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Forsmark site investigation

Interpretation of geophysical borehole measurements and petrophysical data from KFM01D

Håkan Mattsson, Mikael Keisu
GeoVista AB

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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Keywords: Borehole, Logging, Geophysics, Geology, Bedrock, Fractures.

Abstract

This report presents the compilation and interpretations of geophysical logging data and wet density measurements on samples from the cored borehole KFM01D.

The main objective of the investigation is to use the results as supportive information during the geological core mapping and as supportive information during the geological single-hole interpretation. The petrophysical data are used for calibration of the density logging data, and it is also used as supportive information in the rock type classification.

The rocks in the vicinity of KFM01D are completely dominated (90 % of the borehole length) by silicate density indicating a mineral composition that corresponds to granite rock (< 2,680 kg/m^3). Subordinate short sections (< 5 m length) of rocks with higher densities (most often amphibolites) are mainly concentrated in the interval c 475–700 m.

In the section c 405–515 m there is slightly decreased density (c 2,640 kg/m^3 compared to the average of c 2,660 kg/m^3) in combination with a slight increase in the natural gamma radiation, by the amount of c 10 μR/h, which indicates the occurrence of rocks with lower content of dark minerals (possibly in combination with a higher content of quartz) relative to the "normal" metagranite-granodiorite. The observation is supported by the sample measurements.

The natural gamma radiation is mainly in the interval 20–30 μR/h in KFM01D, apart from the section discussed above, along which the natural gamma radiation is mainly 30–35 μR/h. In the section c 410–525 m there is an increased occurrence of positive radiation anomalies, which indicates a concentration of felsic dykes.

The magnetic susceptibility varies greatly in the range c 0.0005–0.0150 SI. In the section c 135–142 m, the magnetic susceptibility is partly increased. Sub-sections of greatly decreased magnetic susceptibility are concentrated at c 470–580 m and 670–740 m. Those low magnetic sections that do not coincide with increased density (normally related to amphibolite dykes) are possibly related to rock alteration and/or increased fracture frequency.

The estimated fracture frequency of KFM01D is generally low. However, a fairly long section with partly increased fracture frequency is indicated at c 105–200 m. Intervals with significantly decreased resistivity are identified in the sections c 105–107 m, 120–133 m and 168–190 m. In the two latter sections there are also caliper anomalies and partly decreased P-wave velocity. The combination of anomalies suggests that the rock has suffered from deformation.

Minor deformation zones are indicated in the sections c 306–308 m, 315–317 m and 570–572 m. These intervals are characterized by greatly decreased resistivity in combination with minor caliper anomalies.

In the section c 665–700 m there are significant caliper anomalies and decreased resistivity in combination with partly decreased magnetic susceptibility and P-wave velocity, which strongly suggest the occurrence of a deformation zone. The section coincides with indicated occurrences of granite (or pegmatite) and amphibolite dykes.

Sammanfattning

Föreliggande rapport presenterar en sammanställning och tolkning av geofysiska borrhålsmätningar och våtdensitetsmätningar på borrkärneprover från kärnborrhålet KFM01D.

Syftet med denna undersökning är framförallt att ta fram ett material som på ett förenklat sätt åskådliggör resultaten av de geofysiska loggningarna, s.k. generaliserade geofysiska loggar. Materialet används dels som stödjande data vid borrkärnekarteringen samt som underlag vid den geologiska enhålstolkningen. Syftet med de petrofysiska mätningarna är dels att kalibrera loggade densitetsdata samt dessutom att fungera som stödjande data för bergartsklassificeringen.

Berggrunden i närheten av KFM01D domineras helt (till 90 %) av bergart(er) med silikatdensitet < 2 680 kg/m^3, vilket indikerar en mineralsammansättning motsvarande den för granit. Korta sektioner (< 5 m) med förhöjd densitet, vilket oftast indikerar förekomst av amfibolit, är främst koncentrerade längs intervallet ca 475–700 m.

Densiteten är något lägre längs sektionen ca 405–515 m (ca 2 640 kg/m^3 jämfört med genomsnittsvärdet 2 660 kg/m^3) i kombination med något förhöjd naturlig gammastrålning, vilket indikerar en bergart med lägre halt mörka mineral (möjligen i kombination med högre kvartshalt) relativt den ”vanliga” metagraniten. Observationen stöds även av laboratoriemätningarna på prover från borrkärnan.

Den naturliga gammastrålningen i KFM01D ligger generellt i intervallet 20–30 µR/h, utom för den sektion som nämns i stycket ovan, längs vilken strålningen ligger i intervallet 30–35 µR/h. Längs intervallet ca 410–525 m finns en förhöjd koncentration av positiva strålningsanomalier vilket tyder på ökad förekomst av felsiska gångar.

Den magnetiska susceptibiliteten uppvisar kraftiga variationer (0,0005–0,0150 SI) längs hela borrhålet. Inom sektionen ca 135–142 m är susceptibiliteten delvis avvikande hög (> 0,0150 SI). Sektioner med avvikande låg susceptibilitet förekommer främst i intervallen ca 470–580 m och 670–740 m. För de sektioner där låg susceptibilitet inte sammanfaller med förhöjd densitet (viket ofta indikerar förekomst av amfibolit) kan den låga susceptibiliteten vara en indikation på mineralomvandling och/eller förhöjd sprickfrekvens

Den beräknade sprickfrekvensen är generellt låg i KFM01D. Delvis förhöjd sprickfrekvens förekommer längs intervallet 105–200 m. Kraftigt sänkt resistivitet kan identifieras längs delsektionerna ca 105–107 m, 120–133 m och 168–190 m. Längs de två senare intervallen finns även caliper-anomalier.

Mindre deformationszoner indikeras längs ca 306–308 m, 315–317 m och 570–572 m. Intervallen karaktäriseras främst av sänkt resistivitet i kombination med caliper-anomalier. Längs sektionen ca 665–700 m förekommer ett flertal större caliper-anomalier och sänkt resistivitet i kombination med delvis sänkt magnetisk susceptibilitet och P-vågshastighet, vilket är en tydlig indikation på en deformationszon. Den möjliga deformationszonen sammanfaller med indikerade förekomst av basiska och felsiska gångar.

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/Laxemar. This document reports the results gained from the interpretation of geophysical borehole logging data from the cored borehole KFM01D in Forsmark (Figure 1-1).

Generalized geophysical loggings related to lithological variations are presented together with indicated fracture loggings, including estimated fracture frequency. Calculations of the estimated salinity and apparent porosity are also presented for the boreholes. The logging measurements were conducted in 2006 by Rambøll /1/. Measurements of petrophysical properties were performed by the Petrophysical Laboratory at Luleå University of Technology in March 2006.

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

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

Activity plan	**Number**	**Version**
Tolkning av geofysiska borrhålsdata från KFM01D	AP PF 400-06-032	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för bestämning av densiteten och porositeten hos det intakta berget	SKB MD 160.002	2.0
Metodbeskrivning för tolkning av geofysiska borrhålsdata	SKB MD 221.003	2.0

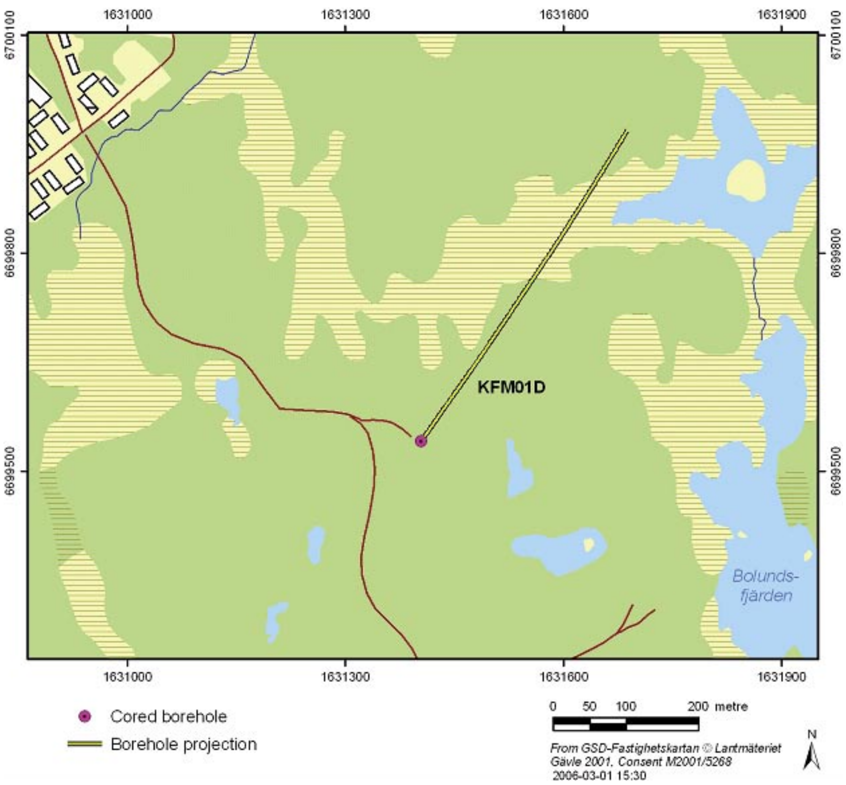

Figure 1-1. Map showing the location of the investigated borehole KFM01D.

2 Objective and scope

The purpose of geophysical measurements in boreholes is to gain knowledge of the physical properties of the bedrock in the vicinity of the borehole. A combined interpretation of the "lithological" logging data silicate density, magnetic susceptibility and natural gamma radiation, together with petrophysical data makes it possible to estimate the physical signature of different rock types. The three loggings are generalized and are then presented in a simplified way. The location of major fractures and an estimation of the fracture frequency along the borehole are calculated by interpreting data from the resistivity loggings, the single point resistance (SPR), caliper and sonic loggings.

An estimation of the salinity and the apparent porosity are presented for the cored boreholes. These parameters indicate saline water and the transportation properties of the rock volume in the vicinity of the borehole.

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

3 Equipment

3.1 Description of equipment for analyses of logging data

The software used for the interpretation are WellCad v3.2 (ALT) and Strater 1.00.24 (Golden Software), that are mainly used for plotting, Grapher v5 (Golden Software), mainly used for plotting and some statistical analyses, and a number of in-house software developed by GeoVista AB on behalf of SKB.

3.2 Description of equipment for analyses of petrophysical data

Masses for the density determinations were measured with a digital Mettler Toledo PG 5002. The measurements were performed by the petrophysical laboratory at Luleå University of Technology.

4 Execution

4.1 Laboratory measurements

The sampling covers 7 samples from KFM01D (Table 4-1) and were collected and delivered by Kenneth Åkerström (SKB). Preparations of the drill cores were performed by a technician at the laboratory of the Division of Applied Geophysics, Luleå University of Technology. The measurements of the wet density were performed according to MD 160.002 (SKB internal controlling document). The instruction is written to conform to rock mechanical measurements on drill cores from deep drillings, where the density determinations are parts of other types of measurements, not directly relevant for the geological core logging. The time to soak the samples (48 hours in this investigation) is e.g. shorter than what is recommended in MD 160.002.

Calibration of instruments for measurements of petrophysical parameters were performed in accordance with the manual for each instrument respectively.

The laboratory measurements of petrophysical parameters produce raw-data files in ascii, binary or Microsoft Excel formats. All data files were delivered via email from the laboratory at the Luleå University of Technology to GeoVista AB. The data were then rearranged and placed in Microsoft Excel files. Back-up files of all raw-data are stored both at GeoVista AB and at the laboratory.

Sample information, section up and section low, for KFM01D is given in Table 4-1.

4.2 Interpretation of the logging data

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

1. Preparations of the logging data (calculations of noise levels, median filtering, error estimations, re-sampling, drift correction, length adjustment).

The loggings are median or mean filtered (generally 5 point filters for the resistivity loggings and 3 point filters for other loggings) and re-sampled to common depth co-ordinates (0.1 m point distance).

The density logging data are calibrated with respect to petrophysical data from KFM01D (this investigation). The magnetic susceptibility logging data are calibrated with respect to a combination of petrophysical data from the boreholes KFM01A and KFM02A /2 and 3/.

Table 4-1. Sample information for KFM01D.

Secup	Seclow
151.40	151.50
209.05	209.15
439.63	439.73
466.36	466.46
653.20	653.30
691.10	691.20
756.85	756.95

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

The silicate density is calculated with reference to /4/, and the data are then divided into 5 sections indicating a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to /5/. 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 /6/; $\sigma = a\,\sigma_w^k\,\varphi^m + \sigma_s$ 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 4-2.

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

$$WS = \frac{400000}{(1.8t + 32)\sqrt[0.88]{\rho}}$$

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

The salinity is only calculated for cored boreholes.

4. Interpretation of the position of large fractures and estimated fracture frequency (classification to fracture logging and calculation of the estimated fracture frequency logging are based on analyses of the short and long normal resistivity, caliper mean, single point resistance (SPR), focused resistivity (140 and 300 cm) and sonic. The position of large fractures is estimated by applying a second derivative filter to the logging data and then locating maxima (or minima depending on the logging method) in the filtered logging. Maxima (or minima) above (below) a certain threshold value (Table 4-3) 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 4-3.

Table 4-2. 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
KFM01D	1.2	10	0.37	1.7

Table 4-3. 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	KFM01D	2.0	1.4	1.4	0.5	1.0	4.0	5.0	–
Weight	KFM01D	4.0	2.56	4.0	2.0	2.56	0.24	1.75	–

5. Report evaluating the results.

4.3 Preparations and data handling

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

Vertical temperature gradient data were retrieved from the data base SICADA 2006-11-14.

4.4 Analyses and interpretations

The analyses of the logging data are made with respect to identifying major variations in physical properties with depth as indicated by the silicate density, the natural gamma radiation and the magnetic susceptibility. Since these properties are related to the mineral composition of the rocks in the vicinity of the borehole they correspond to variations in lithology and in thermal properties.

The resistivity, sonic and caliper loggings are mainly used for identifying sections with increased fracturing and alteration. The interpretation products salinity and apparent porosity help identifying saline ground water and porous rocks.

4.5 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

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 and magnetic susceptibility logs are above the recommended levels. However, the noise levels are most likely low enough to allow a meaningful interpretation of the data. To reduce the influence of the noise, all logs were average 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.

The calibration of the density log is performed by plotting the sample data versus the log data at the corresponding section length coordinate (a so called cross-plot), and then performing a linear regression analysis. In Figure 5-1 a cross plot of the density data of KFM01D is displayed.

The logging versus sample density data show a nice linear distribution with a low amount of scatter and the fitted line is very well defined (though the number of data points is few). However, the slope of the fitted line is larger than 1.0 (it is 1.12) and observe the rather large negative density value of –138.6 kg/m^3 for the density log when the sample density equals zero. The calibration equation indicates that the logging tool suffers from measurement errors regarding both the zero-level (it measures a density of –138.6 kg/m^3 when the density equals zero) and there is also linear misfit of 12% in the equation transforming the measured signal into density values. However, the calibration performed on the density data in this investigation corrects the logging data for these errors. In Figure 5-2 the primary logging density data, the sample density and the calibrated logging density data are presented. In the diagram we can clearly see the large difference between the two loggings (before and after calibration by petrophysical data) and also note that the sample data correlate well with the calibrated logging data.

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

Logging method	KFM01D	Recommended max noise level
Density (kg/m3)	5	3–5
Magnetic susceptibility (SI)	3×10^{-4}	1×10^{-4}
Natural gamma radiation (μR/h)	0.8	0.3
Long normal resistivity (%)	0.2	2.0
Short normal resistivity (%)	0.1	2.0
Fluid resistivity (%)	0.02	2
Fluid temperature (ºC)	3×10^{-4}	0.01
Lateral resistivity (%)	Not used	2
Single point resistance (%)	0.3	No data
Caliper (meter)	0.2×10^{-4}	0.0005
Focused resistivity 300 (%)	4.5	No data
Focused resistivity 140 (%)	0.9	No data
Sonic (m/s)	2	20

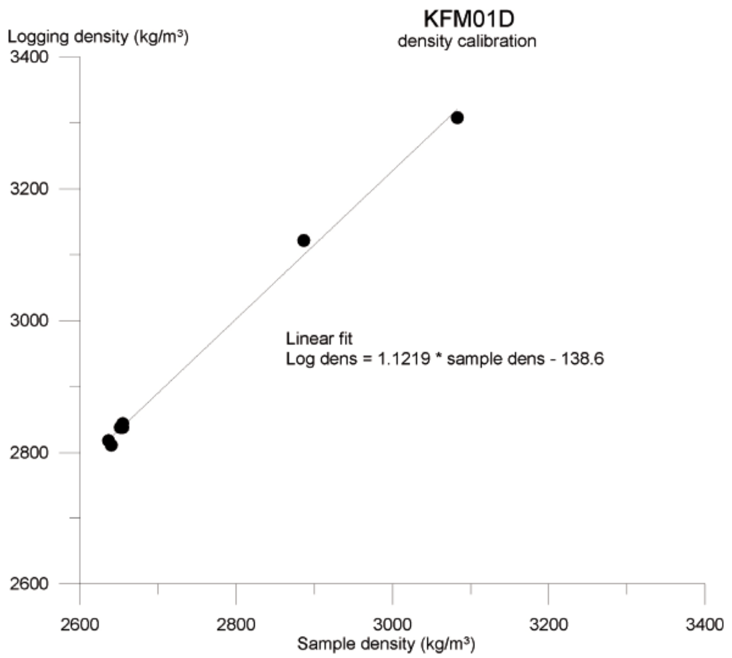

Figure 5-1. *Cross plot of logging density versus sample density for KFM01D.*

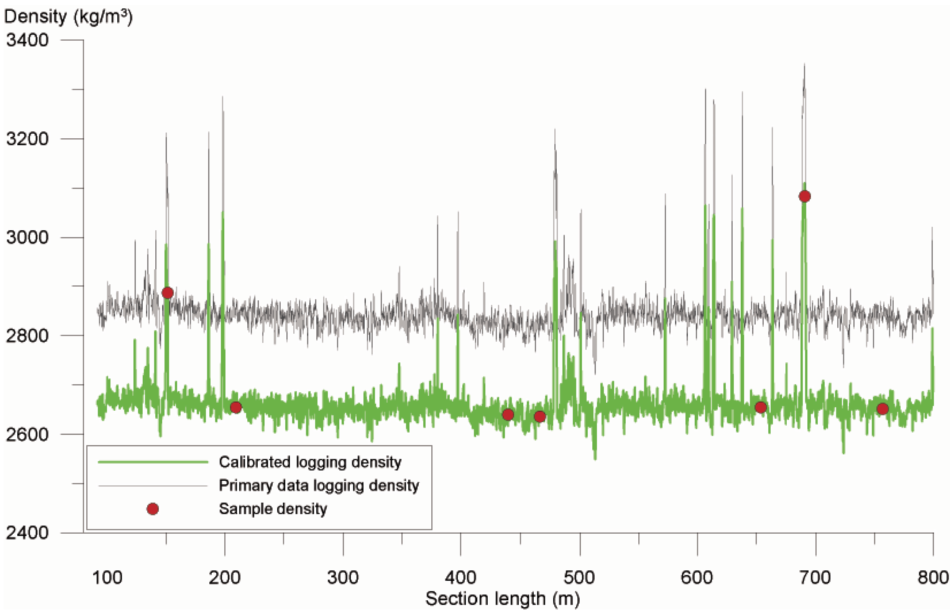

Figure 5-2. *Density data from logging and sample measurements in KFM01D.*

5.2 Interpretation of the logging data

The presentation of interpretation products presented below includes:

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

5.2.1 Interpretation of KFM01D

The results of the generalized logging data and fracture estimations of KFM01D are presented in Figure 5-3 below, and in a more detailed scale in Appendix 1.

The rocks in the vicinity of KFM01D 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 5-3. Subordinate short sections (< 5 m length) of rocks with higher densities occur along

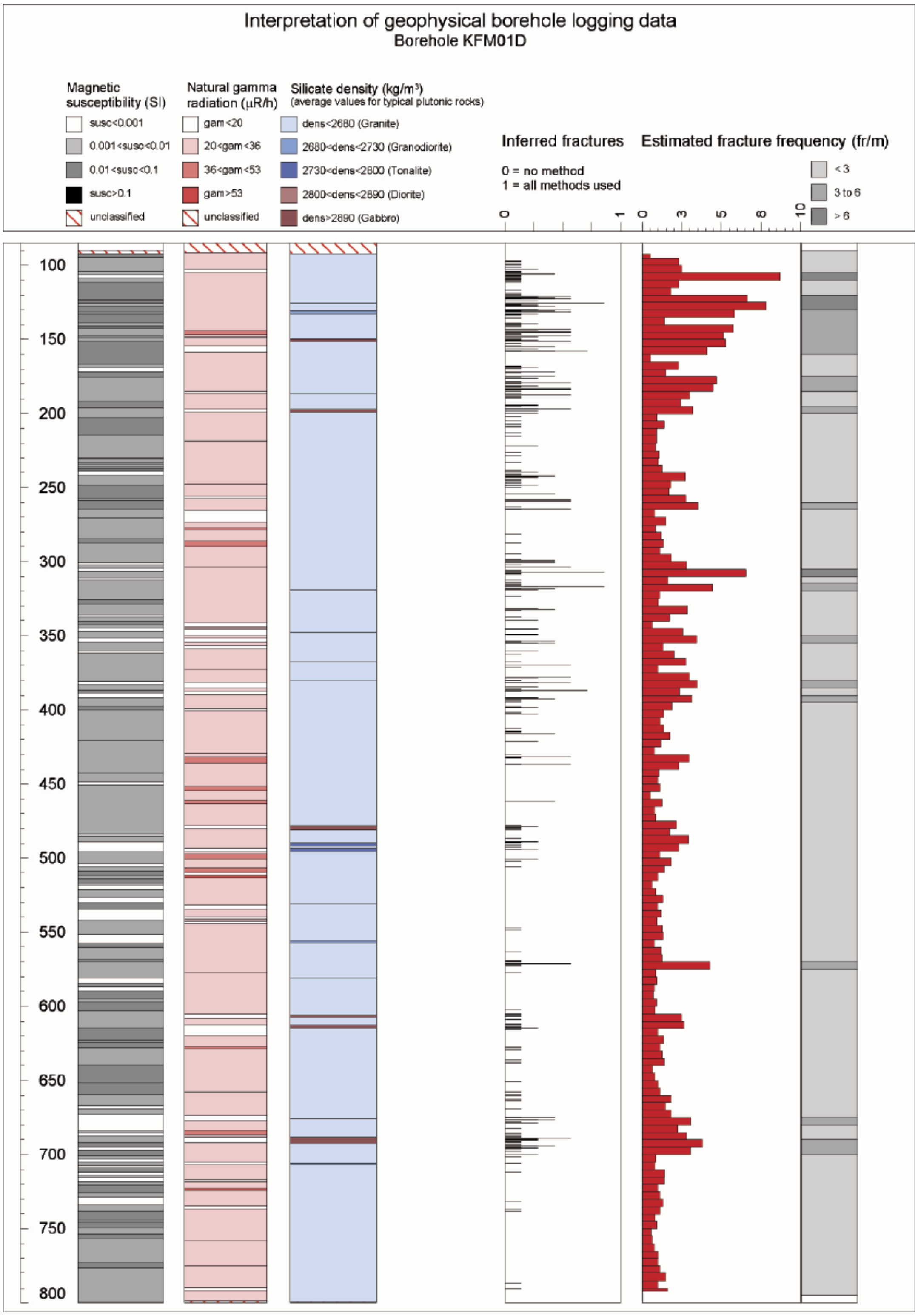

Figure 5-3. Generalized geophysical logs of KFM01D.

the entire borehole length, though mainly concentrated in the interval c 475–700 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 occurrences of amphibolite dykes. Some 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 mafic and felsic dykes are spatially related.

In the section c 405–515 m there is slightly decreased density (c 2,640 kg/m^3 compared to the average of c 2,660 kg/m^3) in combination with a slight increase in the natural gamma radiation, by the amount of c 10 µR/h. There is no significant variation in the magnetic susceptibility data. The combination of physical properties indicates that the rocks along this interval have lower content of dark minerals (possibly in combination with a higher content of quartz) relative to the "normal" metagranite-granodiorite. The observation is supported by the sample measurements. The two samples located at c 439.7 m and 466.4 m have average density of 2,638 kg/m^3, whereas the three granitic samples outside of this interval have an average density of 2,654 kg/m^3.

Partly increased density (c 2,730–2,780 kg/m^3), in combination with decreased magnetic susceptibility and slightly decreased natural gamma radiation, occurs in the interval c 485–495 m.

The natural gamma radiation is mainly in the interval 20–30 µR/h in KFM01D, apart from the section discussed above, along which the natural gamma radiation is mainly 30–35 µR/h. Short sections (often < 0.5 m) 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 section c 410–525 m there is an increased occurrence of positive radiation anomalies, thus indicating a concentration of felsic dykes in this part of the borehole.

The magnetic susceptibility varies greatly in the range c 0.0005–0.0150 SI. In the section c 135–142 m, the magnetic susceptibility is partly increased, showing values in the range 0.030–0.090 SI. In this section there is a slight increase in the density, 2,700 kg/m^3, which indicates that the rock along the interval has a granodioritic composition. Sub-sections of greatly decreased magnetic susceptibility are concentrated at c 470–580 m and 670–740 m. The low magnetic sections that do not coincide with increased density (normally related to amphibolite dykes) are possibly related to rock alteration and/or increased fracture frequency.

The estimated fracture frequency of KFM01D is generally low. However, a fairly long section with partly increased fracture frequency is indicated at c 105–200 m. Intervals with significantly decreased resistivity are identified in the sections c 105–107 m, 120–133 m and 168–190 m. In the two latter sections there are also caliper anomalies and partly decreased P-wave velocity. The combination of anomalies suggests that the rock has suffered from deformation.

Table 5-2. Distribution of silicate density classes with borehole length of KFM01D.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
density < 2,680 (granite)	638	90
2,680 < density < 2,730 (granodiorite)	43	6
2,730 < density < 2,800 (tonalite)	9	1
2,800 < density < 2,890 (diorite)	5	1
density > 2,890 (gabbro)	11	2

Minor deformation zones are indicated in the sections c 306–308 m, 315–317 m and 570–572 m. These intervals are characterized by greatly decreased resistivity in combination with minor caliper anomalies.

In the section c 665–700 m there are significant caliper anomalies and decreased resistivity in combination with partly decreased magnetic susceptibility and P-wave velocity, which strongly suggest the occurrence of a deformation zone. The section coincides with indicated occurrences of granite (or pegmatite) and amphibolite dykes.

The estimated apparent porosity shown in Figure 5-4 (black line) is fairly constant at c 0.65%, which is considered normal for primary crystalline rock in this region. Apparent porosity anomalies are few, small and mainly occur in the sections with indicated increased fracturing. The estimated fluid water salinity (green line in Figure 5-4) is fairly stable (showing only minor anomalies) in the range 7,000–7,700 ppm NaCl. The vertical temperature gradient has an average of 10.8 °C/km. In the section c 150–380 m there is an increased occurrence of temperature anomalies possibly related to the increased fracturing indicated by the resistivity, caliper and sonic logs. A significant negative temperature anomaly occurs at c 250 m, which coincides with caliper and resistivity anomalies indicating the occurrence of a water bearing fracture. In the section c 505–645 m there are several significant temperature anomalies, however all other geophysical logs indicate solid rock and low fracture frequency along the entire interval.

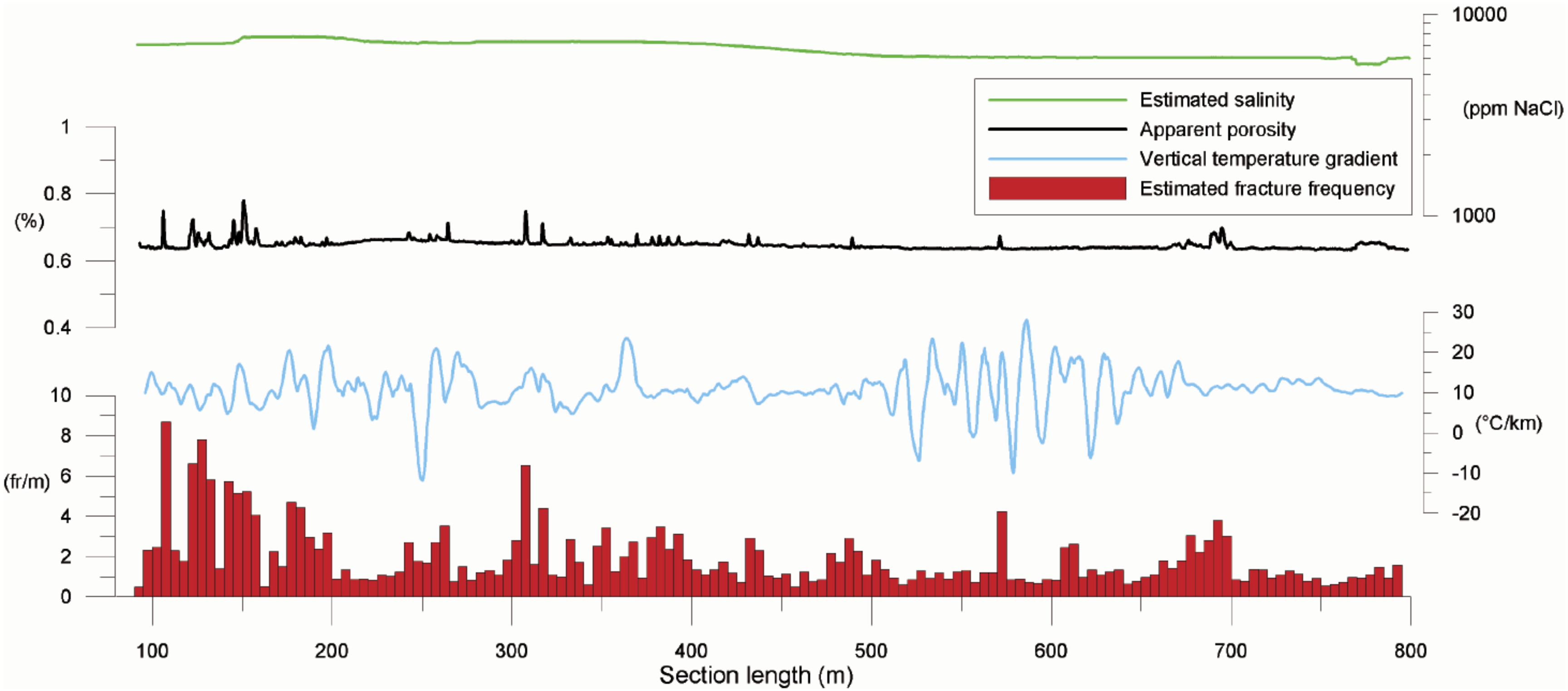

Figure 5-4. *Estimated salinity, apparent porosity, vertical temperature gradient and estimated fracture frequency of KFM01D.*

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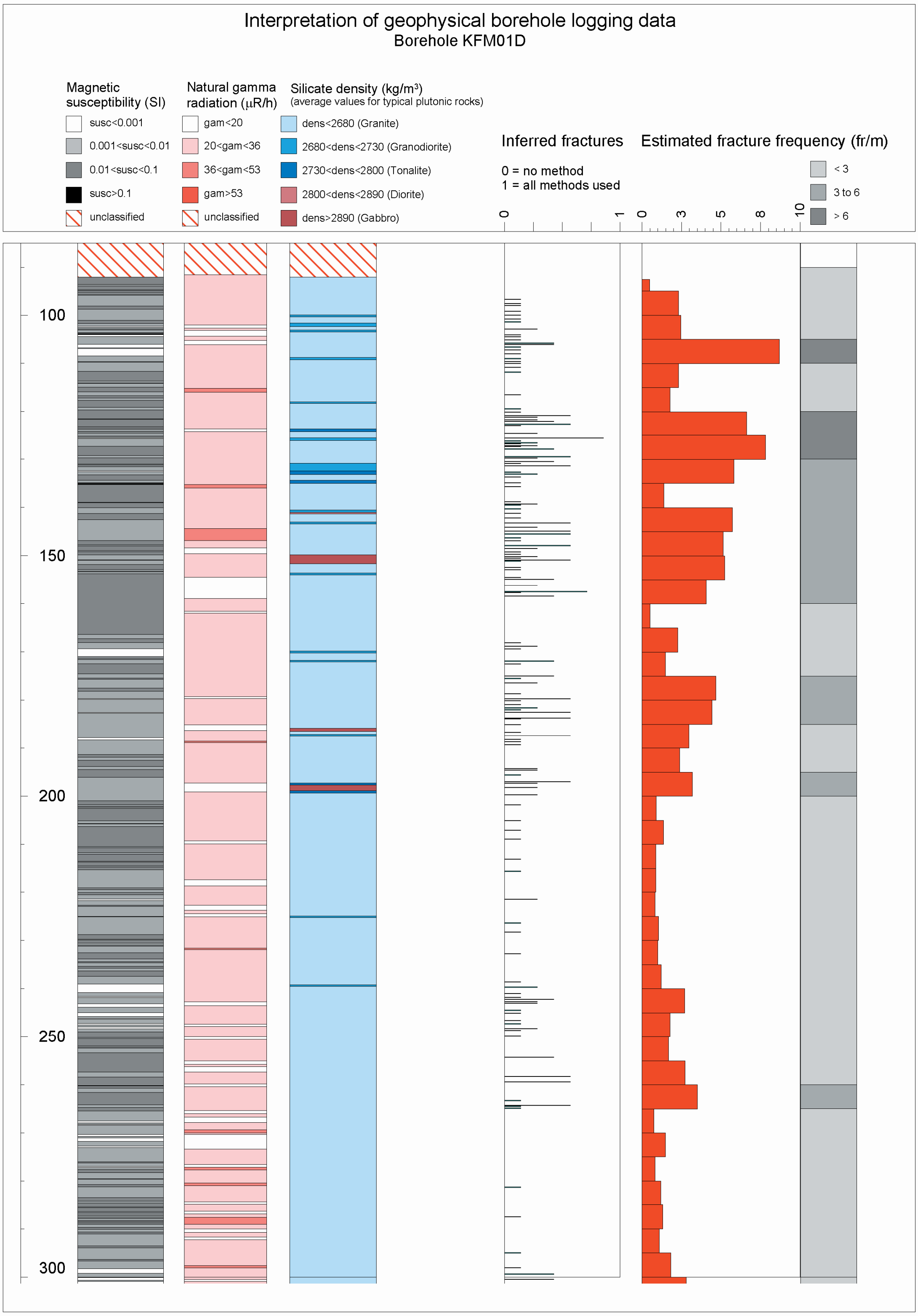
Generalized geophysical loggings of KFM01D

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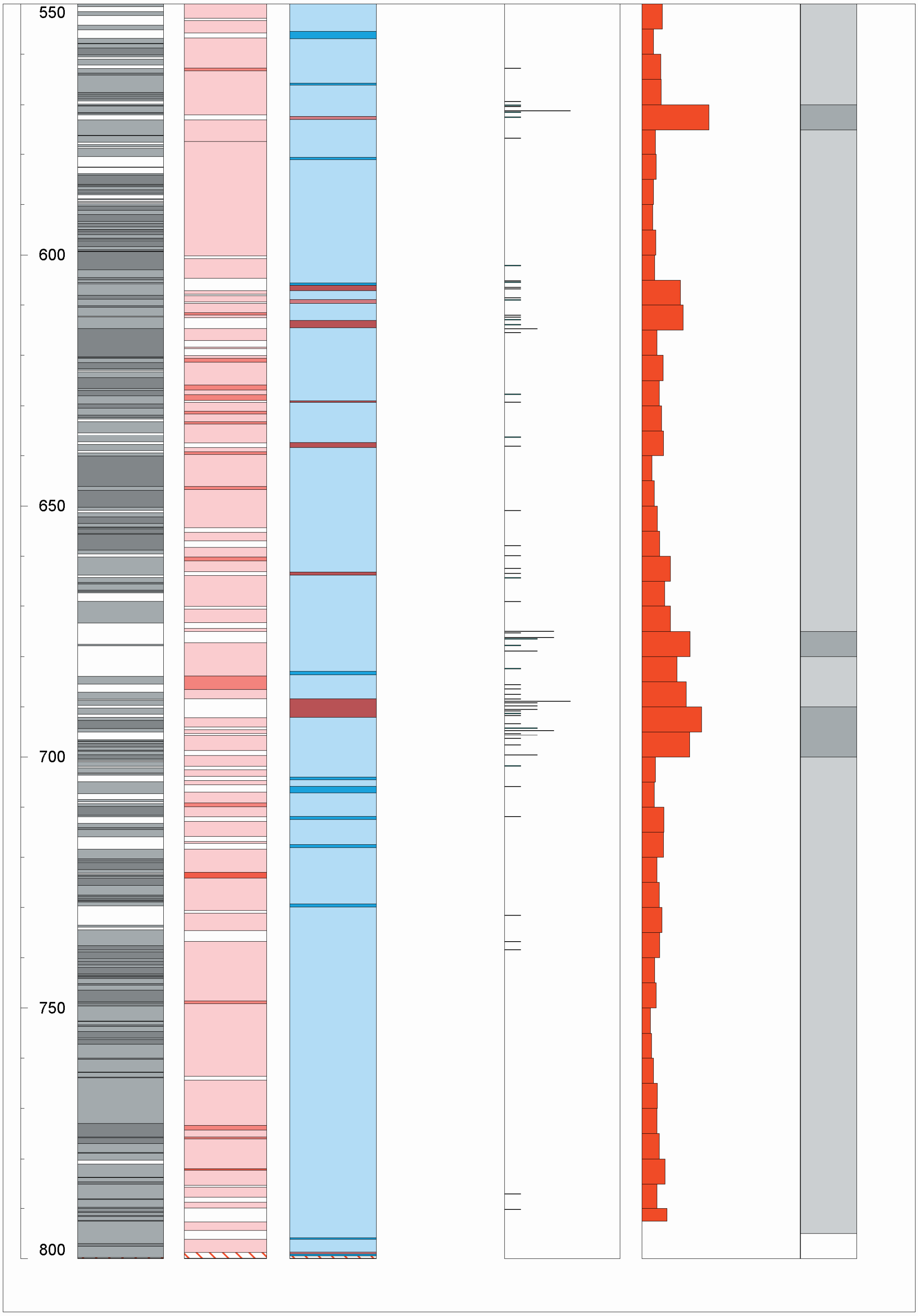
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