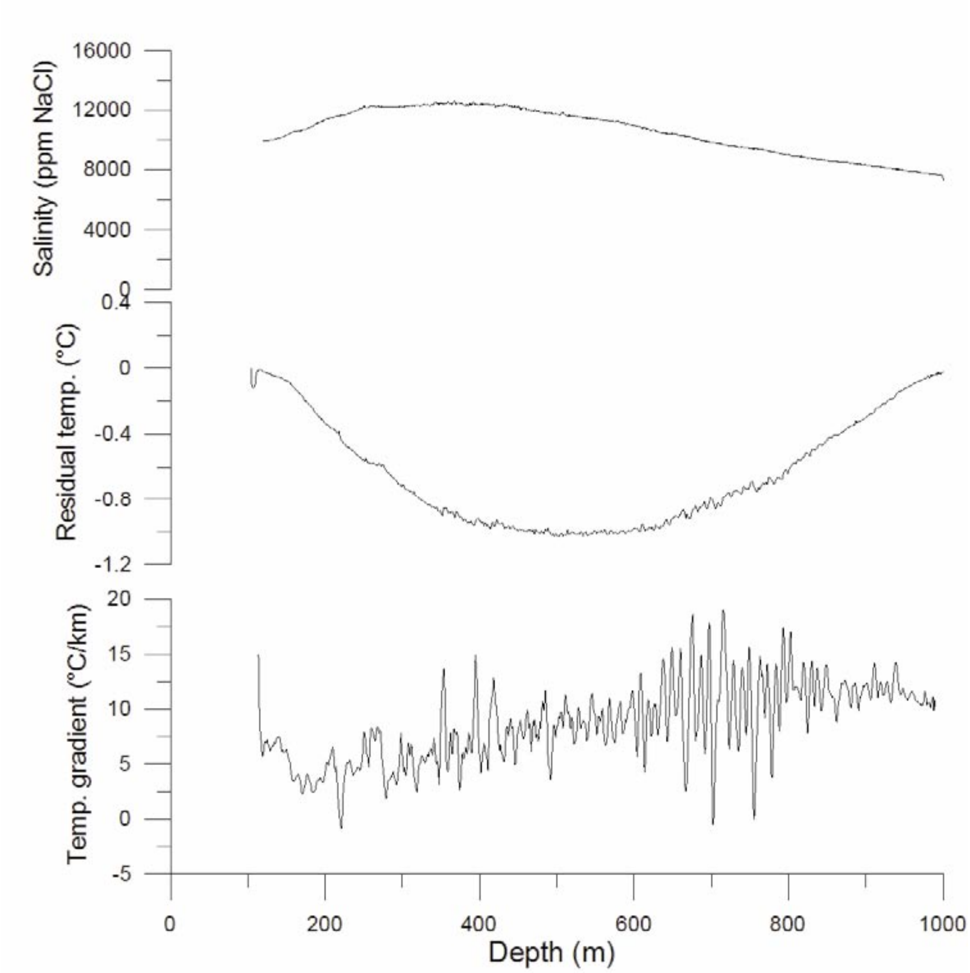



***Figure 4-1.*** *Estimated salinity (top), fluid temperature minus median gradient (centre) and vertical temperature gradient (bottom) for KFM05A.*

### *Interpretation of lithology and fractures*

The results of the generalized data and fracture estimations for the borehole KFM05A are presented in Figure 4-2 (coarse scale) and Appendix 1 (fine scale).

A majority of the rocks along the borehole have silicate densities indicating a mineral composition that corresponds to granite. 77% of the borehole length is classified as "granite" and 14.4% of the length is classified as "granodiorite". Only 5.5% of the borehole length is classified as "diorite" or "gabbro". Apart from a section between 350 and 360 m depth, the high density rocks occur along short sections, most commonly between 430 and 710 m.

The natural gamma radiation generally varies between 20 and 25 μR/h. The data have been classified into "low", "medium", "high" and "very high" radiation by setting threshold values at 20.5, 36.3 and 52.8 μR/h respectively. 70.4% of the borehole length is classified as "medium" radiation. Low radiation generally coincides with high density rocks. High and very high radiation (4.0% of the borehole length) occur as short sections probably corresponding to pegmatite veins at irregular intervals along the hole.

The magnetic susceptibility log has been classified into decades with threshold values of 0.001, 0.01 and 0.1 SI. The susceptibility falls in the class 0.001–0.01 for most of the borehole length down to 345 m. Low magnetic rocks occur more frequently between 345 and 900 m, which might be due to alteration of the rock. The high density rocks also have low susceptibility.

The geophysical logs indicate that the fracture frequency along KFM05A is generally quite low (Figure 4-2). An exception is found between 110 and 180 m. Narrow sections with increased fracturing are also inferred at 260, 425, 610, 715 and 975 m depth. The deeper part of the borehole can be subdivided into parts with virtually no significant fracture related geophysical anomalies (450–590 and 800–890 m) and parts with some inferred fracturing (590– 800 and 890–1,000 m depth). The borders between these long sections are fairly sharp. There is no clear relation between fracturing and low magnetic susceptibility. A fairly large number of "inferred fractures" indicated by one logging method only can be seen in Figure 4-2. These are to be regarded as quite uncertain.

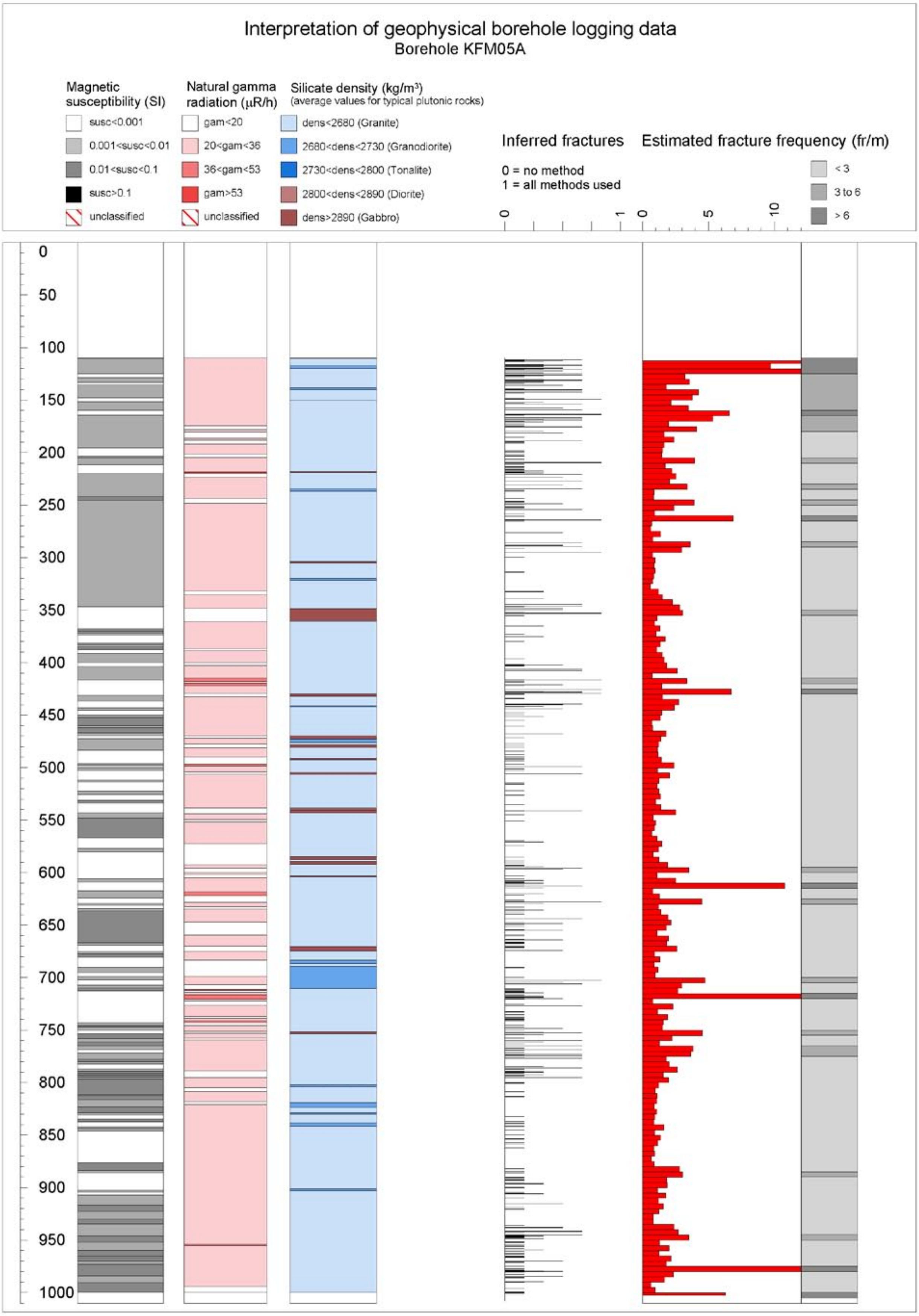



***Figure 4-2.*** *Generalized geophysical logs for KFM05A. The same logs, in a less compressed scale, can be seen in Appendix 1.*

### 4.2.2 Interpretation of HFM14, HFM15 and HFM19

***Vertical temperature gradient and salinity***

The vertical temperature gradient and the estimated salinity for HFM14, HFM15 and HFM19 can be seen in Figures 4-3, 4-4 and 4-5. Temperature anomalies that indicate water bearing fractures can be seen at 21, 43, and 103 m in HFM14, at 18 m in HFM15 and at 102, 152, 165 and 170 m in HFM19. Breaks in the salinity curve indicating water flow can be seen at 103 m in HFM14, 23 and 88 m depth in HFM15 and 108, 154 and 167 m in HFM19. The estimated salinity for HFM14 is very high which might be a result of a calibration error.

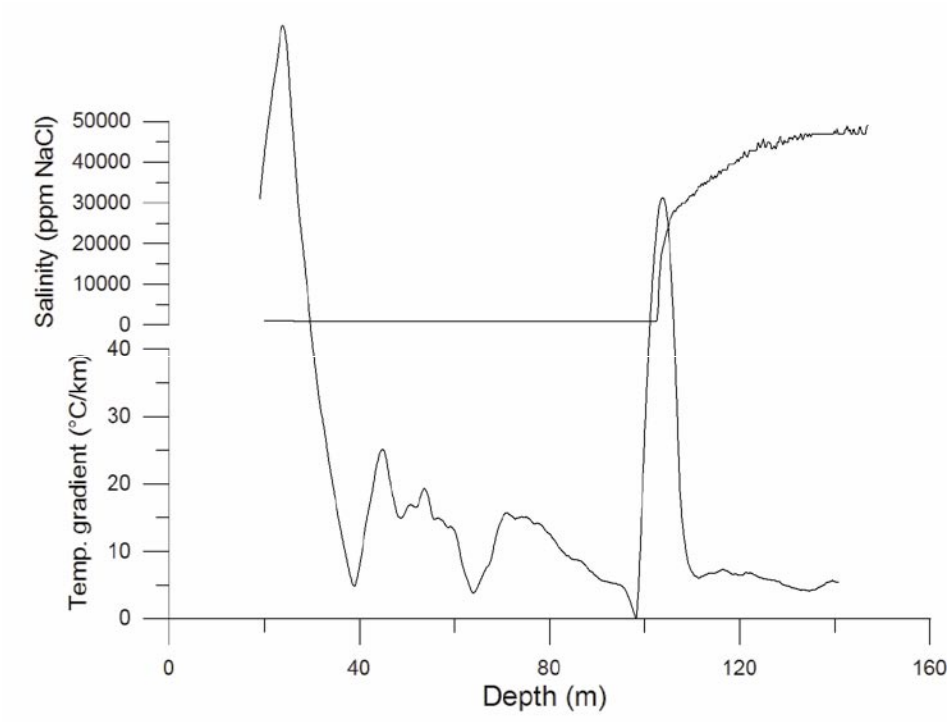



***Figure 4-3.*** *Estimated salinity (top) and vertical temperature gradient (bottom) for HFM14.*

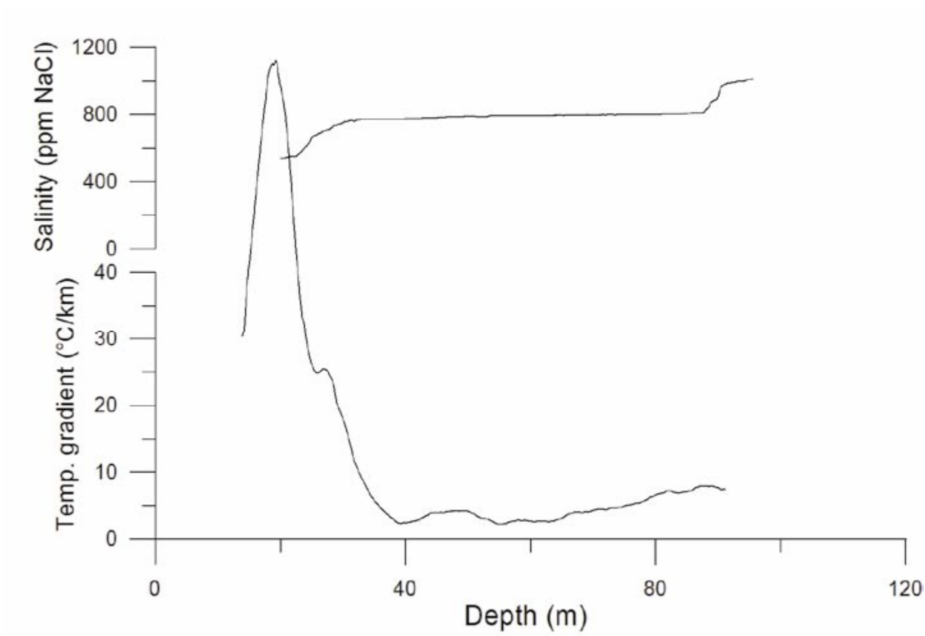



***Figure 4-4.*** *Estimated salinity (top) and vertical temperature gradient (bottom) for HFM15.*

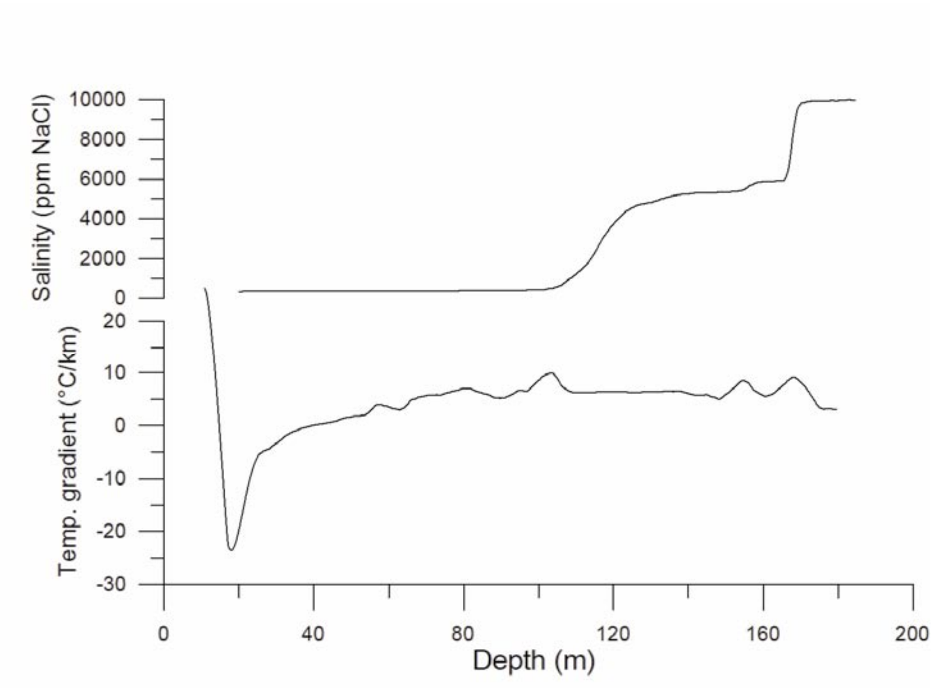



***Figure 4-5.*** *Estimated salinity (top) and vertical temperature gradient (bottom) for HFM19.*

### *Interpretation of rock types and fractures*

The results of the generalized data and fracture estimations for the boreholes HFM14, HFM15 and HFM19 are presented in Figure 4-6 to 4-8.

The rocks at these boreholes seem to have similar petrophysical properties as in the nearby cored borehole KFM05A. Rocks with a silicate density corresponding to a granite dominate completely, with only a few short sections of higher silicate density. The natural gamma radiation falls into the classes "low" and "medium" radiation for most of the borehole lengths. Low radiation occurs predominantly below 80 m in HFM14 and above 55 m in HFM15. The magnetic susceptibility most often falls within the class 0.001–0.01 SI. Low magnetic rocks occur between 50 and 105 m in HFM14, below 55 m in HFM15 and below 170 m in HFM19. No clear correlation between low magnetic susceptibility and fracturing can be seen.

The estimated fracture frequency is in general quite low in the three boreholes. Sections with increased fracture frequency can be seen in HFM14 (67–83 and 97–102 m) and in HFM15 (63–74 m). Distinct geophysical anomalies indicating narrow and possibly water bearing fracture zones occur e.g in HFM14 (at 21 m), in HFM15 (23, 26 and 87 m) and in HFM19 (20, 101, 122, 136 and 170 m).

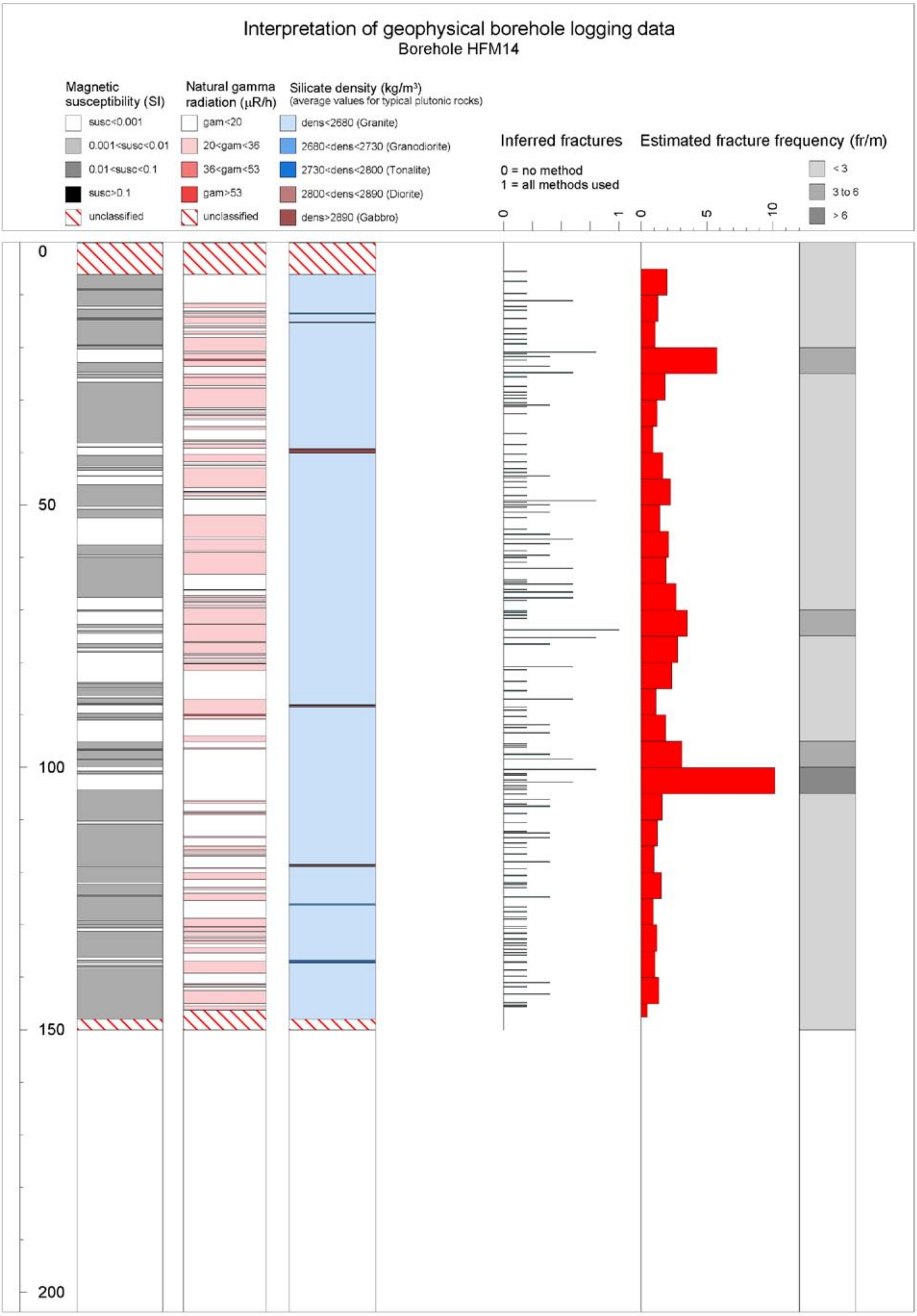



*Figure 4-6. Generalized geophysical logs for HFM14.*

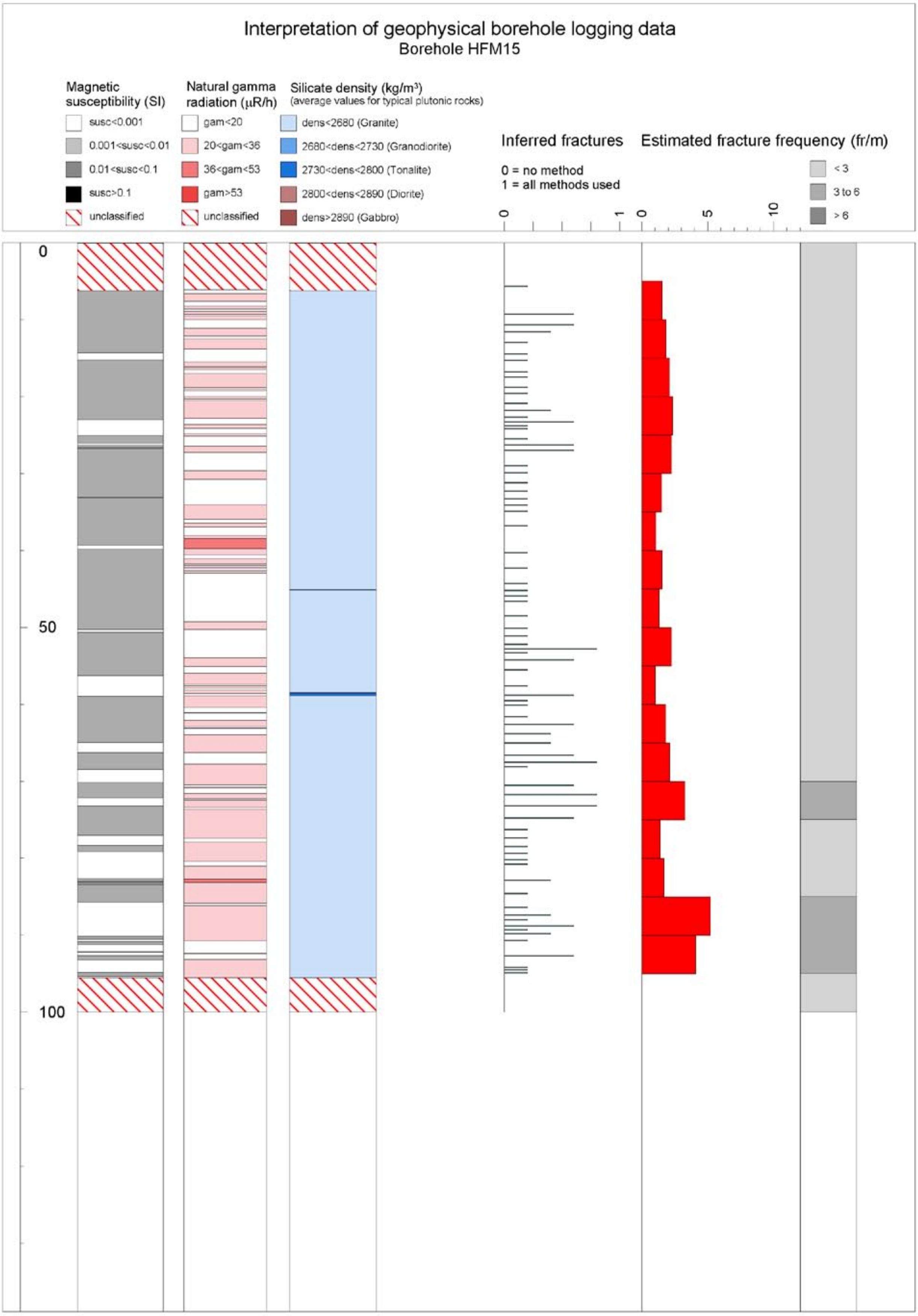



*Figure 4-7. Generalized geophysical logs for HFM15.*

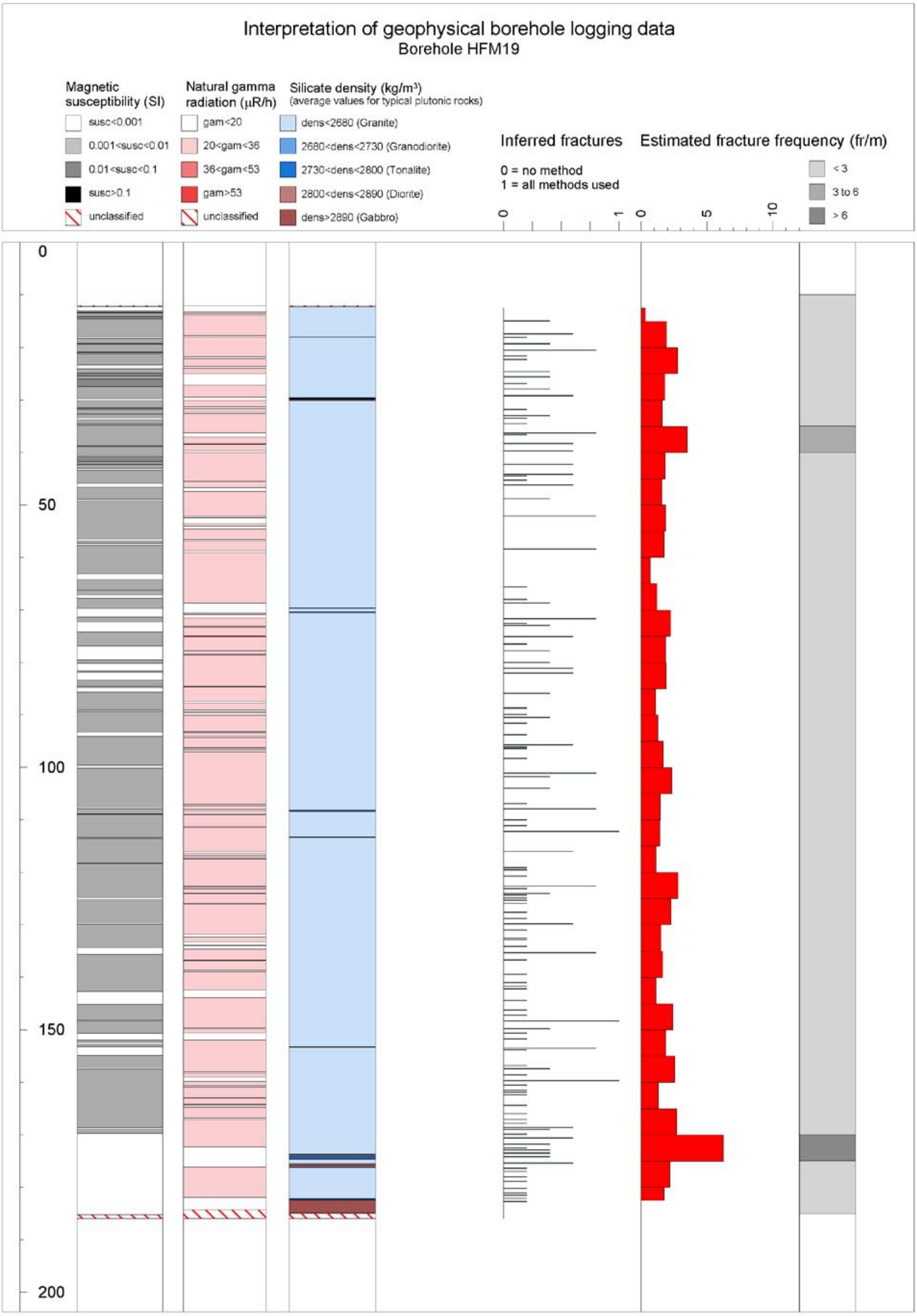



*Figure 4-8. Generalized geophysical logs for HFM19.*

# 5 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 density. The generalized logs have also been delivered as WellCAD-files.

The reference to SICADA is field note no 344 (HFM14, 15 19) and 395 (KFM05A).

# 6 References

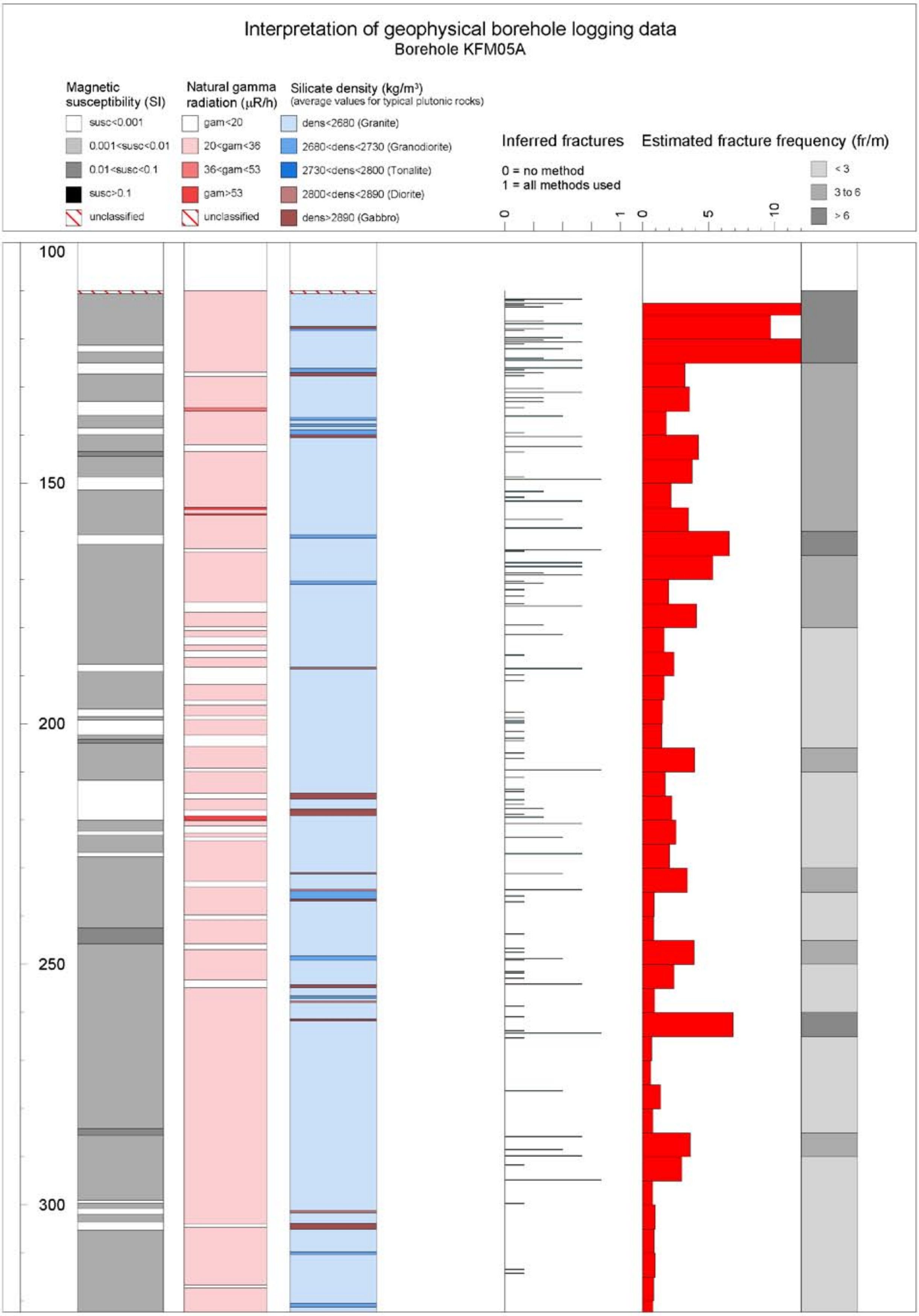

/1/ **Thunehed H, 2002.** Uppskattning av sprickfrekvens med hjälp av geofysisk borrhålsloggning. GeoVista AB, GVR02005.

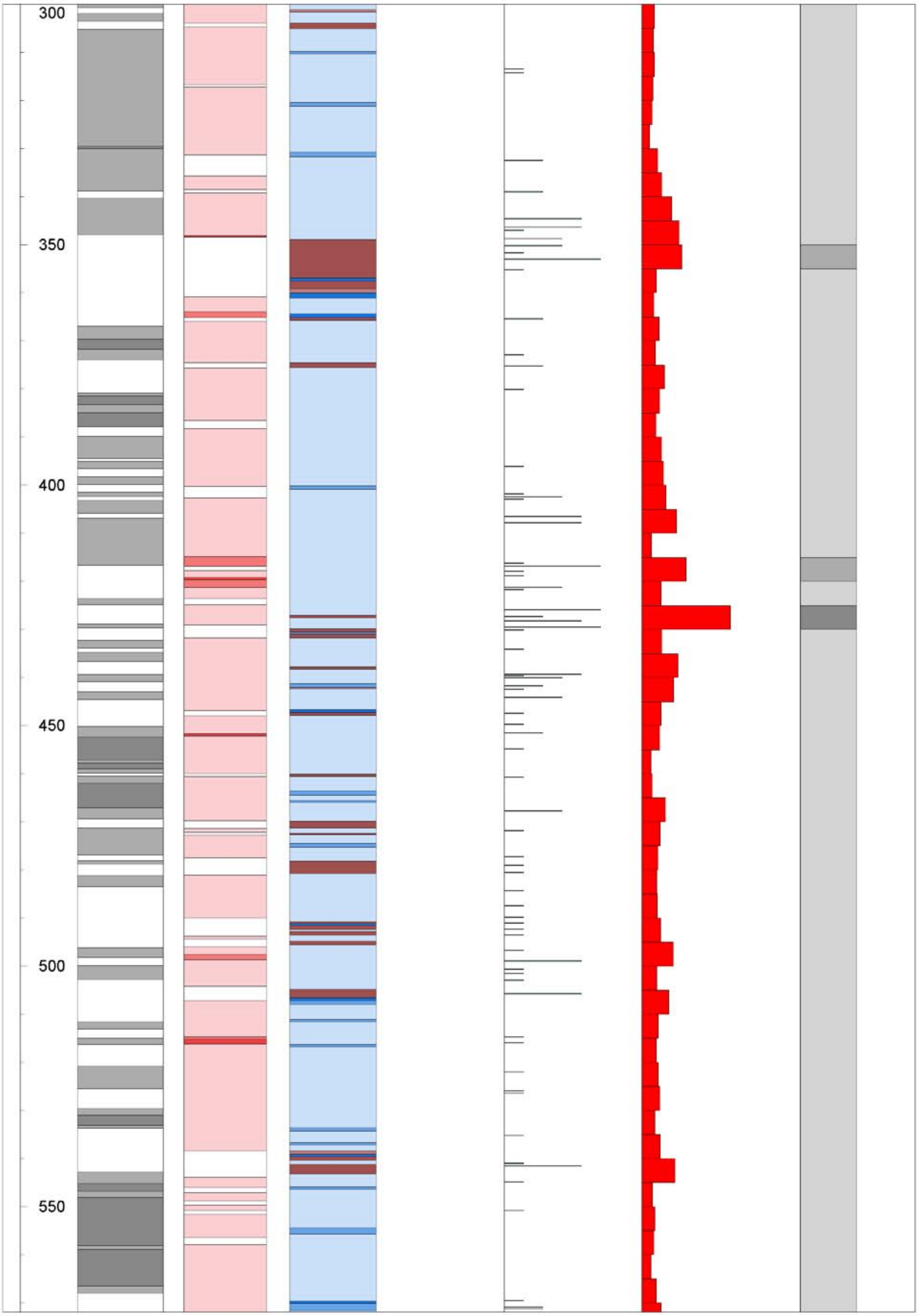
/2/ **Sehlstedt S, 1988.** Description of geophysical data on the SKB data base GEOTAB. SKB TR 88-05, Svensk Kärnbränslehantering AB.

/3/ **Henkel H, 1991.** Petrophysical properties (density and magnetization) of rock from the northern part of the Baltic Shield. Tectonophysics 192, 1–19.

/4/ **Puranen R, 1989.** Susceptibilities, iron and magnetite content of precambrian rocks in Finland. Geological survey of Finland, Report of investigations 90, 45 pp.

## Generalized geophysical logs for the borehole KFM05A

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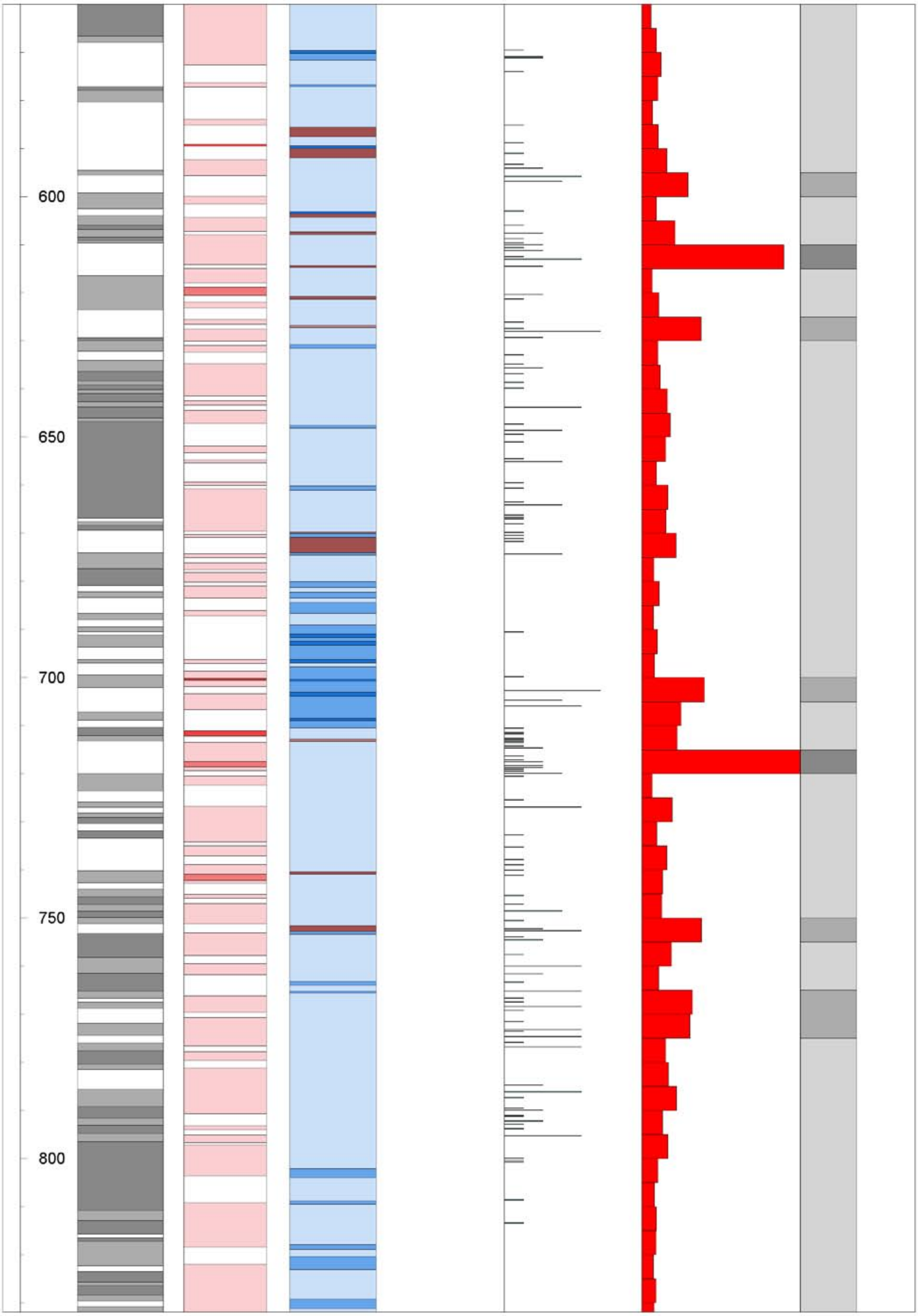

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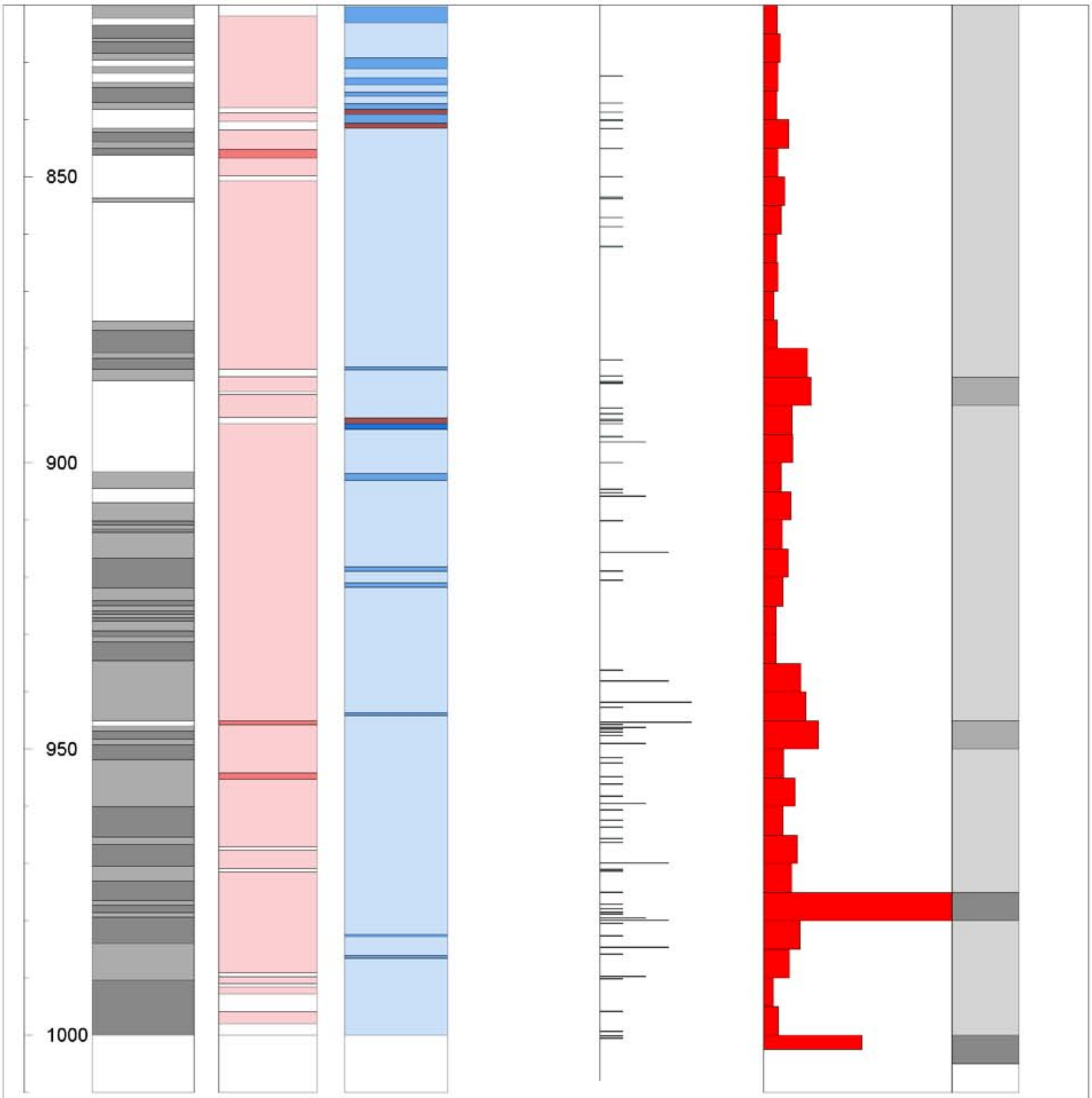
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