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Forsmark site investigation

Interpretation of geophysical borehole measurements from KFM06C

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April 2006

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Abstract

This report presents the compilation and interpretations of geophysical logging data from the cored borehole KFM06C.

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 three loggings density, magnetic susceptibility and natural gamma radiation all show anomalously high noise levels.

The rocks in the vicinity of KFM06C are completely dominated by silicate density indicating a mineral composition that corresponds to granite rock (< 2,680 kg/m^3). A significant section with high density (3,000–3,150 kg/m^3), low magnetic susceptibility (< 0.001 SI) and low natural gamma radiation (< 5 μR/h) is identified at c 744–787 m. This combination of physical properties may indicate the occurrence of a major amphibolite dyke, though there is also a possibility that the borehole is subparallel with a dyke of smaller width. Rocks with silicate density in the interval 2,680–2,730 kg/m^3, which indicate a composition that corresponds to granodiorite, occur in 1–10 m long sections mainly in the intervals c 480–600 m and c 800–900 m.

The natural gamma radiation is mostly in the interval 20–36 μR/h. Sections with lower natural gamma radiation (< 20 μR/h) are fairly common, and generally coincide with increased density. Three significant sections with low natural gamma radiation < 20 μR/h, without the "normal" increase in density related to mafic rocks, are identified at c 430–440 m, 570–610 m and 800–815 m. This could be an indication of alteration of the rocks along these sections. The magnetic susceptibility is mainly in the interval 0.007–0.02 SI. Two fairly long sections with significantly decreased magnetic susceptibility (partly less than 0.001 SI) are identified at c 195–270 m and 745–797 m. The low magnetic susceptibility in these sections may indicate alteration and/or increased fracturing.

The estimated fracture frequency in KFM06C is mainly low and the estimated apparent porosity is in the interval 0.5–0.6%, which is normal for the rocks in this area. Five sections of length 5–15 m with increased fracturing are indicated in the interval 100–250 m. Increased fracture frequency is also indicated in the sections 380–390 m and 530–540 m.

The sections with indicated high fracture frequency are generally characterized by an increased occurrence of low resistivity anomalies, positive apparent porosity anomalies, decreased P-wave velocity and caliper anomalies.

Sammanfattning

Föreliggande rapport presenterar en sammanställning och tolkning av geofysiska borrhålsmätningar från kärnborrhålet KFM06C.

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.

De geofysiska loggarna densitet, magnetisk susceptibilitet och naturlig gammastrålning är alla tre behäftade med anomalt höga brusnivåer.

Resultaten av undersökningarna visar att bergrunden i närheten av KFM06C domineras av en silikatdensitet som indikerar en mineralsammansättning motsvarande den för granit (< 2 680 kg/m^3). Kraftigt förhöjd densitet (3 000–3 150 kg/m^3), låg magnetisk susceptibilitet (< 0,001 SI) och låg naturlig gammastrålning (< 5 μR/h) kan identifieras längs sektionen ca 744–787 m. Denna kombination av fysikaliska egenskaper indikerar förekomst av en mäktig amfibolitgång. Silikatdensitet i intervallet 2 680–2 730 kg/m^3, vilket indikerar en mineralsammansättning motsvarande den för granodiorit, förekommer i 1–10 m långs sektioner, främst i längdintervallen ca 480–600 m och ca 800–900 m.

Den naturliga gammastrålningen ligger generellt i intervallet 20–36 μR/h. Korta sektioner med låg naturlig gammastrålning (< 20 μR/h) i kombination med förhöjd densitet, kopplad till mafiska bergarter, är relativt vanligt förekommande. Tre sektioner med låg naturlig gammastrålning utan den ”normala” förhöjningen i densitet kan identifieras vid ca 430–440 m, 570–610 m och 800–815 m. Detta kan indikera omvandling av berget längs dessa sektioner. Den magnetiska susceptibiliteten ligger generellt i intervallet 0,007–0,02 SI. Kraftigt sänkt magnetisk susceptibilitet, bitvis < 0,001 SI, förekommer längs sektionerna ca 195–270 m och 745–797 m. Den låga susceptibiliteten kan indikera förhöjd sprickfrekvens och/eller omvandling.

Den sprickfrekvens som beräknas utifrån de geofysiska loggarna är generellt låg. Den skenbara porositeten ligger för en stor del av borrhålet i intervallet 0,5–0,6 %, vilket är normalt för bergarterna i undersökningsområdet. Fem stycken 5–15 m långa sektioner med förhöjd sprickfrekvens kan identifieras längs intervallet 100–250 m. Förhöjd sprickfrekvens indikeras även förekomma längs sektionerna 380–390 m och 530–540 m.

De sektioner som indikeras ha förhöjd sprickfrekvens karaktäriseras generellt av hög frekvens av lågresistiva anomalier, förhöjd skenbar porositet, sänkt P-vågshastighet samt större borrhålsdiameter.

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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/Laxemar. This document reports the results gained from the interpretation of geophysical borehole logging data from the cored borehole KFM06C (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 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 400-05-096 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 KFM06C (100–1 000 m).	AP PF 400-05-096	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för tolkning av geofysiska borrhålsdata.	SKB MD 221.003	2.0

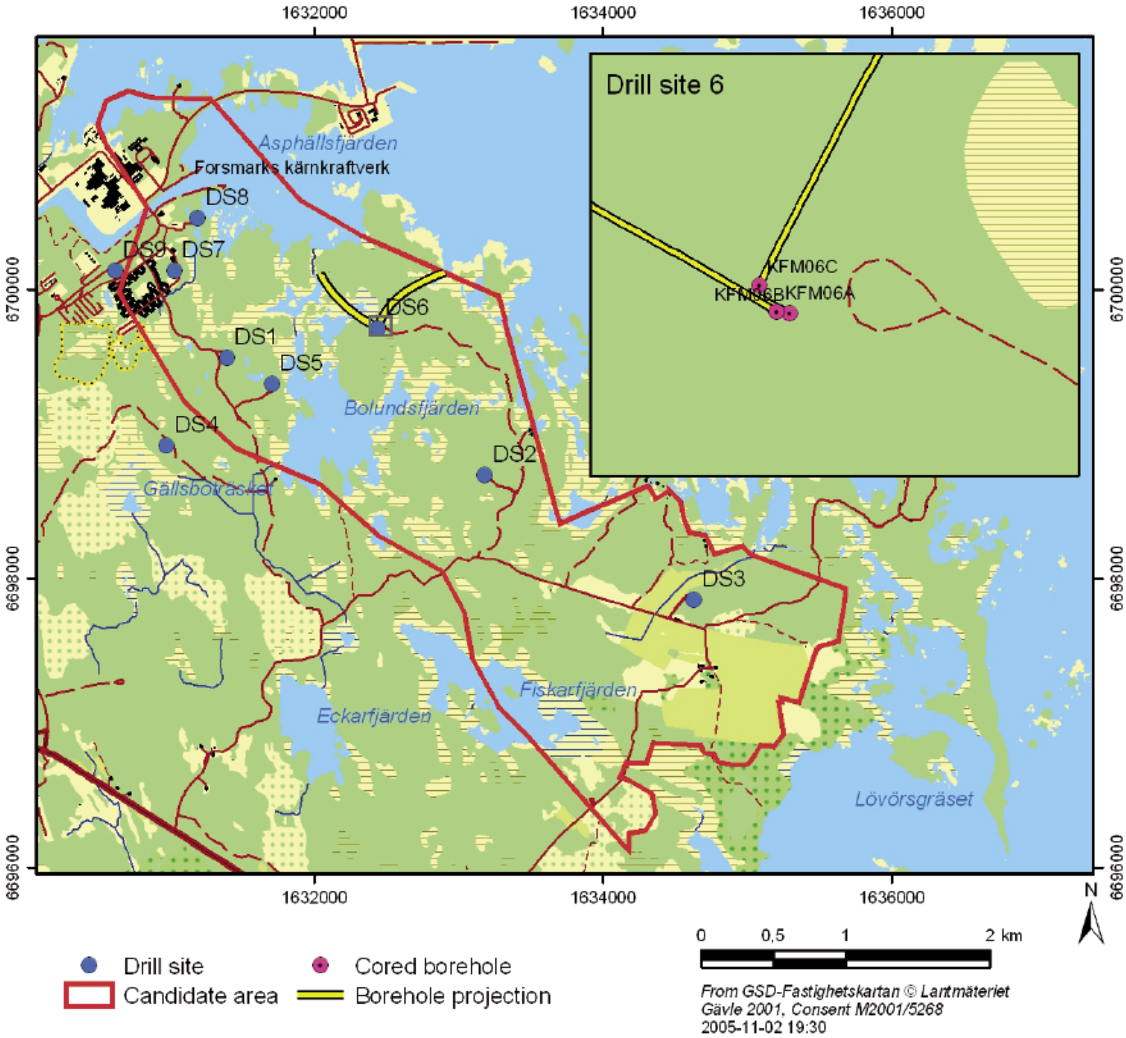

Figure 1-1. *Map showing the location of the investigated borehole KFM06C.*

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 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” (< 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 /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.

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

   $$WS = \frac{400{,}000}{(1.8t + 32)^{0.88}\sqrt{\rho}}$$

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

   The salinity is only calculated for cored boreholes.

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
KFM06C	1.1	10	0.37	1.7

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.
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	KFM06C	2.0	2.0	2.0	0.4	1.5	5.0	5.0	–
Weight	KFM06C	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 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

There is an unusually large number of missing data points (null values) in the magnetic susceptibility logging data. The total borehole length with missing data is c 117 m (c 13% of the total measured borehole length), which corresponds to about 1,170 missing data points.

5.1.1 Noise levels

Noise levels of the raw data for each logging method are presented in Table 5-1. Noise levels are unusually high for the logging methods density, natural gamma radiation and magnetic susceptibility. All these three logs were filtered with 5p average filters to reduce the effect of the noise, but there is still a risk that the high noise levels may have reduced the reliability of the interpretation presented in this report. Average filtering also reduces the possibility of resolving thin anomalies in the logging data.

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	KFM06C	Recommended max noise level
Density (kg/m^3)	47	3–5
Magnetic susceptibility (SI)	9×10^{-4}	1×10^{-4}
Natural gamma radiation (μR/h)	1.9	0.3
Long normal resistivity (%)	0.7	2.0
Short normal resistivity (%)	0.2	2.0
Fluid resistivity (%)	0.03	2
Fluid temperature (°C)	3×10^{-4}	0.01
Lateral resistivity (%)	Not used	2
Single point resistance (%)	0.9	No data
Caliper (m)	0.5×10^{-4}	0.0005
Focused resistivity 300 (%)	15.5	No data
Focused resistivity 140 (%)	5.2	No data
Sonic (m/s)	20	20

5.2 Interpretation of the logging data

The presentation of interpretation products presented below, in the Section 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 KFM06C

The results of the generalized logging data and fracture estimations of KFM06C are presented in Figure 5-1 below, and in a more detailed scale in Appendix 1.

The rocks in the vicinity of KFM06C 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. A significant section with high density (3,000–3,150 kg/m^3), low magnetic susceptibility (< 0.001 SI) and low natural gamma radiation (< 5 µR/h) is identified at c 744–787 m. This combination of physical properties is typical for amphibolites, and the data may indicate the occurrence of a major amphibolite dyke, though there is also a possibility that the borehole is subparallel with a dyke of smaller width. Narrow sections of increased density generally coincide with low susceptibility and low natural gamma radiation and they most likely indicate the occurrences of minor 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. Rocks with silicate density in the interval 2,680–2,730 kg/m^3, which indicate a composition that corresponds to granodiorite, occur in 1–10 m long sections mainly in the intervals c 480–600 m and c 800–900 m.

The natural gamma radiation is mainly in the interval 20–36 µR/h. Sections with lower natural gamma radiation (< 20 µR/h) are fairly common, and generally coincide with increased density as noted in the former paragraph. Three significant sections with low natural gamma radiation < 20 µR/h, without the "normal" increase in density related to mafic rocks, are identified at c 430–440 m, 570–610 m and 800–815 m. This could be an indication of alteration of the rocks along these sections. The magnetic susceptibility is mainly in the interval 0.007–0.02 SI. Two fairly long sections with significantly decreased magnetic susceptibility (partly less than 0.001 SI) are identified at c 195–270 m and 745–797 m. The low magnetic susceptibility in these sections may indicate alteration and/or increased fracturing. Also along the sections c 105–130 m, 415–475 m, 515–550 m and 915–985 there is partly decreased magnetic susceptibility.

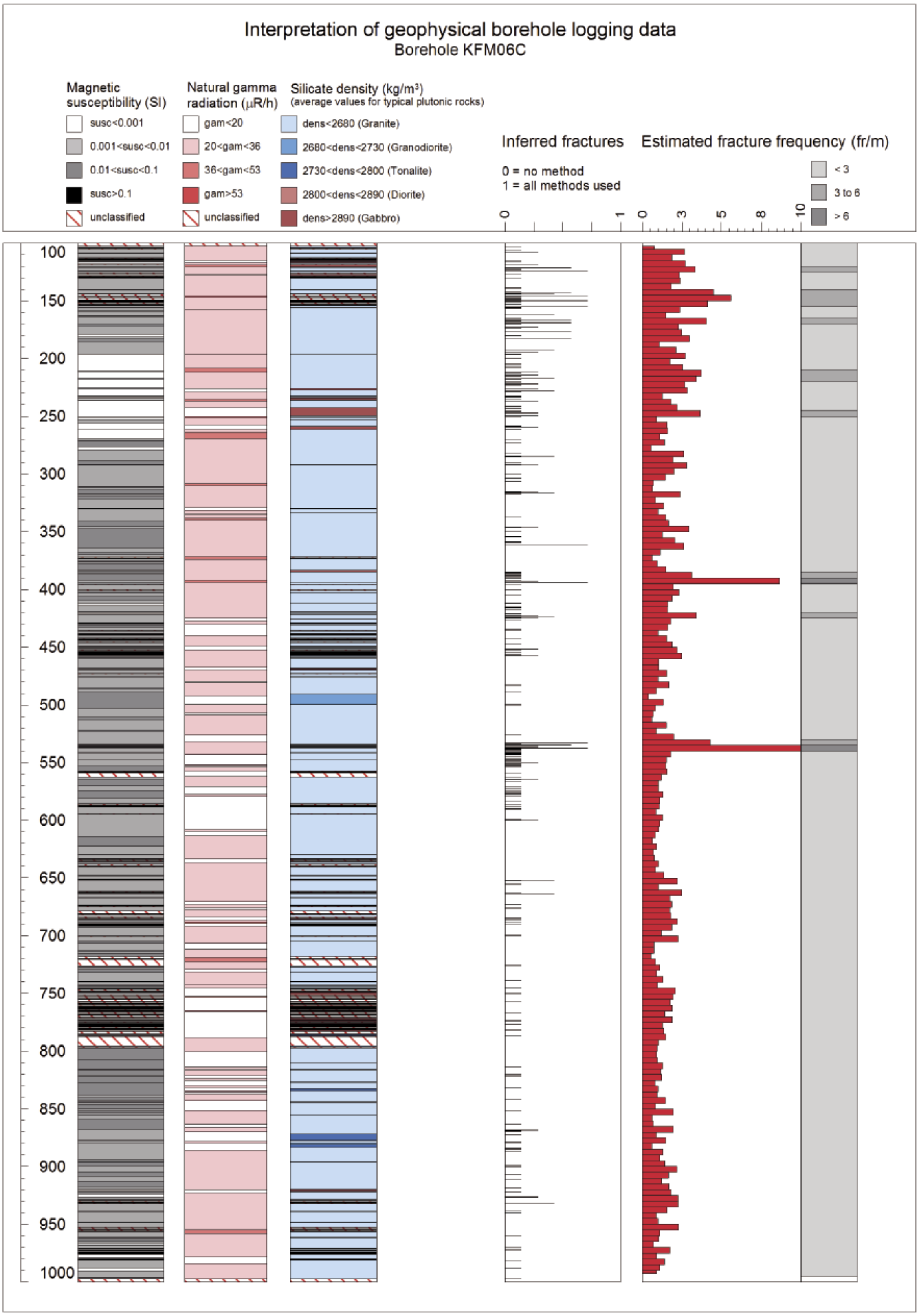

Figure 5-1. Generalized geophysical logs of KFM06C.

Table 5-2. Distribution of silicate density classes with borehole length of KFM06C.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	690	88
2,680 < dens < 2,730 (granodiorite)	34	4
2,730 < dens < 2,800 (tonalite)	19	3
2,800 < dens < 2,890 (diorite)	10	1
dens > 2,890 (gabbro)	29	4

The estimated fracture frequency in KFM06C is mainly low. The estimated apparent porosity shown in Figure 5-2 (black line) is mainly in the interval 0.5–0.6%, which is normal for the rocks in this area. Five 5–15 m long sections with increased fracturing are indicated in the interval 100–250 m. Increased fracture frequency is also indicated in the sections 380–390 m and 530–540 m.

In large parts of the section 100–250 m there is an increased occurrence of low resistivity anomalies. Several positive apparent porosity anomalies occur in the interval c 140–190 m and these coincide with decreased P-wave velocity in the section c 145–155 m.

The section 380–390 m is mainly characterized by low resistivity and caliper anomalies, but it also coincides with a sharp decrease in the estimated fluid water salinity and with indications of increased rock porosity (Figure 5-2).

Section 530–540 m is characterized by a major decrease in the electric resistivity and in the P-wave velocity; there are also caliper anomalies and decreased magnetic susceptibility.

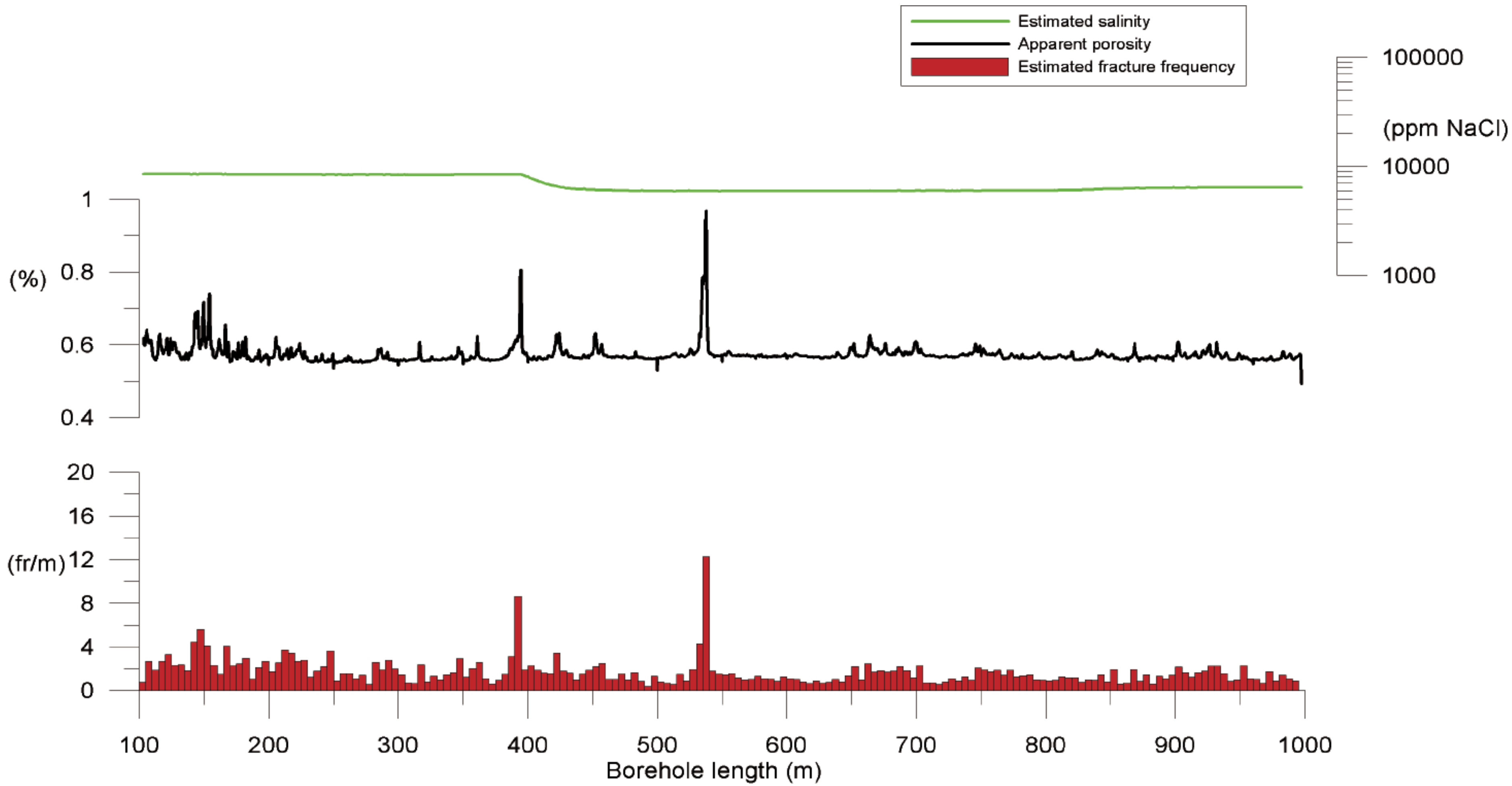

Figure 5-2. *Estimated salinity, apparent porosity and estimated fracture frequency of KFM06C.*

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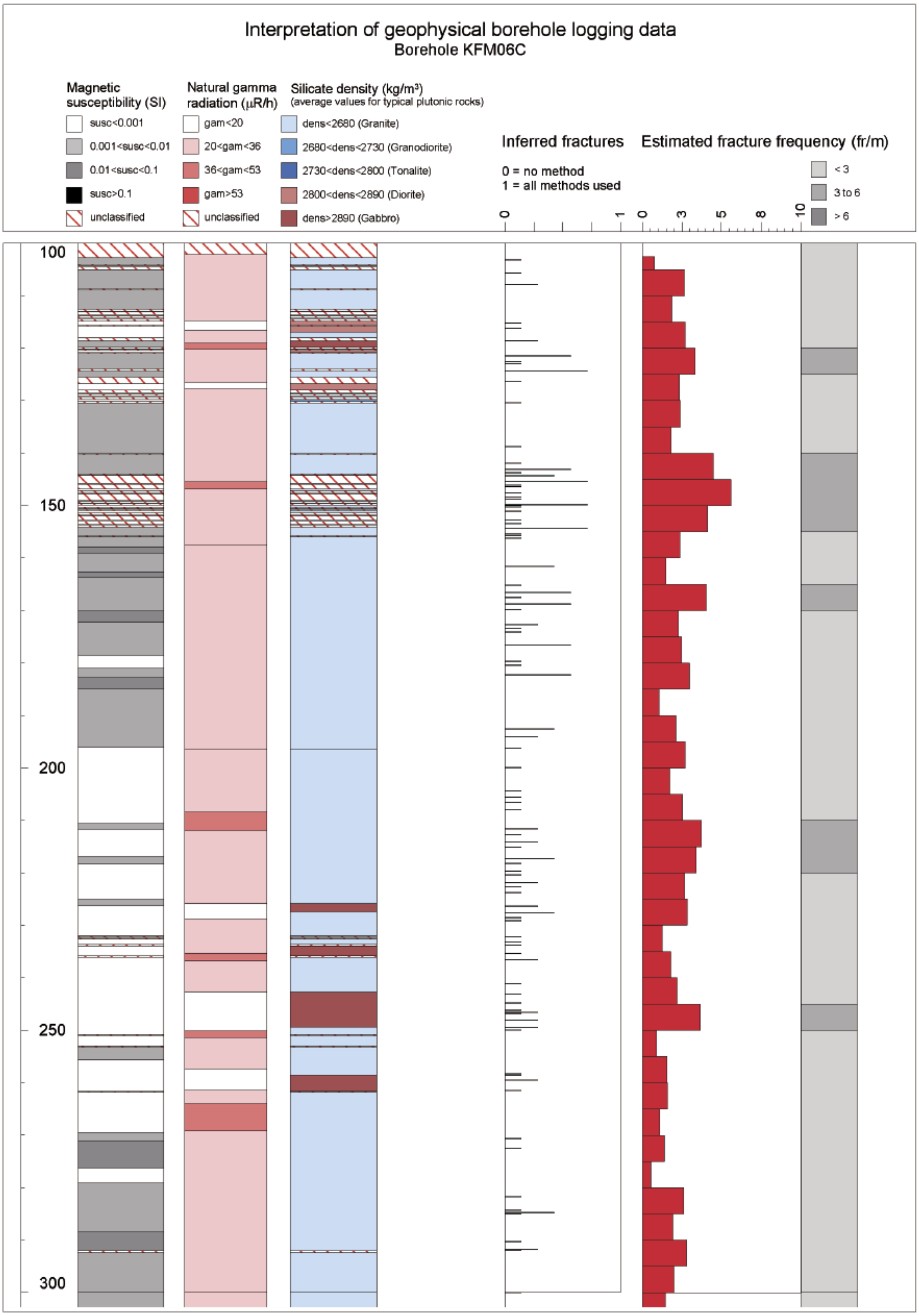
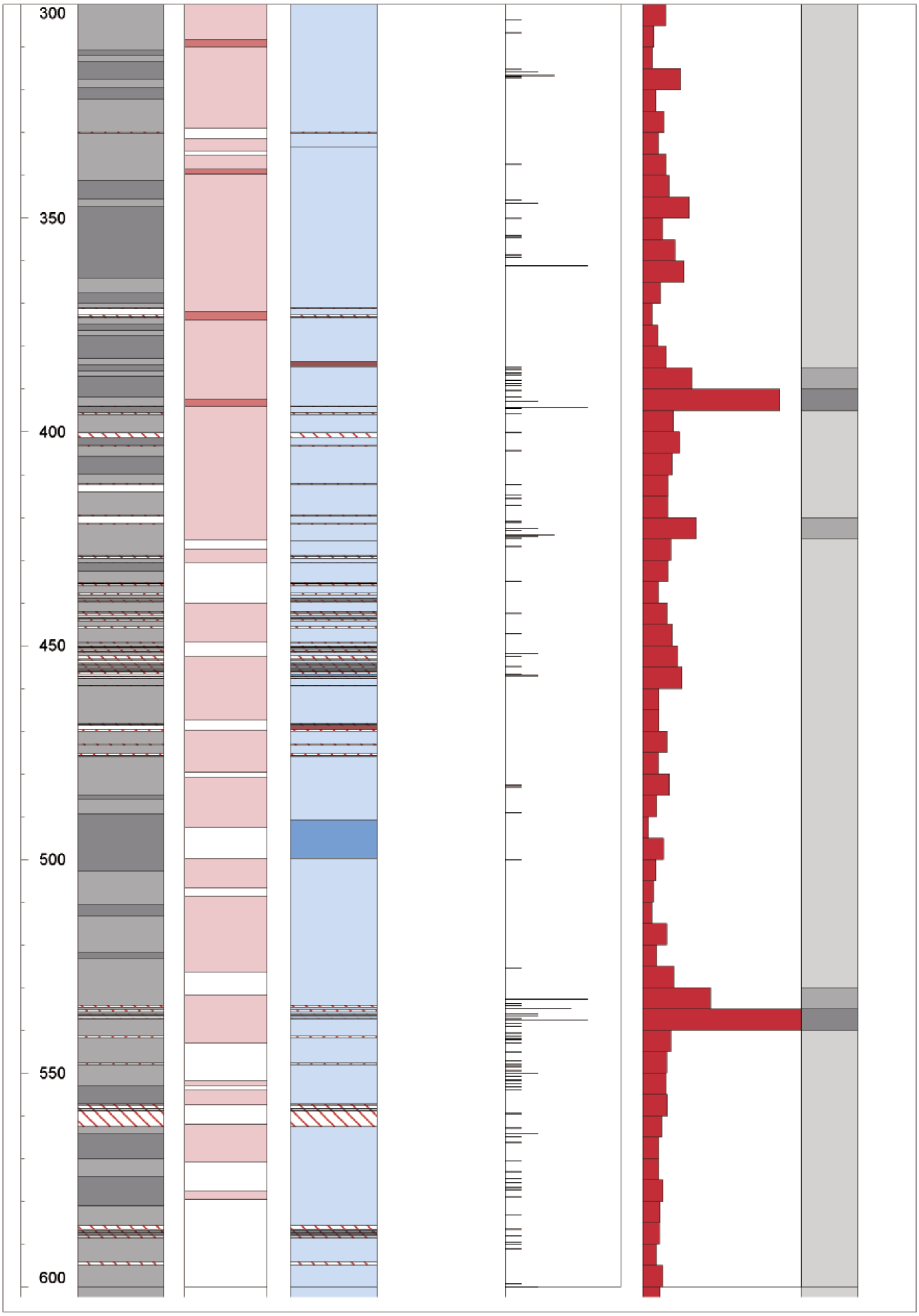
Generalized geophysical loggings of KFM06C

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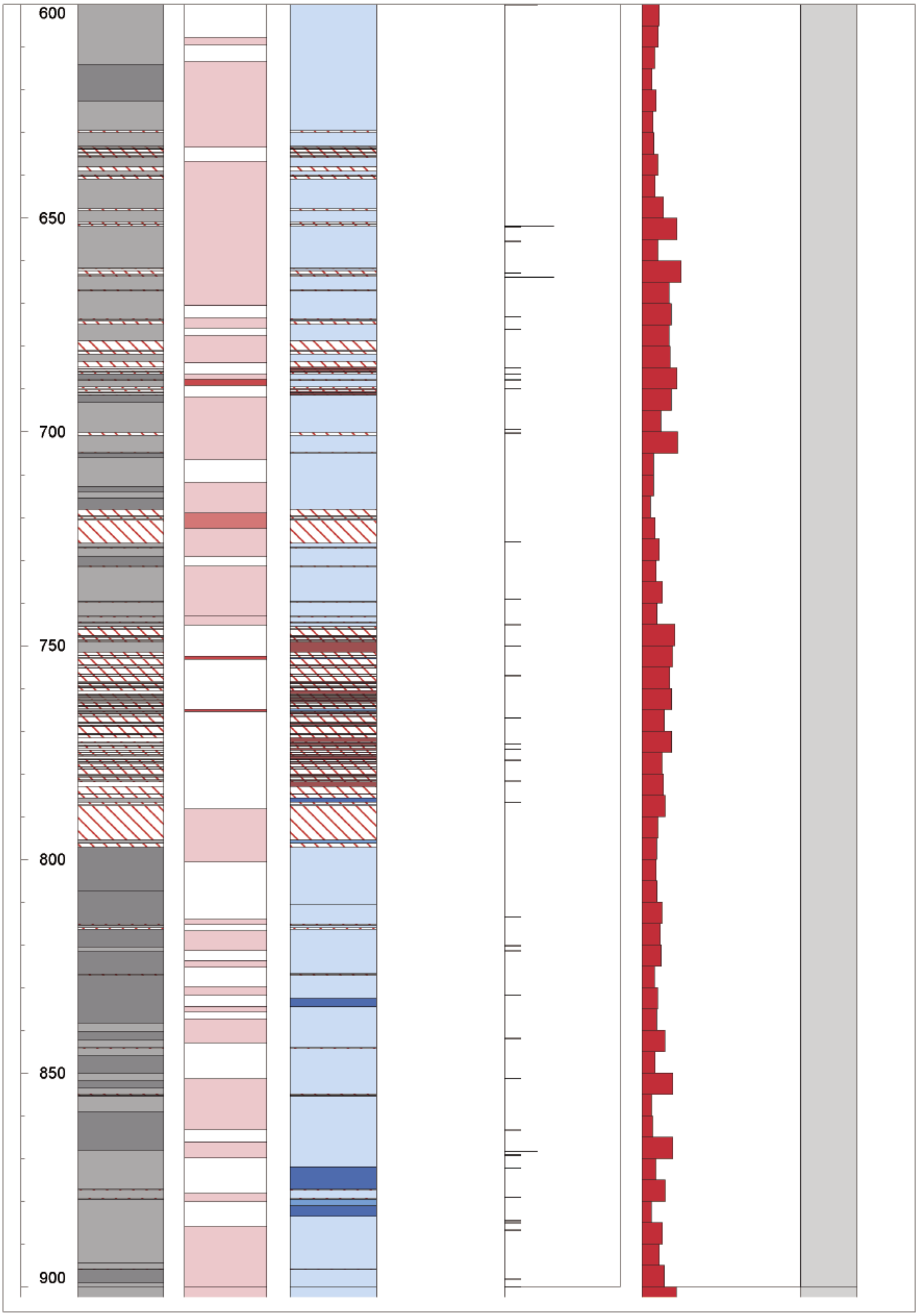
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