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Forsmark site investigation

Interpretation of geophysical borehole measurements from KFM07A

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March 2005

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Abstract

This report presents the compilation and interpretations of geophysical logging data from the cored borehole KFM07A.

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 vicinity of KFM07A 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 along the entire borehole length. These intervals 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 coincide with 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. In the lowermost c. 200 m of KFM07A (section 800–1,000 m) there is a larger occurrence of positive radiation anomalies compared to the rest of the borehole.

The magnetic susceptibility in KFM07A is mainly in the interval 0.001–0.01 SI. However, large occurrences of both high and low magnetic intervals show that the magnetite content in the rocks varies greatly.

Increased fracturing is mainly indicated in the sections c. 100–200 m and 800–1,000 m. Both sections are characterized by numerous low resistivity anomalies, intervals with low P-wave velocity and several caliper anomalies. The fluid temperature gradient log indicates that some fractures in these sections are water bearing. Along the section c. 200–800 m the estimated fracture frequency is generally low.

Sammanfattning

Föreliggande rapport presenterar en sammanställning och tolkning av geofysiska borrhålsmätningar från kärnborrhålet KFM07A.

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 KFM07A helt domineras av silikatdensitet som indikerar en mineralsammansättning motsvarande den för granit (< 2 680 kg/m^3). Korta sektioner med hög densitet förekommer längs hela borrhålet och de sammanfaller ofta med låg naturlig gammastrålning och låg magnetisk susceptibilitet. Denna kombination av egenskaper är typisk för amfibolit.

Den naturliga gammastrålningen ligger huvudsakligen i intervallet 20–36 μR/h. Korta sektioner med hög naturlig gammastrålning förekommer bitvis, och dessa anomalier indikerar troligen förekomst av pegmatitgångar och/eller gångar av finkornig granit. Flera indikerade pegmatit- eller granitgångar sammanfaller med indikerade amfibolitgångar vilket tyder på att förekomsten av sura och basiska gångar är rumsligt förknippad. En relativt högre förekomst av högstrålande bergarter finns längs borrhålets nedersta ca 200 m (sektionen 800–1 000 m).

Den magnetiska susceptibiliteten i KFM07A ligger generellt i intervallet 0,001–0,01 SI. Det finns dock ett stort antal låg- och högmagnetiska sektioner som visar att magnetithalten i bergrunden runt borrhålet varierar kraftigt.

Förhöjd sprickfrekvens indikeras längs sektionerna ca 100–200 m och 800–1 000 m. Båda sektionerna karakteriseras av flertalet lågresistiva anomalier, intervall med låg P-vågshastighet och caliperanomalier. Vätsketemperaturgradientloggen indikerar dessutom förekomst av flera vattenförande sprickor längs båda dessa sektioner. I övriga delar av borrhålet, sektionen 200–800 m, är den uppskattade sprickfrekvensen låg.

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 geophysical borehole logging data from the cored borehole KFM07A 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 KFM07A. 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 and method description MD 221.003, SKB internal controlling documents), 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)	AP PF 400-05-022	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för tolkning av geofysiska borrhålsdata	SKB MD 221.003	2.0

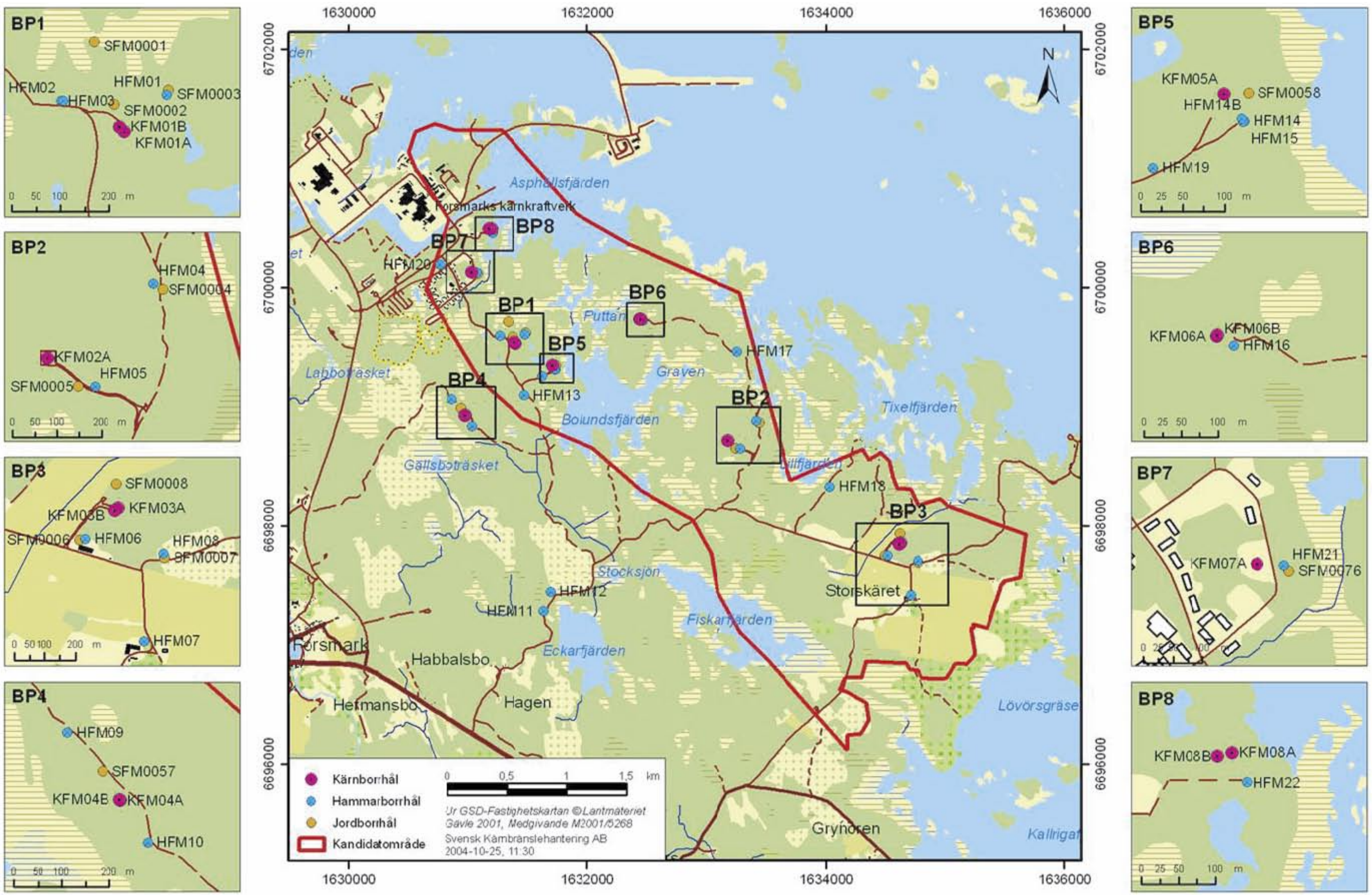

Figure 1-1. *Map showing the location of the investigated borehole KFM07A.*

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 of KFM07A were calibrated by use of a combination of petrophysical data from the boreholes KFM01A and KFM02A /1 and 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), σ_w = pore water conductivity (S/m), φ = volume fraction of pore space, σ_s = surface conductivity (S/m) and "a", "k" and "m" are constants. Since "a", "k" and "m" may vary with variations in the borehole fluid resistivity, estimations of the constants are performed with reference to the actual fluid resistivity in each borehole respectively. The constants used in this investigation are presented in Table 4-1.

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
KFM07A	0.50	10	0.37	1.7

The vertical temperature gradient (°C /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 φ = borehole inclination. The estimated water salinity is calculated as ppm NaCl in water following the simple relation from Crain's Petrophysical Handbook where:

$$WS = \frac{400000}{(1.8t + 32)\cdot \rho^{\frac{1}{0.88}}}$$

WS = Water salinity (ppm NaCl), t = temperature (°C) and ρ = 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 /1/. The linear coefficients (weights) used are presented in Table 4-2.

5. Report evaluating the results.

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	KFM07A	2.0	3.0	2.0	1.2	1.5	1.5	5.0	–
Weight	KFM07A	4.0	2.56	8.0	4.0	1.28	0.24	1.75	–

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	KFM07A	Recommended max noise level
Density (kg/m^3)	12	3–5
Magnetic susceptibility (SI)	1.6×10^{-4}	1×10^{-4}
Natural gamma radiation (μR/h)	0.5	0.3
Long normal resistivity (%)	0.1	2.0
Short normal resistivity (%)	0.02	2.0
Fluid resistivity (%)	0.3	2
Fluid temperature (°C)	0.002	0.01
Lateral resistivity (%)	Not used	2
Single point resistance (%)	0.1	No data
Caliper (metre)	0.6×10^{-5}	0.0005
Focused resistivity 300 (%)	2.4	No data
Focused resistivity 140 (%)	0.5	No data
Sonic (m/s)	17	20

5.2 Interpretation of the logging data

The presentation of interpretation products presented below, in the chapter 5.2.1 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 KFM07A

The results of the generalized logging data and fracture estimations of KFM07A are presented in Figure 5-1 below, and in a more detailed scale in Appendix 1.

The rocks in the vicinity of KFM07A 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. In the lowermost c. 200 m of KFM07A (section 800–1,000 m) there is a larger occurrence of positive radiation anomalies compared to the rest of the borehole. Several sections with low natural gamma radiation, without the “normal” increase in density related to amphibolites, are identified mainly in the lower half of the borehole, especially in the interval c. 800–930 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 KFM07A is mainly in the interval 0.001–0.01 SI. However, along the section c. 470–950 m there is a large number of short intervals with higher susceptibility (> 0.01 SI) as well as lower susceptibility (< 0.001 SI), which shows that the magnetite content in the rocks varies greatly along this section of the borehole.

Large variations in the natural gamma radiation and the magnetic susceptibility clearly coincide along the lower half of KFM07A.

Table 5-2. Distribution of silicate density classes with borehole length of KFM07A.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	819	92
2,680 < dens < 2,730 (granodiorite)	23	3
2,730 < dens < 2,800 (tonalite)	14	1
2,800 < dens < 2,890 (diorite)	16	1
dens > 2,890 (gabbro)	21	2

Increased fracturing is mainly indicated in the sections c. 100–200 m and 800–1,000 m. Both sections are characterized by numerous low resistivity anomalies, intervals with low P-wave velocity and several caliper anomalies. The low resistivity anomalies generally coincide with a decrease in the magnetic susceptibility.

In the section c. 200–800 m there are only few indications of increased fracturing.

The estimated apparent porosity shown in Figure 5-2 (black line) is mainly in the interval 0.5–0.8%, which is reasonable in comparison to the petrophysical data from this area. Apparent porosity anomalies are low in amplitude and occur mainly in the sections c. 100–200 m and 800–1,000 m. The linear trend (increase) in the apparent porosity log in the interval c. 600–1,000 m, which is anti-correlated to the salinity log (the green line in Figure 5-2) is an effect of the extremely low fluid resistivity (high salinity), and this is most likely an artifact not related to true variations in the rock porosity. It is an indication that the borehole fluid is not in chemical equilibrium with the pore fluid of the rocks in the vicinity of the borehole, otherwise this trend should have been removed in the calculation of the apparent porosity.

The fluid temperature gradient log shows a couple of very distinct anomalies in the section 100–200 m and also several anomalies in the section 800–1,000 m, which indicates that the increased fracturing along these two sections coincides with water bearing fractures. Also at the section co-ordinates c. 487 m and 687 m there are two rather distinct temperature gradient anomalies that indicate water bearing fractures.

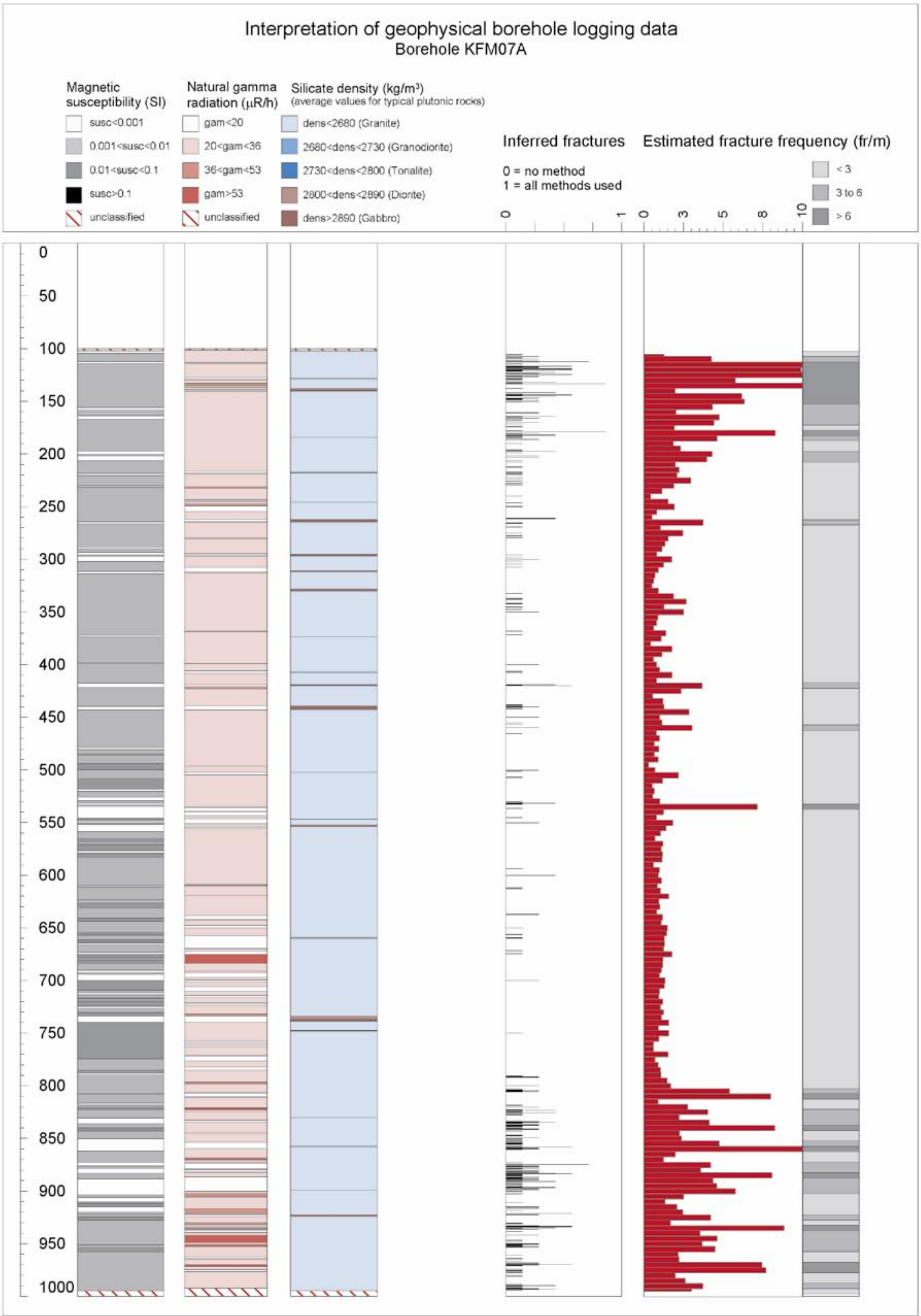

Figure 5-1. *Generalized geophysical logs of KFM07A.*

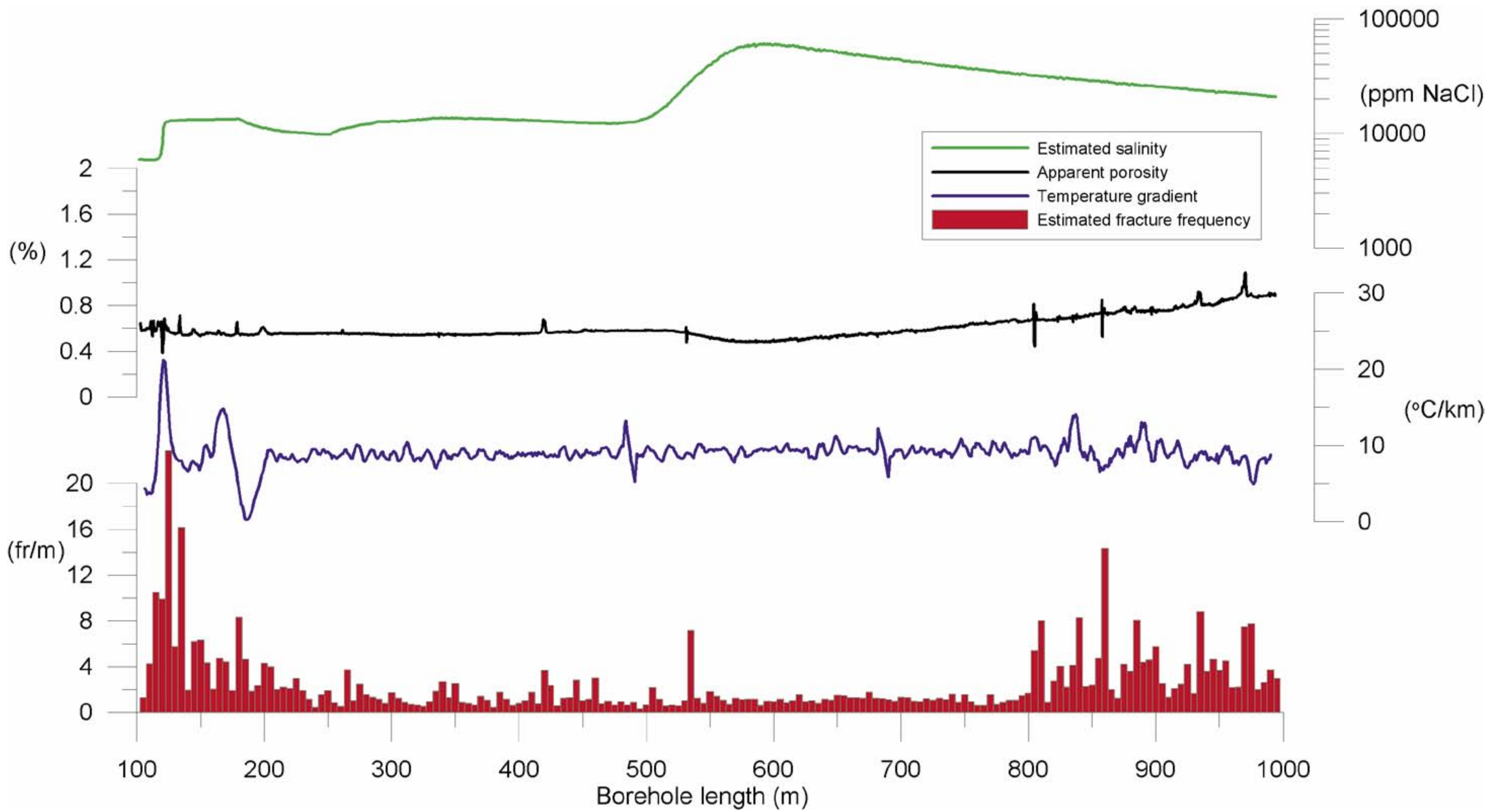

Figure 5-2. *Estimated salinity, apparent porosity, vertical temperature gradient and estimated fracture frequency of KFM07A.*

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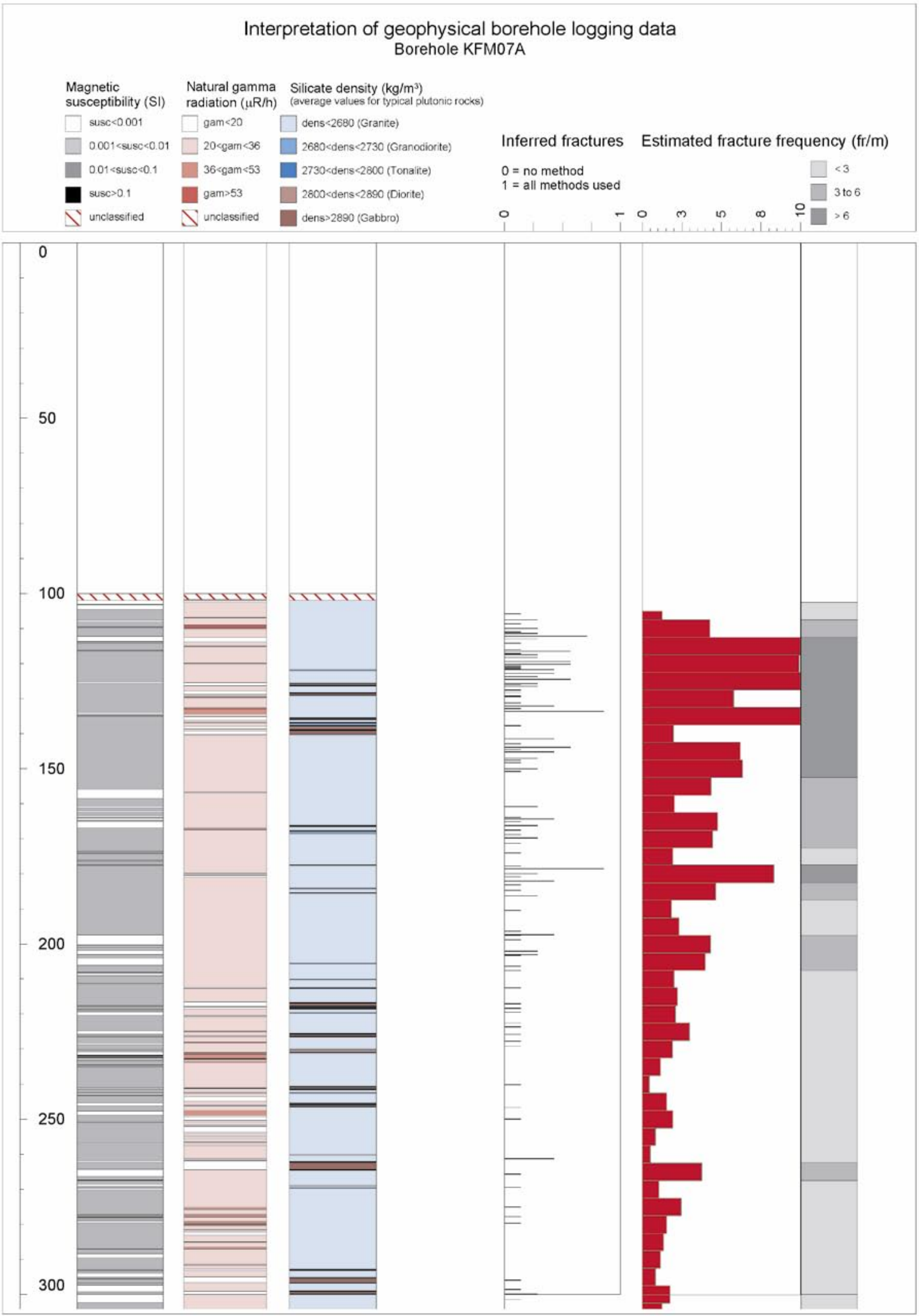
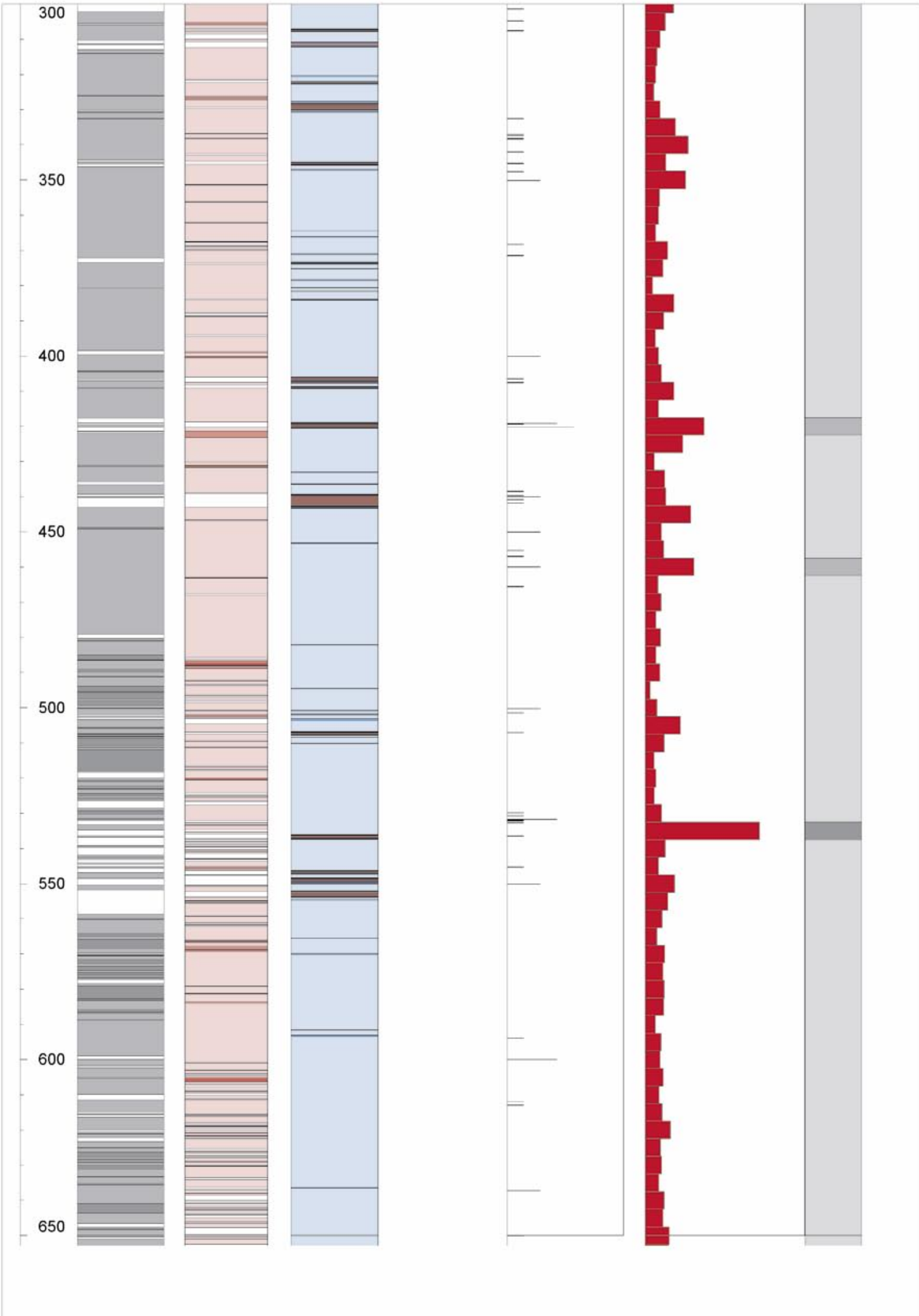
Appendix 1

Generalized geophysical loggings of KFM07A

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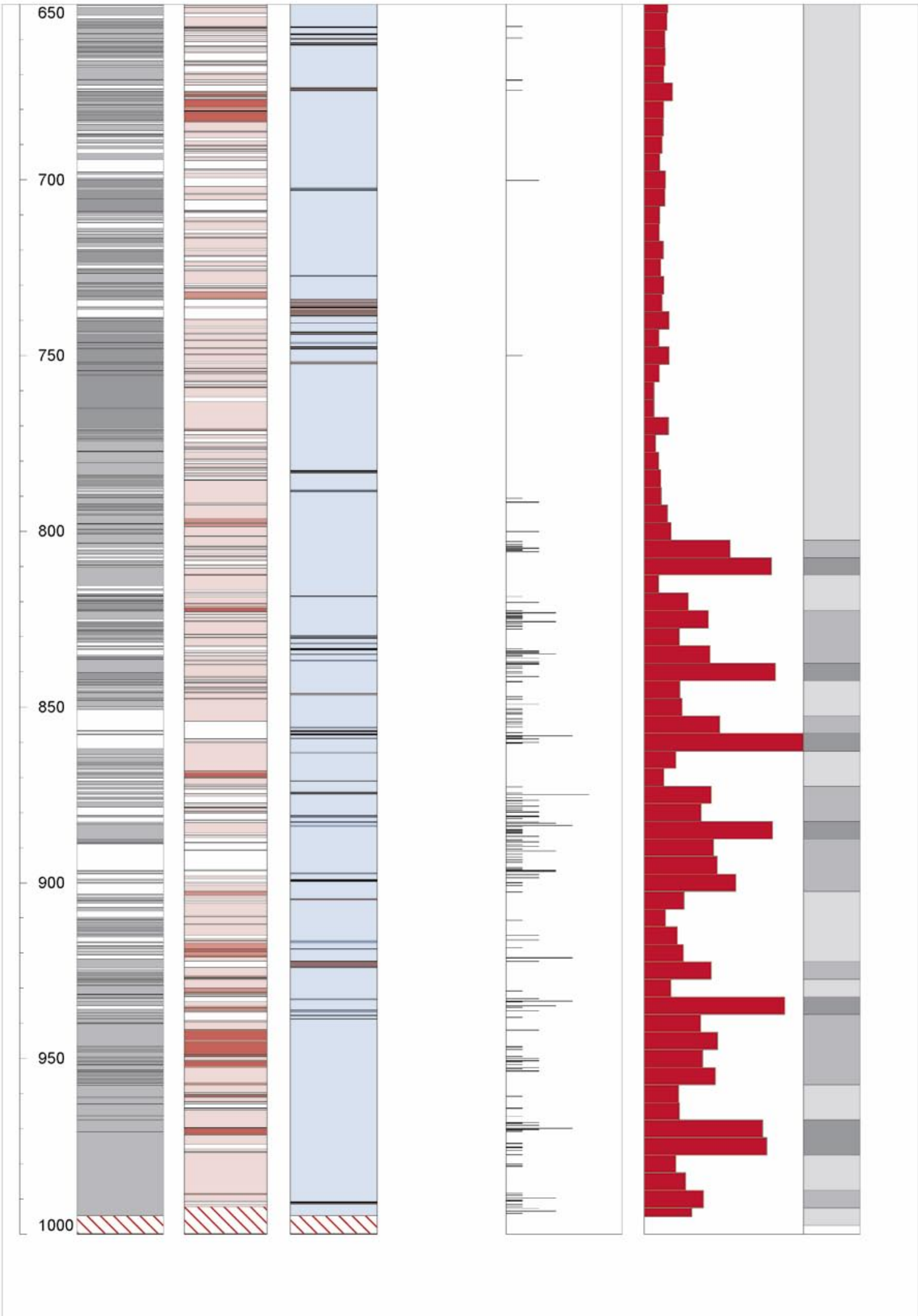
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