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Forsmark site investigation

Interpretation of borehole geophysical measurements in KFM02A, KFM03A, KFM03B and HFM04 to HFM08

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April 2004

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Abstract

This report presents the compilation and interpretation of geophysical logging data from the cored boreholes KFM02A, KFM03A and KFM03B and the percussion drilled holes HFM04, HFM05, HFM06, HFM07 and HFM08.

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 KFM02A is dominated by rock types with a silicate density and thus a mineral composition that corresponds to granite. A c 60 m section between 240 and 300 m has very low density and is known to correspond to an occurrence of vuggy granite. The rock between 904 and 939 m depth has a silicate density corresponding to diorite. Most of the rock has, for the area, normal values of magnetic susceptibility and natural gamma radiation. An exception is above 310 m and between 460 and 520 m depth where the magnetic susceptibility is low. This might be an effect of alteration of the rock.

The geophysical logs indicate that the fracture frequency along KFM02A is, in general, very low. An exception is between 410 and 515 m depth. Increased fracture frequency is also inferred at 80 to 95 m, 110 to 130 m, 160 to 175 m and 265 to 280 m depth.

The rocks at HFM04 and HFM05 appear to have roughly the same petrophysical properties as the nearby KFM02A. Narrow but possibly water bearing fracture zones are inferred at 63, 166 and 187 m (HFM04) and 107, 155 and 183 m (HFM05).

The bedrock in the vicinity of KFM03A is dominated by rock types with a silicate density and thus a mineral composition that corresponds to granite. The rock between 220 and 250 m depth has a silicate density corresponding to tonalite and between 285 to 350 m to tonalite/diorite. Minor occurrences of high density rock and rock with high natural gamma radiation can be found at irregular intervals along the borehole. Although of small volume, these rocks may be of significance since they seem to correlate with fractures. Most of the rock has, for the area, normal values of magnetic susceptibility and natural gamma radiation. Exceptions are mainly the rocks with tonalite/diorite silicate density which show low susceptibility and radiation.

The geophysical logs indicate that the fracture frequency along KFM03A is generally very low. Increased fracture frequency is inferred at 35 to 42 m, 100 to 135 m, 355 to 415 m and 790 to 815 m depth. Some narrow but possibly water bearing fractures are also inferred, the most prominent one at 643 m.

The rock at HFM06, HFM07 and HFM08 appear to have roughly the same petrophysical properties as the nearby KFM03A. Increased fracture frequency is inferred at 44 to 71 m (HFM06) and 120 to 140 m (HFM08) and narrow but possibly water bearing fractures at 57 m (HFM07) and 90 m (HFM08).

Sammanfattning

Denna rapport presenterar resultatet av tolkningen av geofysiska loggningsdata från kärnborrhålen KFM02A, KFM03A och KFM03B och hammarborrhålen HFM04, HFM05, HFM06, HFM07 och HFM08.

Det huvudsakliga syftet med detta arbete är att ta fram resultat som kan tjäna som stödjande underlag vid kärnkarteringen samt vid enhålstolkningen av de aktuella borrhålen.

Berggrunden vid KFM02A domineras av bergarter med en silikatdensitet och därmed en mineralsammansättning som motsvarar granit. En ca 60 m lång sektion av hålet uppvisar mycket låg densitet och motsvaras av en volym med porös granit. Mellan 904 och 939 m djup förekommer bergarter med en silikatdensitet som motsvaras av diorit. Det mesta av berggrunden har, för området, normala värden för magnetisk susceptibilitet och naturlig gammastrålning. Ett undantag från detta är ovanför 310 m djup samt mellan 460 och 520 m djup där den magnetiska susceptibiliteten är låg. Detta kan vara en effekt av omvandling.

De geofysiska loggarna indikerar att sprickfrekvensen i KFM02A generellt sett är mycket låg. Ett undantag är mellan 410 och 515 m djup. Förhöjd sprickfrekvens är också indikerad vid 80 till 95 m, 110 till 130 m, 160 till 175 m och vid 265 till 280 m djup.

Berggrunden vid HFM04 och HFM05 uppvisar ungefär samma petrofysiska egenskaper som i det närbelägna KFM02A. Smala men troligen vattenförande sprickor har indikerats vid 62, 166 och 187 m (HFM04) och 107, 155 och 183 m (HFM05).

Berggrunden vid KFM03A domineras av bergarter med silikatdensitet och därmed en mineralsammansättning som motsvaras av granit. Mellan 220 och 250 m djup uppträder berg med en silikatdensitet som motsvaras av tonalit och mellan 285 och 350 m djup motsvarar silikatdensiteten tonalit/diorit. Smärre förekomster av bergarter med hög densitet eller hög naturlig gammastrålning förekommer här och där längs hålet. Även om dessa volymmässigt är underordnade kan de vara av betydelse eftersom de i vissa fall förefaller korrelera med sprickor. Det mesta av berget har, för området, normala värden för magnetisk susceptibilitet och naturlig gamma-strålning. Undantag från detta är framför allt bergarterna med silikatdensiteter motsvarande tonalit/diorit som har låg susceptibilitet och strålning.

De geofysiska loggarna indikerar att sprickfrekvensen i KFM03A generellt sett är mycket låg. Förhöjd sprickfrekvens indikeras vid 35 till 42 m, 100 till 135 m, 355 till 415 m och 790 till 815 m djup. Smala men troligen vattenförande sprickzoner har indikerats, den mest signifikanta vid 643 m djup.

Berggrunden vid HFM06, HFM07 och HFM08 uppvisar ungefär samma petrofysiska egenskaper som det närliggande KFM03A. Förhöjd sprickfrekvens är indikerad vid 44 till 71 m (HFM06) och 120 till 140 m (HFM08) och smala men troligen vattenförande sprickor vid 57 m (HFM07) och 90 m (HFM08).

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 boreholes KFM02A, KFM03A and KFM03B and the percussion drilled boreholes HFM04, HFM05, HFM06, HFM07 and HFM08 at Forsmark. The location of the boreholes is shown in Figure 1-1 (drill site 2) and Figure 1-2 (drill site 3), respectively.

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 in the cored holes were conducted by Rambøll /1/ whereas the percussion drilled holes were logged by Malå GeoScience /2/.

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 plan AP PF 400-03-91 (SKB internal controlling document).

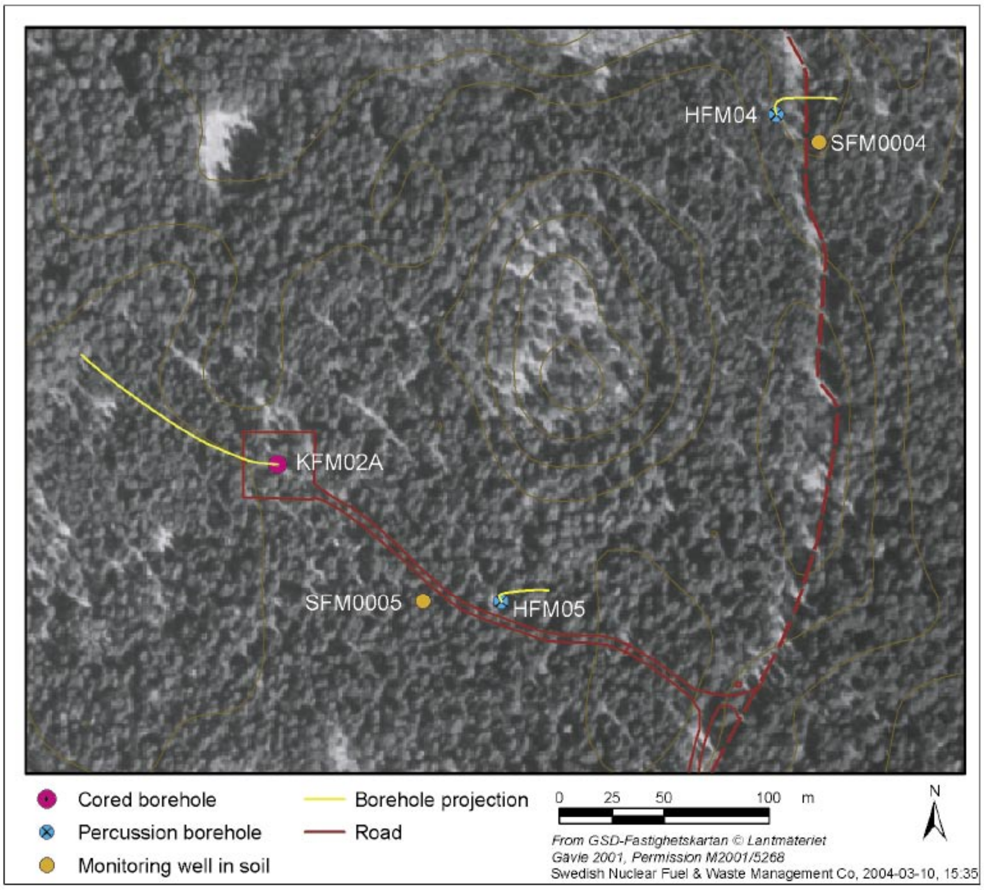


Figure 1-1. Forsmark site investigation. Drill site 2.

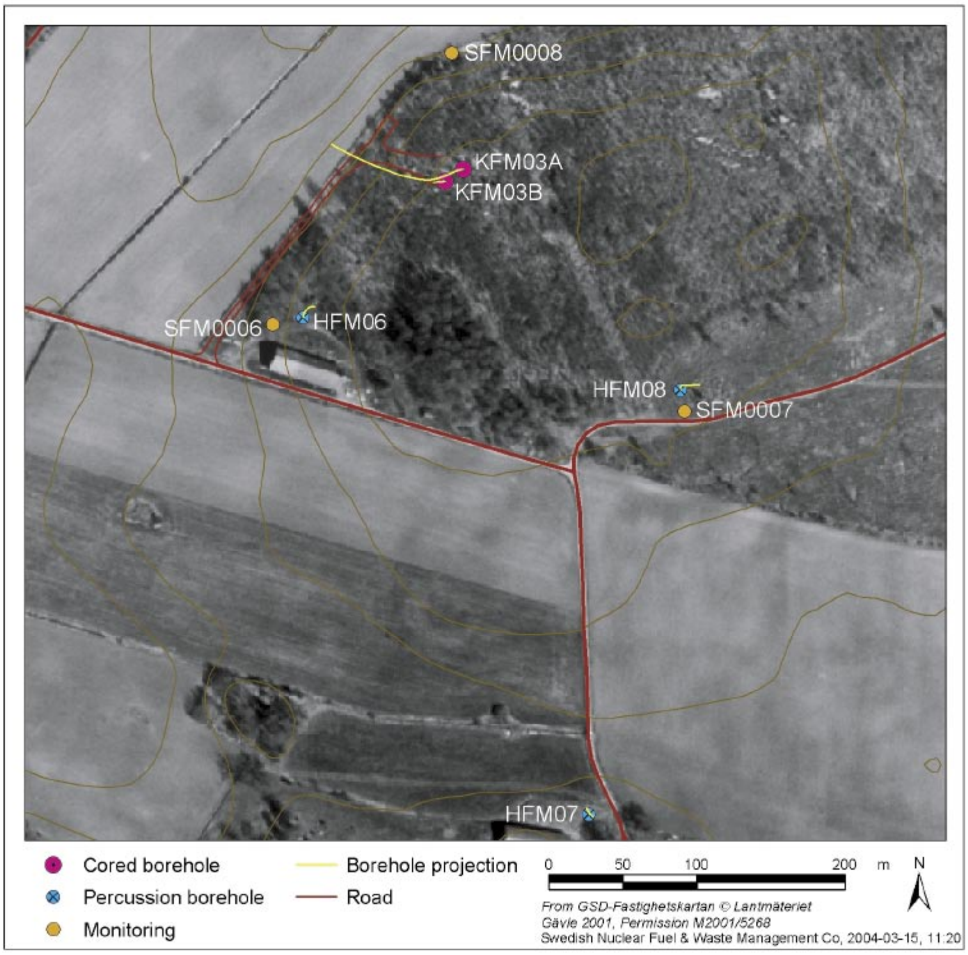


***Figure 1-2**. Forsmark site investigation. Drill site 3.*

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

The main objective of these investigations is to provide supportive information to the geological core mapping and as supportive information 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), which is 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 /3/.

3.1 Logging data

3.1.1 Logging data, cored holes and percussion drilled part of KFM03A

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)
Sonic
Caliper mean
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. No normal, lateral resistivity or SPR measurements were performed in the boreholes. Sonic data have been rejected for some sections.

3.1.2 Logging data, other percussion drilled holes

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

Lateral resistivity
Short normal resistivity
SPR (Single-point-resistance)
Magnetic susceptibility
Natural gamma radiation
Fluid resistivity
Fluid temperature
Density (gamma-gamma)
Caliper

The density, resistivity and SPR equipment used in the percussion drilled holes are not up to the standards required for these types of loggings, as has also been pointed out by the contractor before the surveys. The density log has not been possible to calibrate accurately and it has a tendency to drift during measurements. A slowly varying trend has therefore been subtracted from the density logs in the percussion boreholes assuming that the dominating silicate density is the same as in the cored boreholes.

The electrical logs, especially the short normal and the SPR, give anomalies of sometimes peculiar shape and unrealistic magnitude. They have still been used in the interpretations since the anomalies seem to be related to low resistivity features as fracture zones.

The levels of the magnetic susceptibility logs were adjusted by a comparison of data from HFM02, a hole that has been logged by both contractors. Histograms of measured susceptibilities also show similar characteristics as histograms for the cored holes. The level of the natural gamma radiation log was clearly different between the two contractors. Comparative data are not fully conclusive. The data from the percussion boreholes have been multiplied with a constant factor that gives results that are comparable to the cored holes.

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 are average filtered (3 to 7 point triangular filters, where shorter filters have been used for methods with short wave-length anomalies). 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 (4.5 m sections for the percussion boreholes) according to the following equation /4/:

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

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:

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

where WS = Water salinity (ppm NaCl), t = temperature (°C) and ρ = 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 /5/ and the data are then divided into 5 intervals indicating a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to /6/. The intervals are bounded by the threshold values

granite < 2680 kg/m^3
2680 kg/m^3 < granodiorite < 2730 kg/m^3
2730 kg/m^3 < tonalite < 2800 kg/m^3
2800 kg/m^3 < diorite < 2890 kg/m^3
2890 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 of focused resistivity, caliper mean and sonic data for the cored boreholes and of lateral resistivity, short normal resistivity, SPR (not HFM05) and caliper for the percussion drilled holes)

The position of large, individual fractures is estimated by applying a second derivative filter (deconvolution filter for lateral resistivity) 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 boreholes 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 programs *fract_det* and *fract_latres*, and weights used for estimating position of fractures and calculation of estimated fracture frequency, respectively.

	Borehole	Sonic	Focused res. 300	Focused res. 140	Caliper
Threshold	KFMxxx	1.5	1.4	1.0	0.2
Weight	KFMxxx	4.0	4.0	2.56	not used
	Borehole	**SPR**	**Short normal resist.**	**Caliper**	**Lateral resist.**
Threshold	HFMxxx	0.9	0.6	0.6	1.2
Weight	HFMxxx	2.56	2.63	not used	2.86

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 and 4-2. 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.

A qualitative inspection was performed on the logs. The data were checked for spikes and/or other obvious incorrect data points. Such erroneous data points were discovered in the sonic log of KFM02A. Most sections with bad sonic data from this hole were short but the data from depths of 339 to 377 m and 907 to 979 m had to be rejected. Sonic data were also rejected for a large portion of the uppermost 100 m of KFM03A where the borehole diameter is large.

Table 4-1. Noise levels in geophysical logging data for cored boreholes.

Logging method	KFM02A (below 100m)	KFM03A (below 100m)	KFM03B	Recommended max noise level
Density (kg/m3)	64	53	24	3 – 5
Magnetic susceptibility (SI)	$1.9 \cdot 10^{-4}$	$7.3 \cdot 10^{-4}$	$7.5 \cdot 10^{-4}$	$1 \cdot 10^{-4}$
Natural gamma radiation (μR/h)	2.9	2.7	1.5	0.3
Fluid resistivity (%)	0.2	0.2	1.7	2.0
Fluid temperature (°C)	0.0015	0.0035	0.015	0.01
Caliper (mm)	0.041	0.035	0.085	0.5
Focused resistivity 300 (%)	8.7	11.2	8.2	—
Focused resistivity 140 (%)	—	2.0	4.0	—
Sonic (m/s)	88	70	125	20

Table 4-2. Noise levels in geophysical logging data for percussion drilled boreholes.

Logging method	HFM04	HFM05	HFM06	HFM07	HFM08	Recommended max noise level
Density (kg/m3)	33	34	27	36	32	3 – 5
Magnetic susceptibility (SI)	$2.5 \cdot 10^{-4}$	$2.6 \cdot 10^{-4}$	$7.5 \cdot 10^{-4}$	$3.8 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$
Natural gamma radiation (μR/h)	4.4	4.6	4.4	4.2	5.0	0.3
Fluid resistivity (%)	0.3	0.3	0.3	0.1	0.5	2.0
Fluid temperature (°C)	0.0015	0.0013	0.0021	0.0024	0.0014	0.01
Caliper (mm)	0.07	0.08	0.23	0.25	0.08	0.5
Lateral resistivity (%)	1.4	1.4	2.4	2.3	1.6	2.0
Short normal resistivity (%)	1.4	4.3	4.2	2.0	4.8	2.0
SPR (%)	1.1	—	1.2	1.2	1.8	—

4.1.2 Comparison between logging and petrophysical data for KFM02

A quality control of the gamma-gamma and the magnetic susceptibility logs is performed by comparing the log data to the petrophysical data at the corresponding depths. In Figure 4-1 the gamma-gamma (density) log is plotted versus wet density sample measurements. Data from KFM01A were also included since hardly any rocks with high density had been sampled in KFM02A. The correlation is good except for one sample that was located at a density gradient in the log and two samples of low-density vuggy granite. A linear fit to the data (solid line in Figure 4-1) was used to calibrate the density logs performed by Rambøll. An examination of data for the percussion drilled part of KFM03A did however show that the density was underestimated by around 3%. The data were corrected for this difference. The accuracy of the fit, excluding the three points above, is better than 30 kg/m^3. This number indicates the absolute accuracy of the density log data.

A similar plot between the susceptibility logging and susceptibility measured on core samples is shown in Figure 4-2. There is an excellent correlation between logging and petrophysical data, the slope of the fitted line is however 0.662, which indicates that the logging measurements underestimate the true magnetic susceptibility. The fit was used to calibrate the logging data. The accuracy of the fit is around 10^{-3} SI.

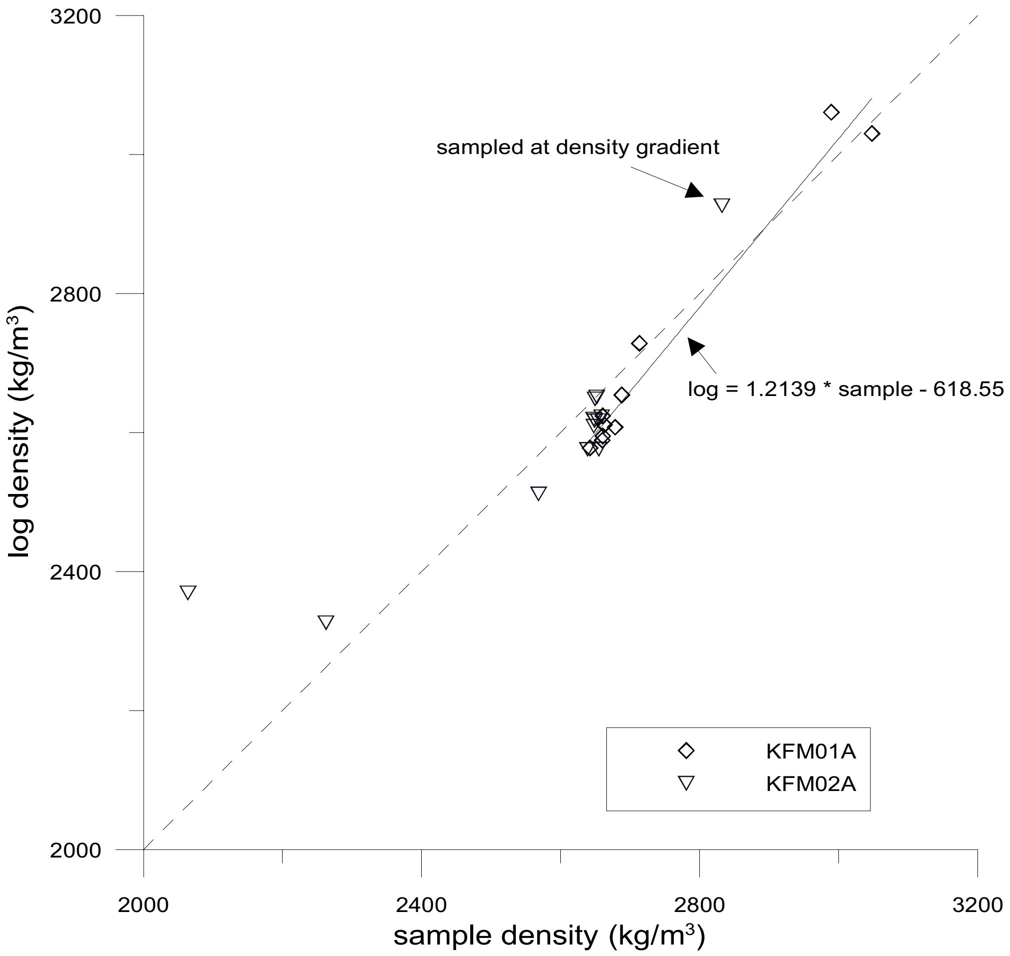


Figure 4-1. *Cross plot of density logging data versus density data from core samples.*

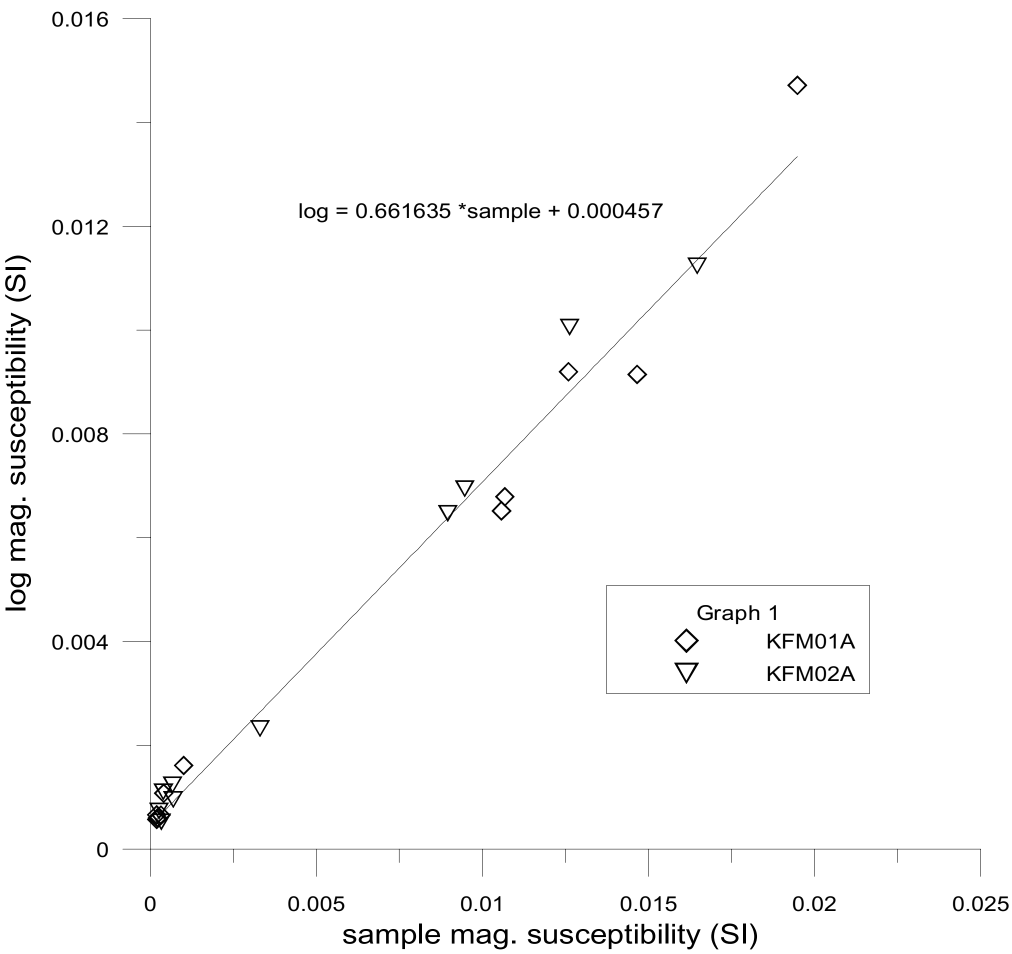


Figure 4-2. *Cross plot of magnetic susceptibility logging data versus susceptibility data from core samples.*

4.2 Interpretation of the logging data

The interpretation logs presented in this report are:

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

4.2.1 Interpretation of KFM02A

The results of the generalized data and fracture estimations for the borehole KFM02A are presented in Appendix 1 and Appendix 2. A version (100–1000 m) in less detailed scale can be seen in Figure 4-4. The percussion drilled upper 100 m were logged by Malå GeoScience whereas the core drilled deeper part of the hole was logged by Rambøll. This should be kept in mind if comparisons are made, although the generalized logs should be more or less independent on actual logging methods used. It should also be noted that the density log of Malå GeoScience has been difficult to calibrate.

Vertical temperature gradient and salinity

The median vertical temperature gradient in KFM02A is 11.5 °C/km. A few anomalies are seen at depths ca 178, 280, 296, 424, 517, 805, 870 and 946 m (Figure 4-3). These anomalies are likely to correspond to water bearing fractures although the exact location of the fracture might be difficult to determine. A long section between 540 to 790 m depth is notably free of temperature anomalies.

A residual temperature where a gradient of 11.5 °C/km has been subtracted is also shown in Figure 4-3.

The estimated salinity varies between 6100 and 9800 ppm NaCl (Figure 4-3). Breaks in the salinity plot that might correspond to water bearing fractures can be seen at 291, 417, 516, 897 and 930 m depth. The exact depth of the corresponding fractures is however difficult to determine. It should be noted that borehole temperature and salinity might be affected by non-equilibrium with the surrounding rock at the time of logging.

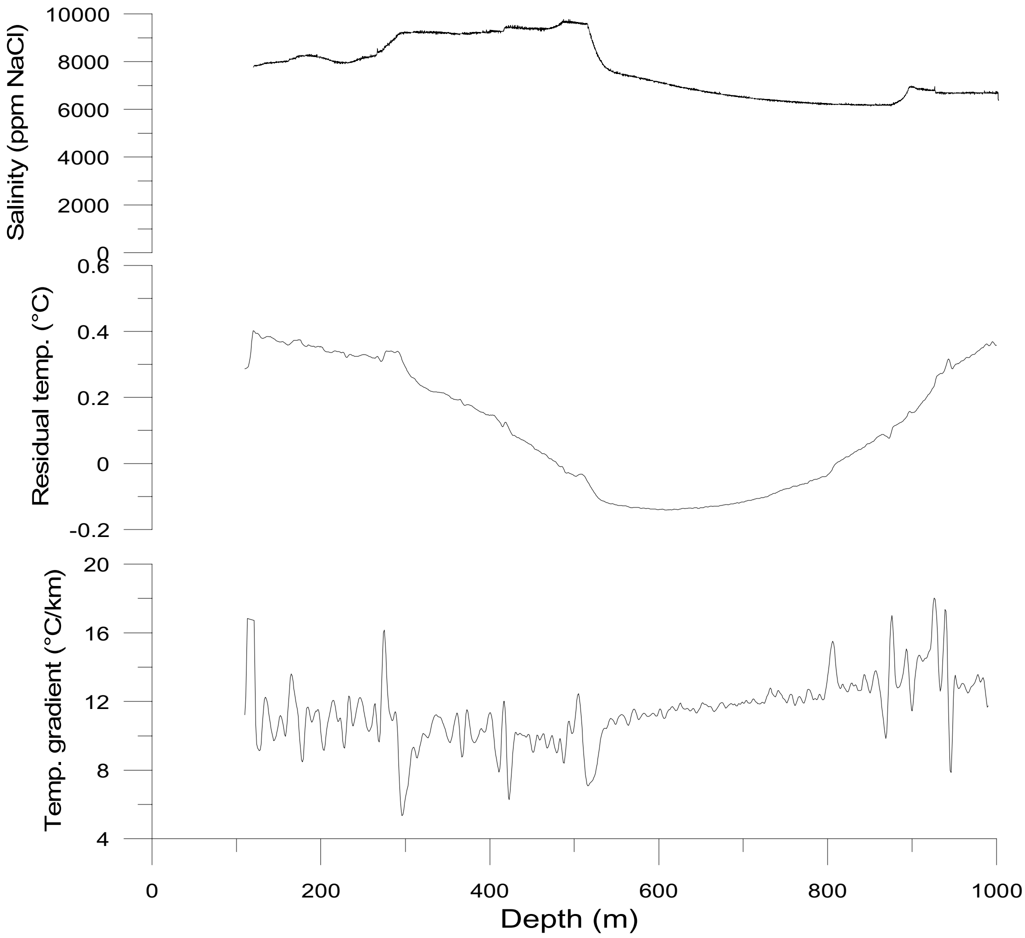


Figure 4-3. *Estimated salinity (top), fluid temperature minus median gradient (centre) and vertical temperature gradient (bottom) for KFM02A.*

Interpretation of lithology and fractures

A majority of the rocks along the borehole have silicate densities indicating a mineral composition that corresponds to granitic rocks. 87% of the borehole length (cored part) is classified as "granite" and 8.7% of the length is classified as "diorite" or "gabbro". Apart from a section between 904 and 939 m depth the high density rocks occur along short sections, most commonly above 240 m and below 800 m depth.

The natural gamma radiation generally varies between 23 μR/h and 31 μR/h. The data have been classified into "low", "normal", "high" and "very high" radiation by setting threshold values at 20.5, 36.3 and 52.8 μR/h respectively. Low radiation generally coincides with high density rocks. High and very high radiation occur as short sections probably corresponding to pegmatite veins at irregular intervals along the hole, but also at longer intervals at 172 to 197 and 482 to 516 m depth.

The magnetic susceptibility log has been classified into decades with threshold values of 0.001, 0.01 and 0.1 SI. The susceptibility takes values of the two intermediate classes for most of the borehole length. Low susceptibility however dominates from 95 to 313 m and from 460 to 520 m depth, most likely due to oxidation of magnetite. The high density rocks also have low susceptibility.

The geophysical logs indicate that the fracture frequency along KFM02A is generally very low (Figure 4-4). An exception is between 410 and 515 m depth. Increased fracture frequency is also inferred at 80 to 95 m, 110 to 130 m, 160 to 175 m and 265 to 280 m depth. The apparent fracture frequency is higher than the actual fracture frequency where the vuggy granite occurs since geophysical anomalies become very strong in this type of rock. The vuggy granite has low resistivity and P-wave velocity. The sections with increased apparent fracture frequency also have low magnetic susceptibility except between 410 and 460 m depth where the magnetic susceptibility takes normal to high values. Thin fractures indicated by prominent resistivity and caliper anomalies occur in the upper part of the borehole but have not affected the magnetic susceptibility significantly.

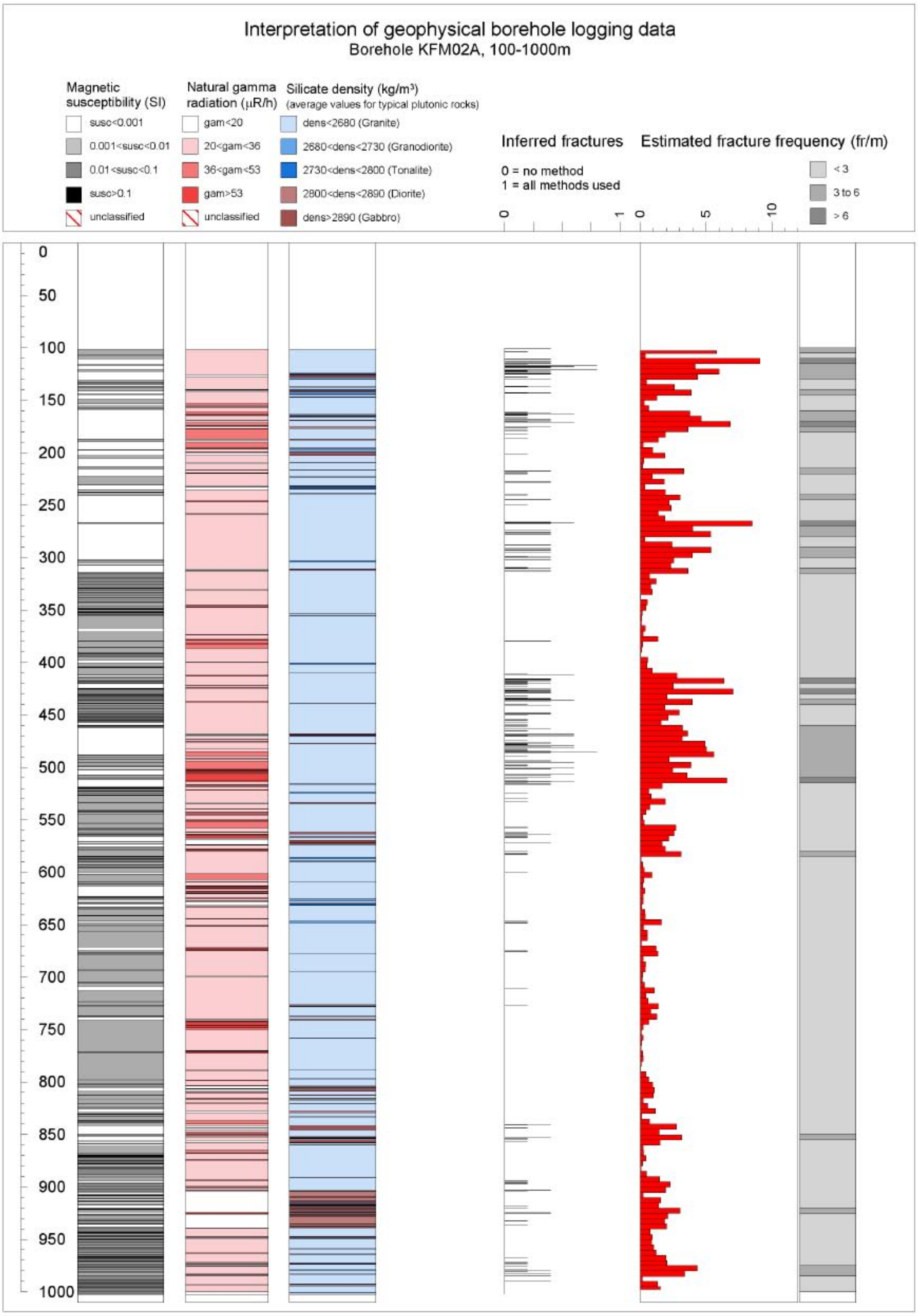


Figure 4-4. Generalized geophysical logs for KFM02A. The same logs, in a less compressed scale, can be seen in Appendix 2.

4.2.2 Interpretation of HFM04 and HFM05

The results of the generalized data and fracture estimations for the boreholes HFM04 and HFM05 are presented in Figure 4-7 and 4-8.

Vertical temperature gradient and salinity

The vertical temperature gradient and the estimated salinity for HFM04 and HFM05 can be seen in Figures 4-5 and 4-6. Temperature anomalies that indicate water bearing fractures can be seen at 63, 123, 139, 166 and 187 m depth in HFM04 and at 106 and 156 m depth in HFM05. Breaks in the salinity curve indicating water flow can be seen at 63, 166 and 185 m depth in HFM04. Minima in the salinity plot, indicating inflow of meteoric water, can be seen at 112 and 132 m depth in HFM05.

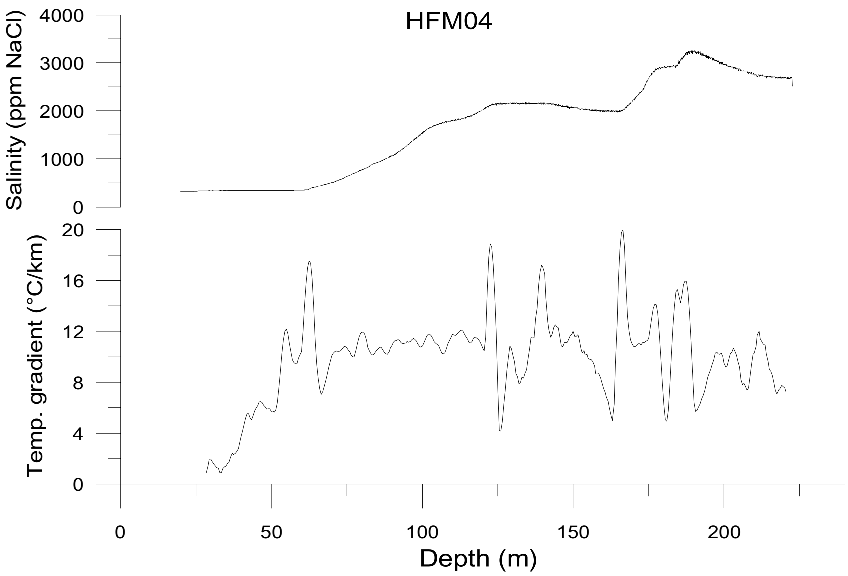


Figure 4-5. *Estimated salinity (top) and vertical temperature gradient (bottom) for HFM04.*

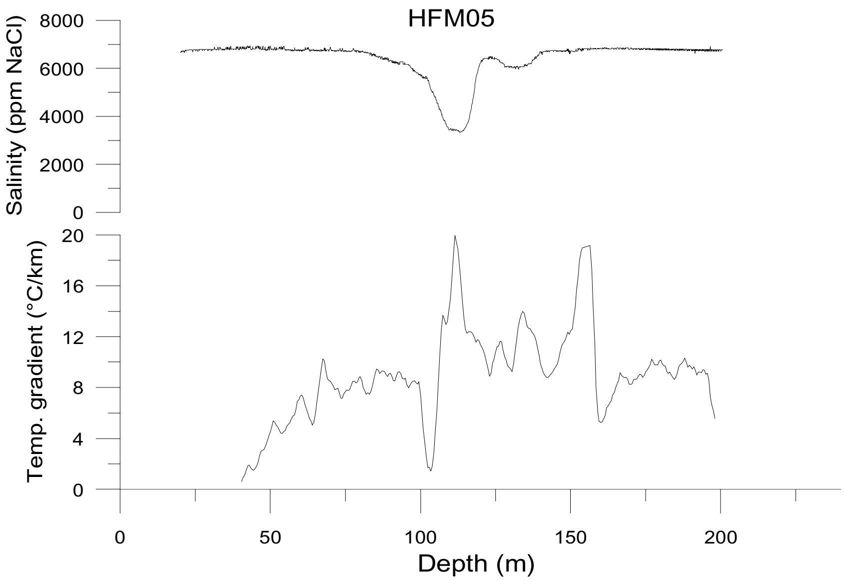


Figure 4-6. *Estimated salinity (top) and vertical temperature gradient (bottom) for HFM05.*

Interpretation of rock types and fractures

The rocks intersected by HFM04 and HFM05 seem to have similar petrophysical properties as those found in the nearby cored borehole KFM02A. Rocks with a silicate density corresponding to a granite composition seem to dominate, although it should be kept in mind that the density log used in these holes has been difficult to calibrate. The density seems to increase slightly at around 90 m depth in HFM04 with a corresponding decrease in natural gamma radiation. The differences are however too small to be clearly visible in the generalized logs in Figure 4-7. The natural gamma radiation is higher in HFM05 than in the other holes, alternating between “normal” and “high”. High radiation values usually coincide with low magnetic susceptibility. Low magnetic susceptibility can also be seen between 130 and 155 m depth in HFM04. The major fractures do not seem to have influenced the magnetic susceptibility except quite close to the fractures.

No continuous section with increased fracture frequency can be seen in HFM04 or HFM05. Instead, the holes seem to be characterized by distinct geophysical anomalies indicating narrow and possibly water bearing fracture zones at 63, 79 and 187 m (HFM04) and 107, 155 and 183 m (HFM05).

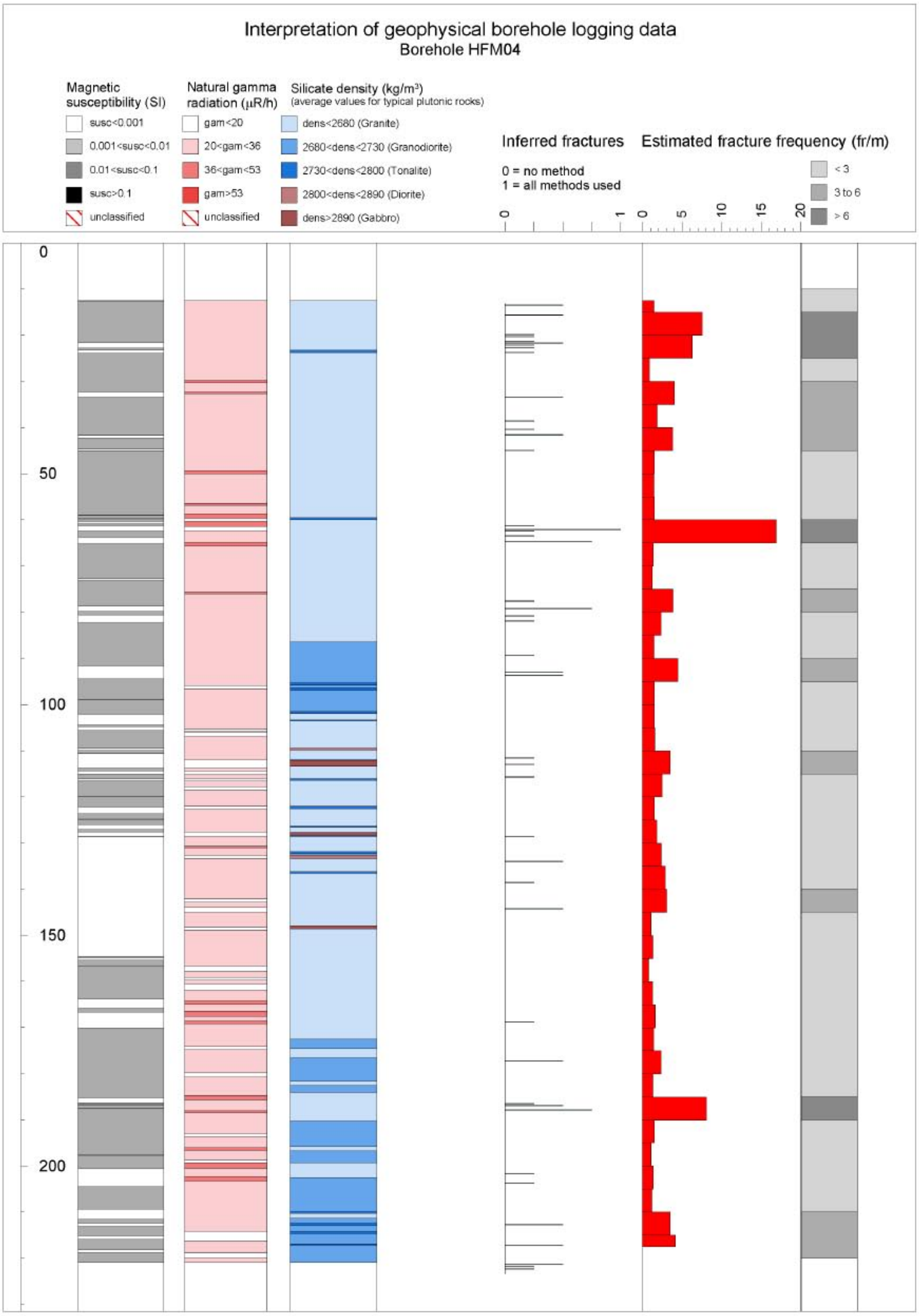


Figure 4-7. Generalized data and fracture estimations for borehole HFM04.

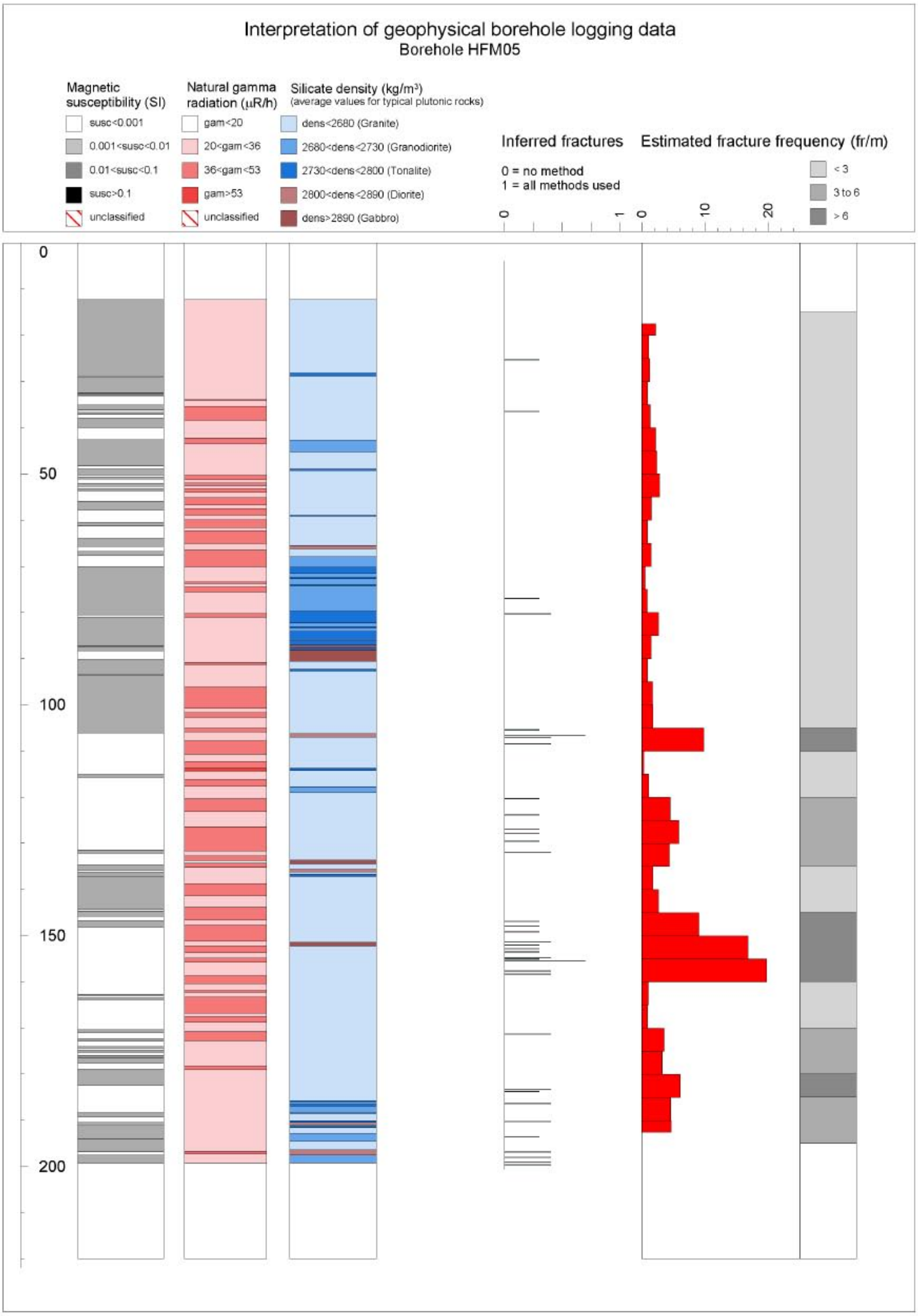


Figure 4-8. Generalized data and fracture estimations for borehole HFM05.

4.2.3 Interpretation of KFM03A

The results of the generalized data and fracture estimations for the borehole KFM03A are presented in Appendix 3. A version in less detailed scale can be seen in Figure 4-10. Both the percussion drilled upper 100 m and the core drilled deeper part of the hole was logged by Rambøll /1/. Sonic data for the percussion drilled upper 100 m were partly of poor quality and have not been used in the interpretation.

Vertical temperature gradient and salinity

The median vertical temperature gradient in KFM03A is 11.7 °C/km. A few anomalies are seen at depths of ca 394, 454, 644, 777 and 943 m (Figure 4-9). These anomalies are likely to correspond to water bearing fractures although the exact location of the fracture might be difficult to determine.

A residual temperature where a gradient of 11.7 °C/km has been subtracted is also shown in Figure 4-9.

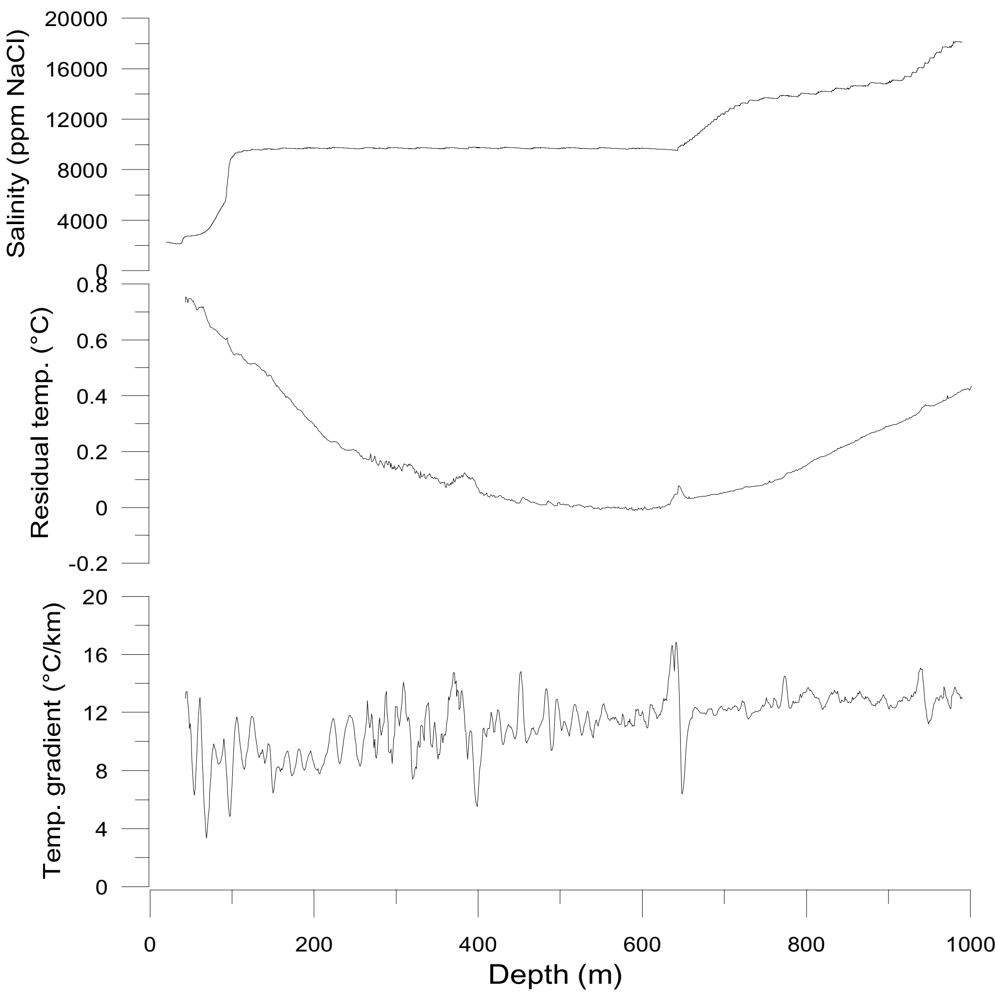


***Figure 4-9.** Estimated salinity (top), fluid temperature minus median gradient (centre) and vertical temperature gradient (bottom) for KFM03A.*

The estimated salinity is around 2000 ppm NaCl in the uppermost part of KFM03A and increases rapidly to 9700 ppm at 100 m depth. The salinity is then stable until 644 m depth and a further increase to 18000 ppm can be seen in the deepest part of the hole (Figure 4-9). Breaks in the salinity plot that might correspond to water bearing fractures can be seen at 39 and 644 m depth. The exact depth of the corresponding fractures is however difficult to determine. It should be noted that borehole temperature and salinity might be affected by non-equilibrium with the surrounding rock at the time of logging.

Interpretation of lithology and fractures

A majority of the rocks along the borehole have silicate densities indicating a mineral composition that corresponds to granitic rocks. 81% of the borehole length is classified as "granite" and 6.0% of the length is classified as "tonalite" and 7.3% as "diorite". The rock between 220 and 250 m depth has a silicate density corresponding to tonalite and between 285 to 350 m to tonalite/diorite. Minor occurrences of high density rock can be found at irregular intervals along the hole.

The natural gamma radiation generally varies between 20 μR/h and 25 μR/h which is slightly lower than in KFM02A. The data have been classified into "low", "normal", "high" and "very high" radiation by setting threshold values at 20.5, 36.3 and 52.8 μR/h respectively. Low radiation generally coincides with high density rocks. High and very high radiation occur as short sections probably corresponding to pegmatite veins at irregular intervals along the hole. No long continuous intervals with high gamma radiation can be found in 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 takes values of the two intermediate classes for most of the borehole length with silicate densities corresponding to granite. Low susceptibility however dominates the tonalite- and tonalite/diorite-density sections mentioned above.

The geophysical logs indicate that the fracture frequency along KFM03A in general is very low (Figure 4-10). Only a few 5 m-sections have inferred fracture frequencies of more than 6 fractures/m. Increased fracture frequency is inferred at 35 to 42 m, 100 to 135 m, 355 to 415 m and 790 to 815 m depth. Pronounced sonic and resistivity anomalies are correlated with high density (possibly amphibolite) and/or high radiation (possibly pegmatite) anomalies. The magnetic susceptibility of the host rock seems to be affected only close to the inferred fractures.

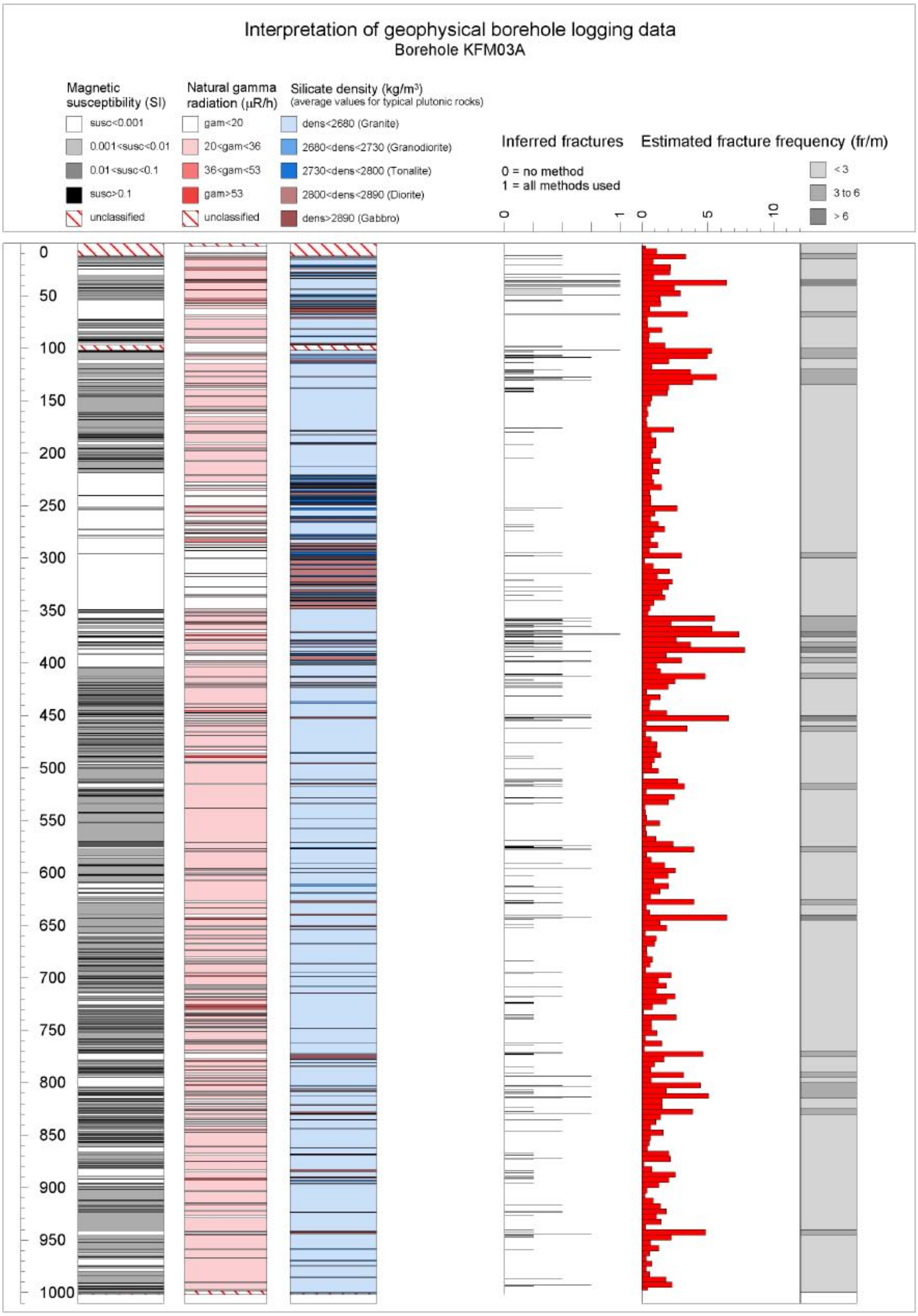


Figure 4-10. Estimated fracture frequency, based on geophysical logs, for KFM03A.

4.2.4 Interpretation of KFM03B

The results of the generalized data and fracture estimations for the borehole KFM03B, which is a short cored hole close to KFM03A, are presented in Figure 4-12.

Vertical temperature gradient and salinity

The vertical temperature gradient and the estimated salinity for KFM03B can be seen in Figure 4-11. The temperature gradient data have a somewhat peculiar appearance which might be an effect of a non-equilibrium situation relative the surrounding rock. Temperature anomalies that indicate water bearing fractures can still be seen at 31, 39 and 65 m depth in KFM03B. Breaks in the salinity curve indicating water flow can be seen at 50 and 65 m depth.

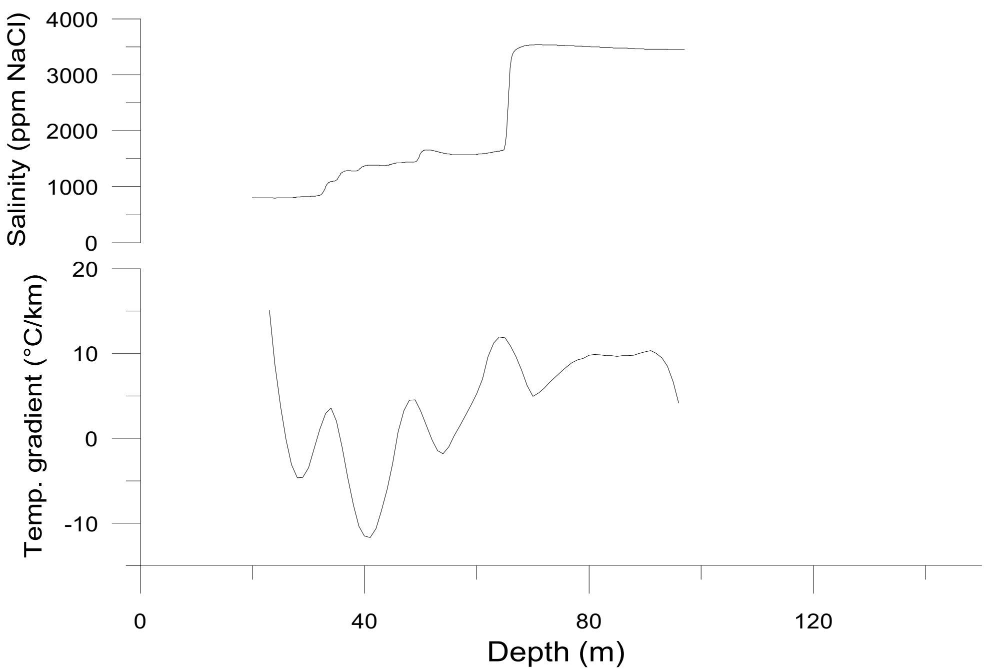


Figure 4-11. *Estimated salinity (top) and vertical temperature gradient (bottom) for KFM03B.*

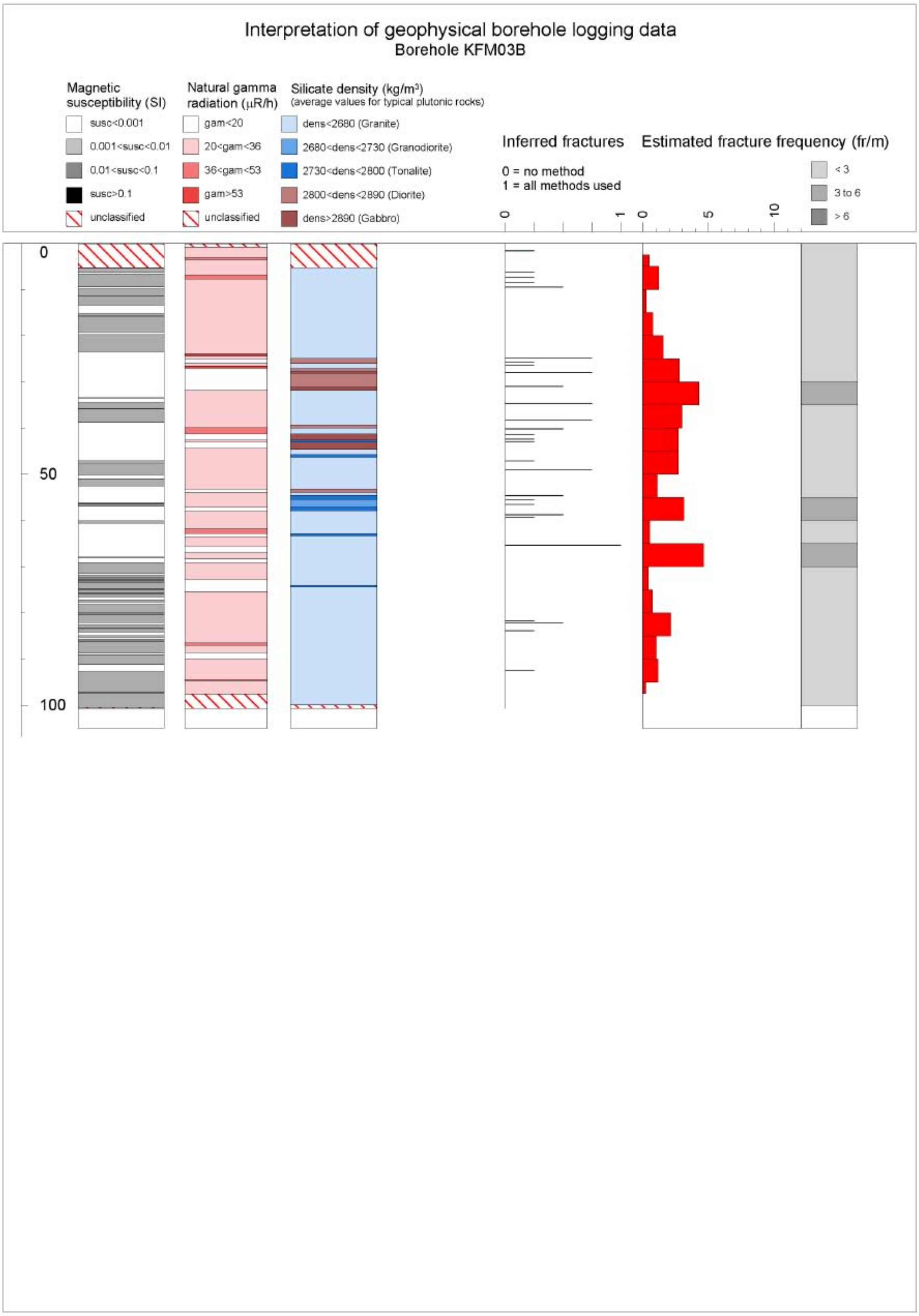


Figure 4-12. Estimated fracture frequency, based on geophysical logs, for KFM03B.

Interpretation of rock types and fractures

The distance between KFM03B and KFM03A is quite short and the rocks seem to have very similar petrophysical properties. Histograms of silicate density, natural gamma radiation and magnetic susceptibility for both holes (above 100 m depth) can be seen in Figure 4-13. The similarity in distributions between the two holes indicates that the difference in borehole diameter has not affected the measurements significantly, except for the correction of the density of 3%. It should however be noted that the comparison of magnetic susceptibility data is not conclusive due to the skewness of histogram.

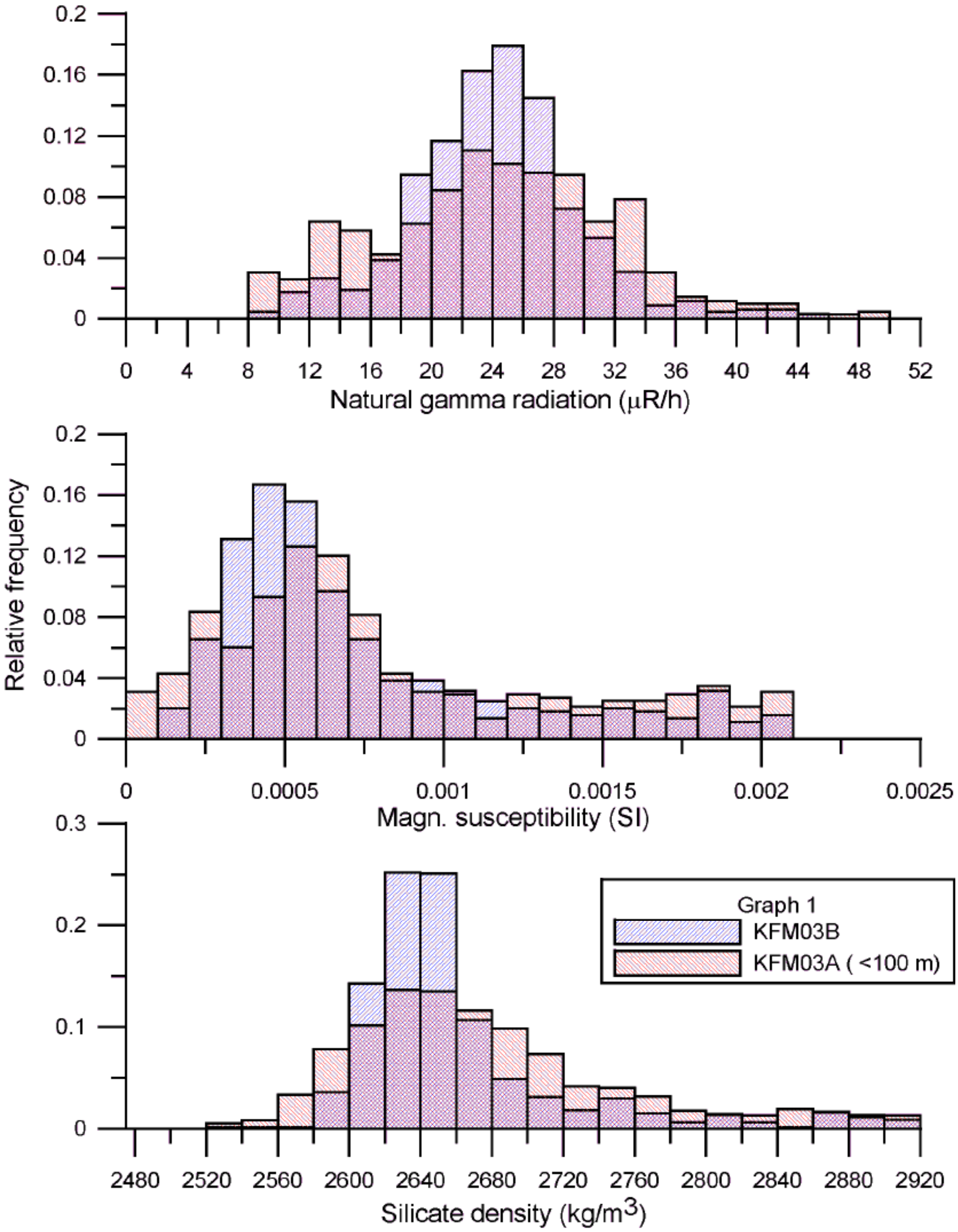


***Figure 4-13.** Histograms showing the distribution of natural gamma radiation, magnetic susceptibility and silicate density for KFM03A and KFM03B. The holes are located very close to each other but KFM03A is percussion drilled whereas KFM03B is core drilled. The diameter of KFM03A is thus considerably larger.*

Rocks with a silicate density corresponding to a granite composition dominate. Short sections with high density rocks occur and also short sections with high natural gamma radiation. The spatial correlation with similar anomalies in KFM03A is not clear, indicating an irregular spatial distribution of different rock types. The magnetic susceptibility has low values for the high density rocks and predominantly values between 0.001 and 0.01 SI for the granite-density rocks.

A number of fractures are inferred by the geophysical logs between 24 and 40 m depth. A distinct anomaly can also be seen at 65 m. The positions of inferred fractures correlate very well to KFM03A.

4.2.5 Interpretation of HFM06, HFM07 and HFM08

The results of the generalized data and fracture estimations for the boreholes HFM06, HFM07 and HFM08 are presented in Figure 4-17 to 4-19.

Vertical temperature gradient and salinity

The vertical temperature gradient and the estimated salinity for HFM06, HFM07 and HFM08 can be seen in Figure 4-14 to 4-16. Temperature anomalies that indicate water bearing fractures can be seen at 45, 54, 64, 71 and 77 m depth in HFM06, at 60 and 70 m in HFM07 and at 76, 119 and 140 m depth in HFM08. Breaks in the salinity curve indicating water flow can be seen at 71 m depth in HFM06, 60 m in HFM07 and 95 and 122 m in HFM08. It should be noted that borehole temperature and salinity might be affected by non-equilibrium with the surrounding rock at the time of logging.

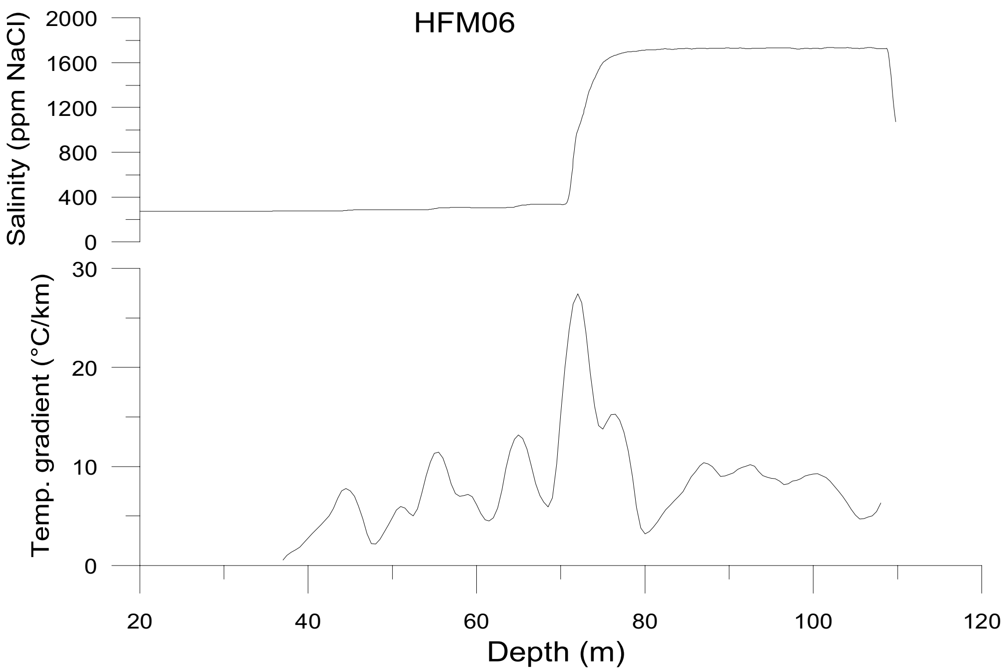


Figure 4-14. *Estimated salinity (top) and vertical temperature gradient (bottom) for HFM06.*

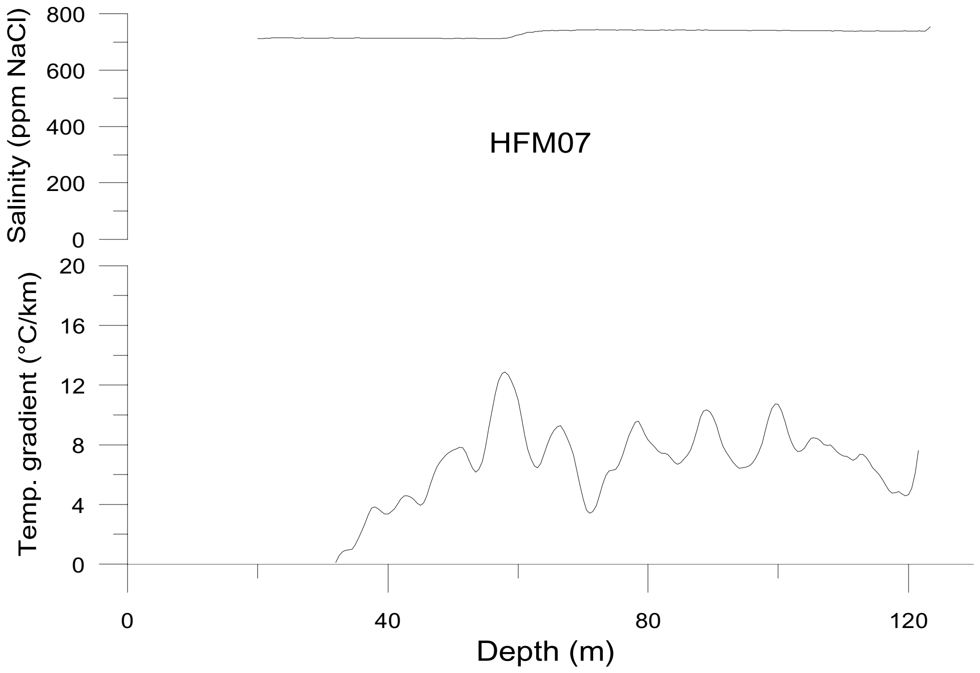


Figure 4-15. *Estimated salinity (top) and vertical temperature gradient (bottom) for HFM07.*

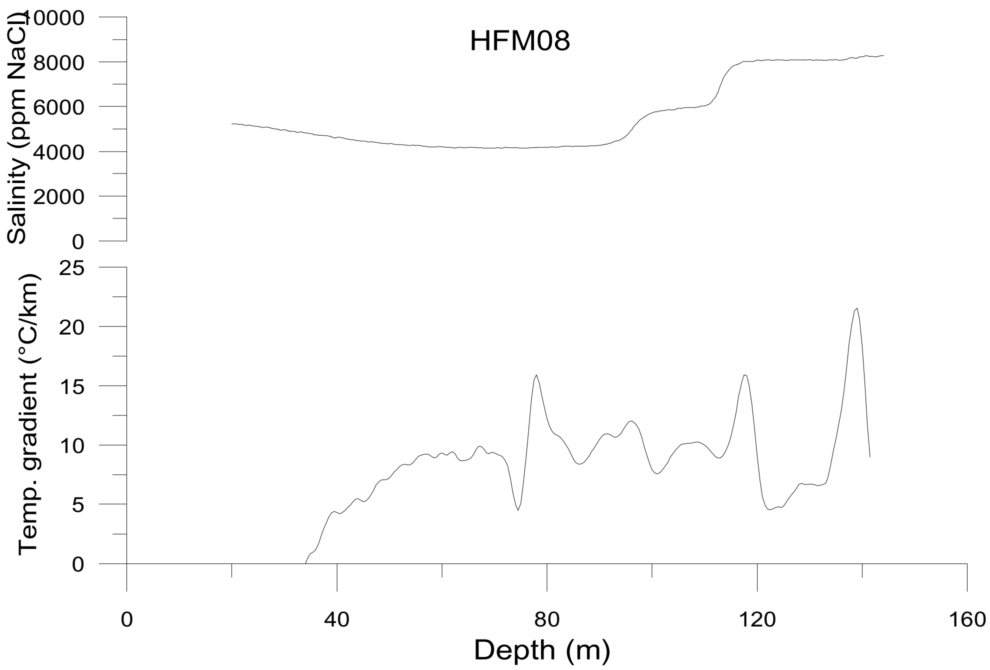


Figure 4-16. *Estimated salinity (top) and vertical temperature gradient (bottom) for HFM08.*

Interpretation of rock types and fractures

The rocks in HFM06, HFM07 and HFM08 seem to have similar petrophysical properties as those found in the cored borehole KFM03A. Rocks with a silicate density corresponding to a granitic composition seem to dominate, although it should be kept in mind that the density log used in these holes has been difficult to calibrate. High density rocks seem to be more common in HFM08 but this might at least partly be due to measurement errors. The natural gamma radiation is higher in HFM08 compared to the other holes. The magnetic susceptibility takes values between 0.001 and 0.01 for most of the rock volume. No section with lower susceptibility is longer than 15 m. The large fractures do not seem to have influenced the magnetic susceptibility except quite close to the fractures.

Several fractures are inferred between 42 and 71 m depth in HFM06. A similar section with inferred fractures can be seen in HFM08 between 120 and 140 m depth. Distinct geophysical anomalies indicating fractures are also seen at 21 m in HFM06, at 57, 67 and 83 m in HFM07 and at 90 m depth in HFM08.

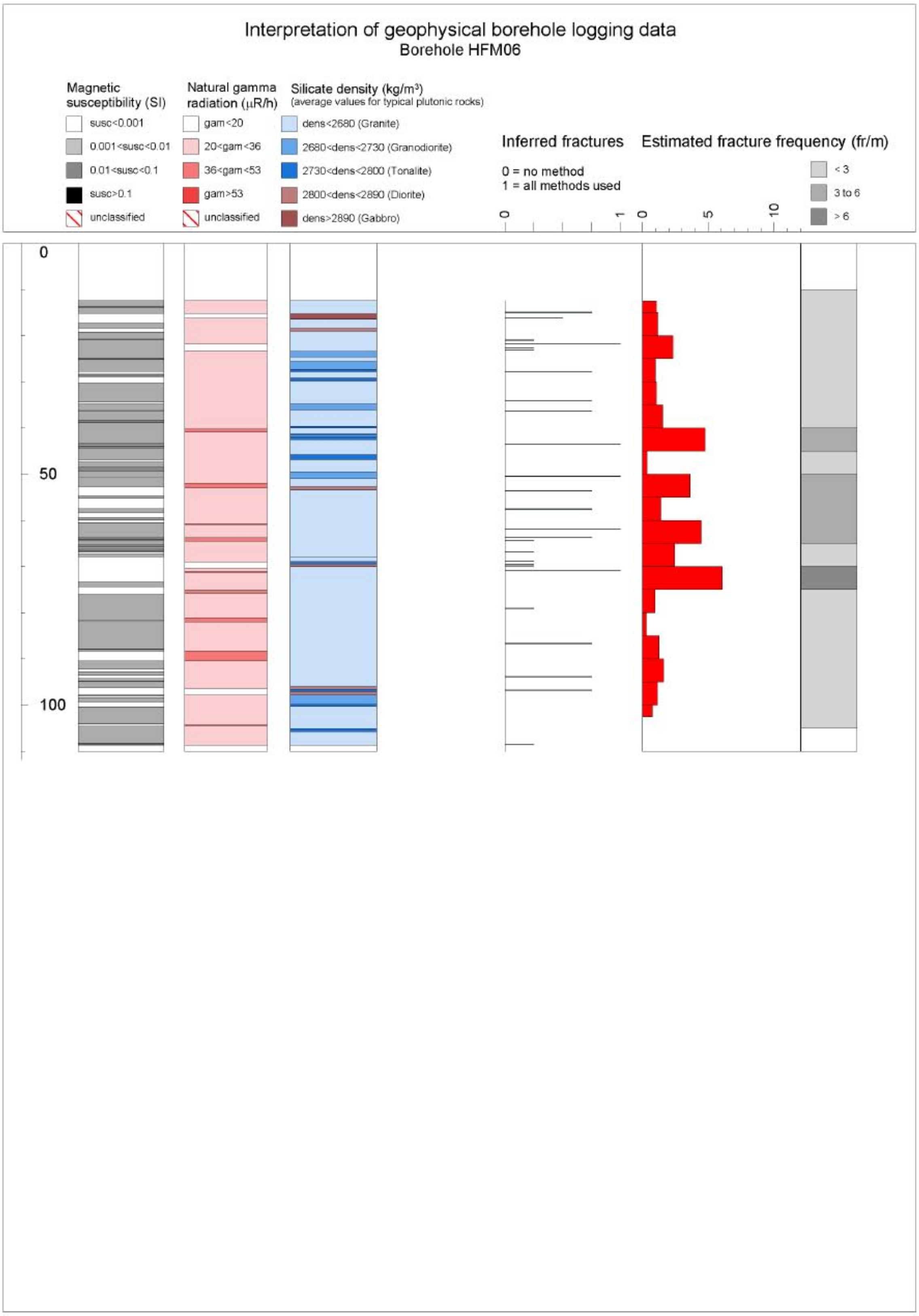


Figure 4-17. Generalized data and fracture estimations for borehole HFM06.

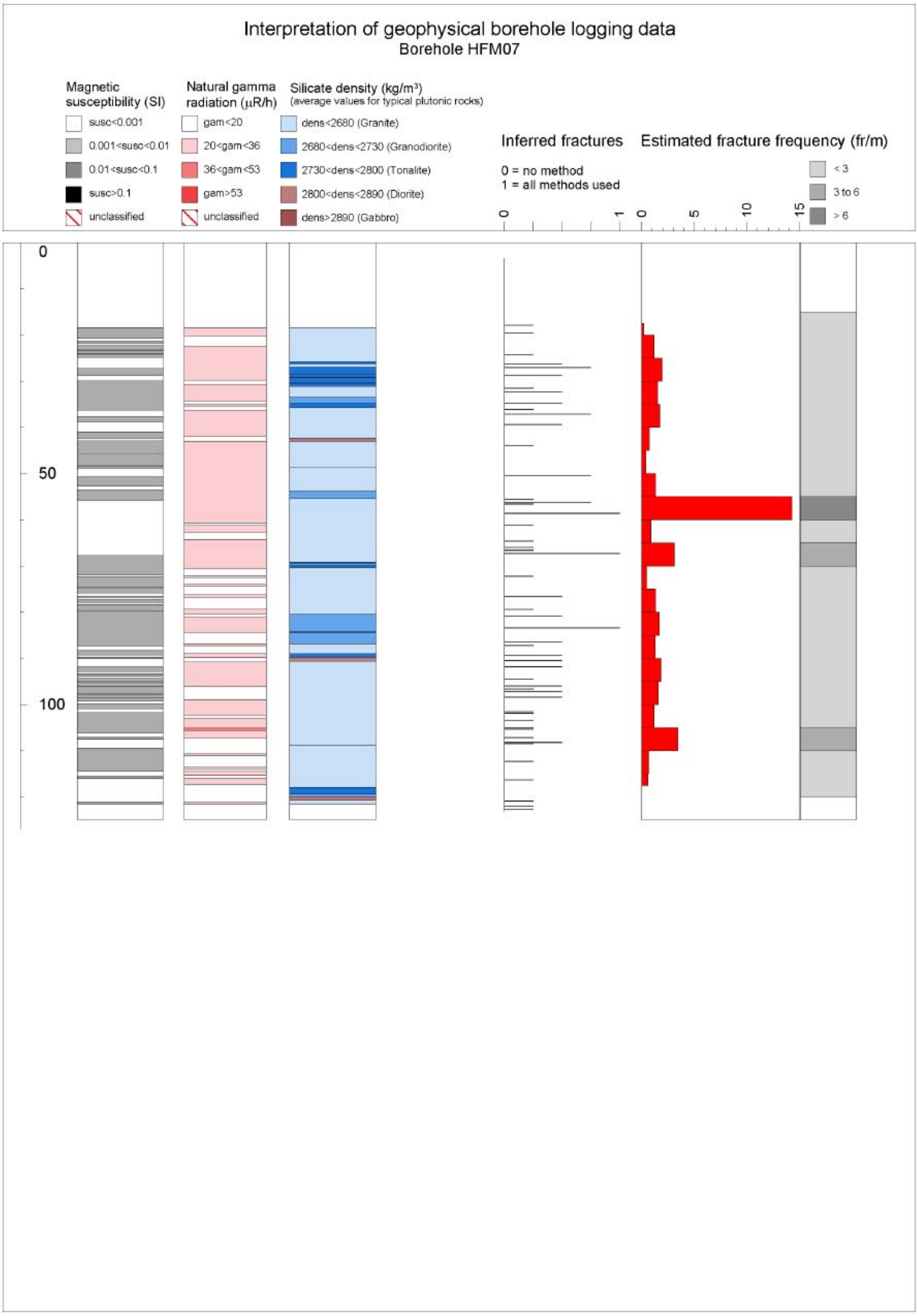


Figure 4-18. *Generalized data and fracture estimations for borehole HFM07.*

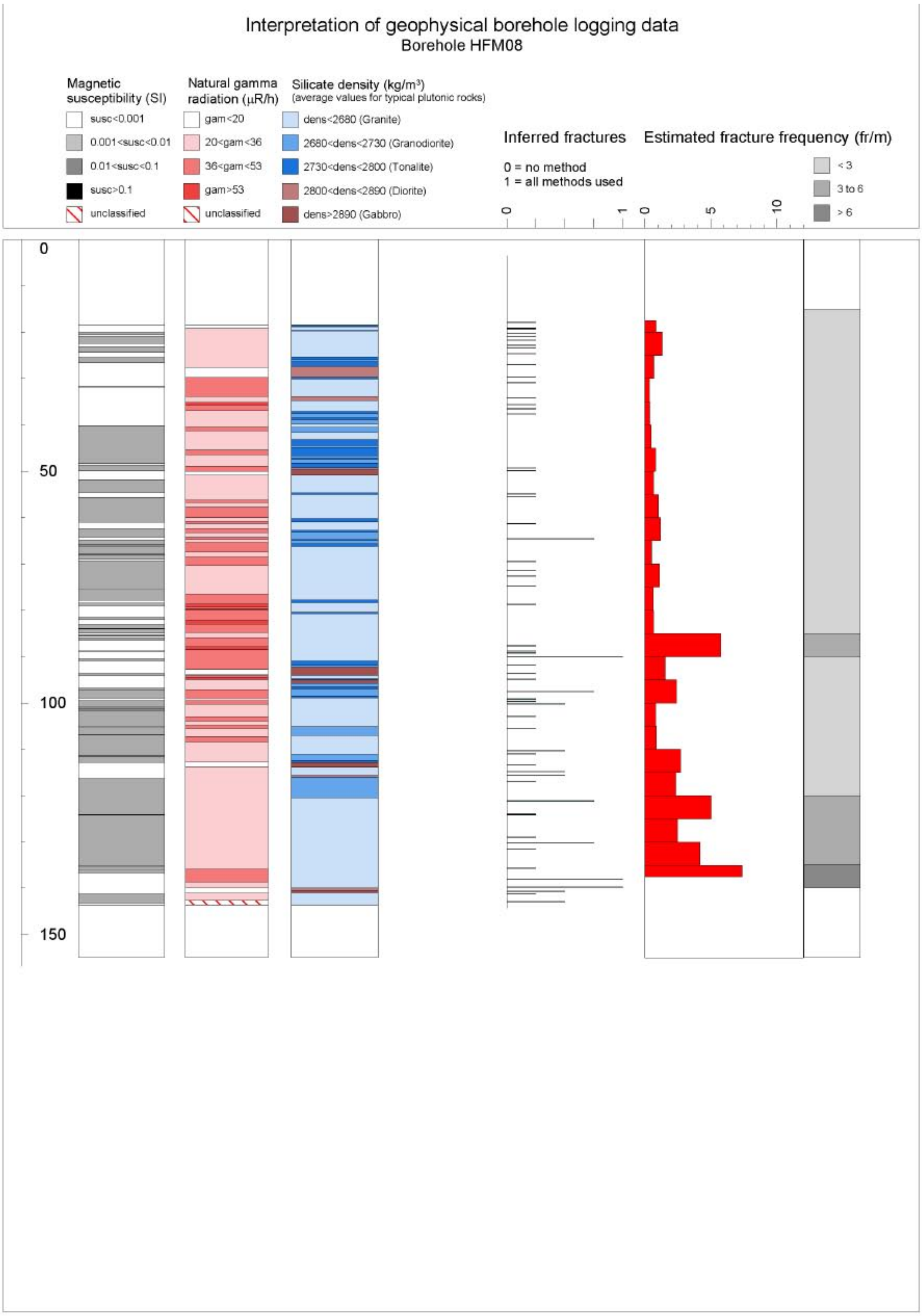


Figure 4-19. Generalized data and fracture estimations for borehole HFM08.

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 Forsmark no 336.

6 References

/1/ **Nielsen U T, Ringgaard J, 2004.** Geophysical borehole logging in borehole KFM02A, KFM03A, KFM03B and HFM07. SKB P-04-98, Svensk Kärnbränslehantering AB.

/2/ **Nilsson P, Aaltonen J, 2003.** Geophysical, radar and BIPS logging in boreholes HFM06, HFM07 and HFM08. SKB P-03-54, Svensk Kärnbränslehantering AB.

/3/ **Thunehed H., 2002.** Uppskattning av sprickfrekvens med hjälp av geofysisk borrhålsloggning. GeoVista AB, GVR02005.

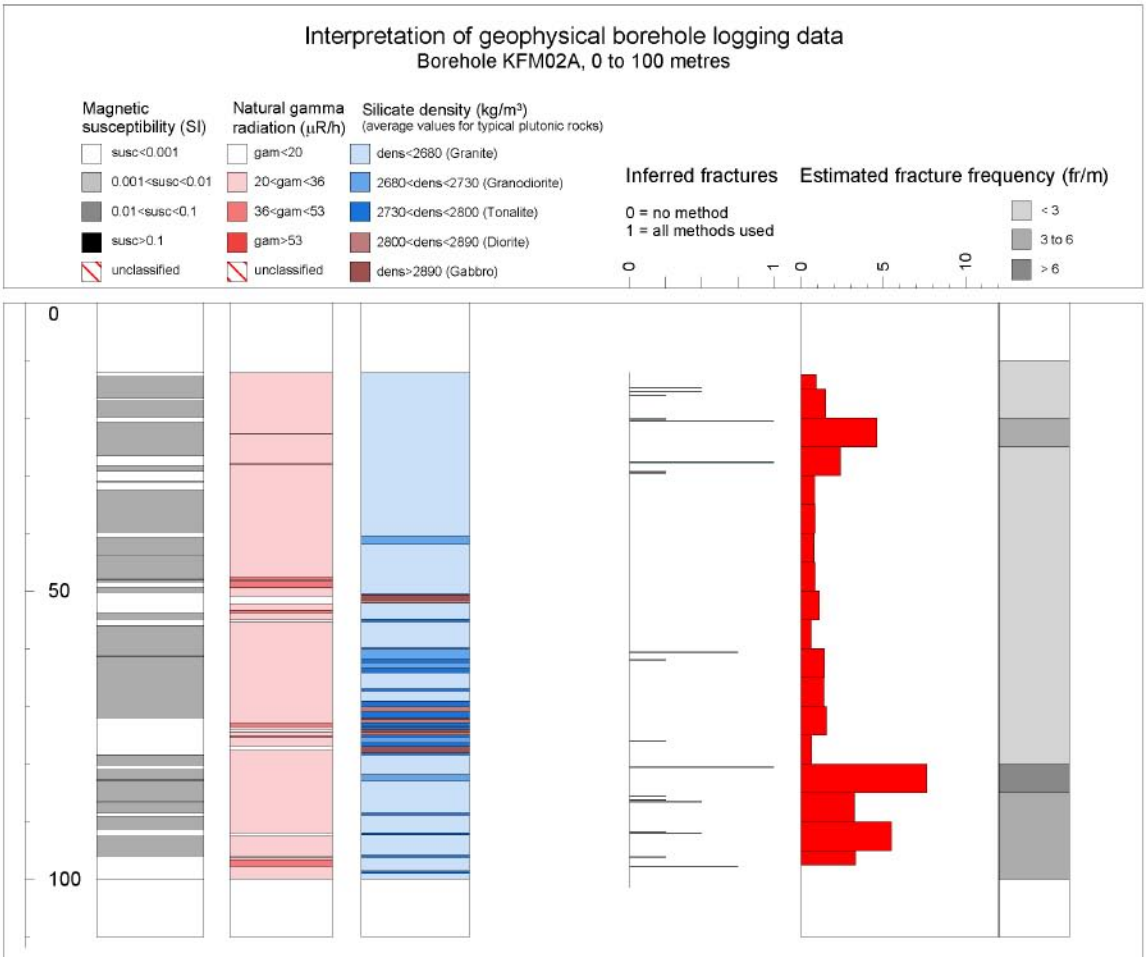
/4/ **Sehlstedt S, 1988.** Description of geophysical data on the SKB data base GEOTAB. SKB TR 88-05, Svensk Kärnbränslehantering AB.

/5/ **Henkel H, 1991.** Petrophysical properties (density and magnetization) of rock from the northern part of the Baltic Shield. Tectonophysics 192, 1–19.

/6/ **Puranen R, 1989.** Susceptibilities, iron and magnetite content of precambrian rocks in Finland. Geological survey of Finland, Report of investigations 90, 45 pp.

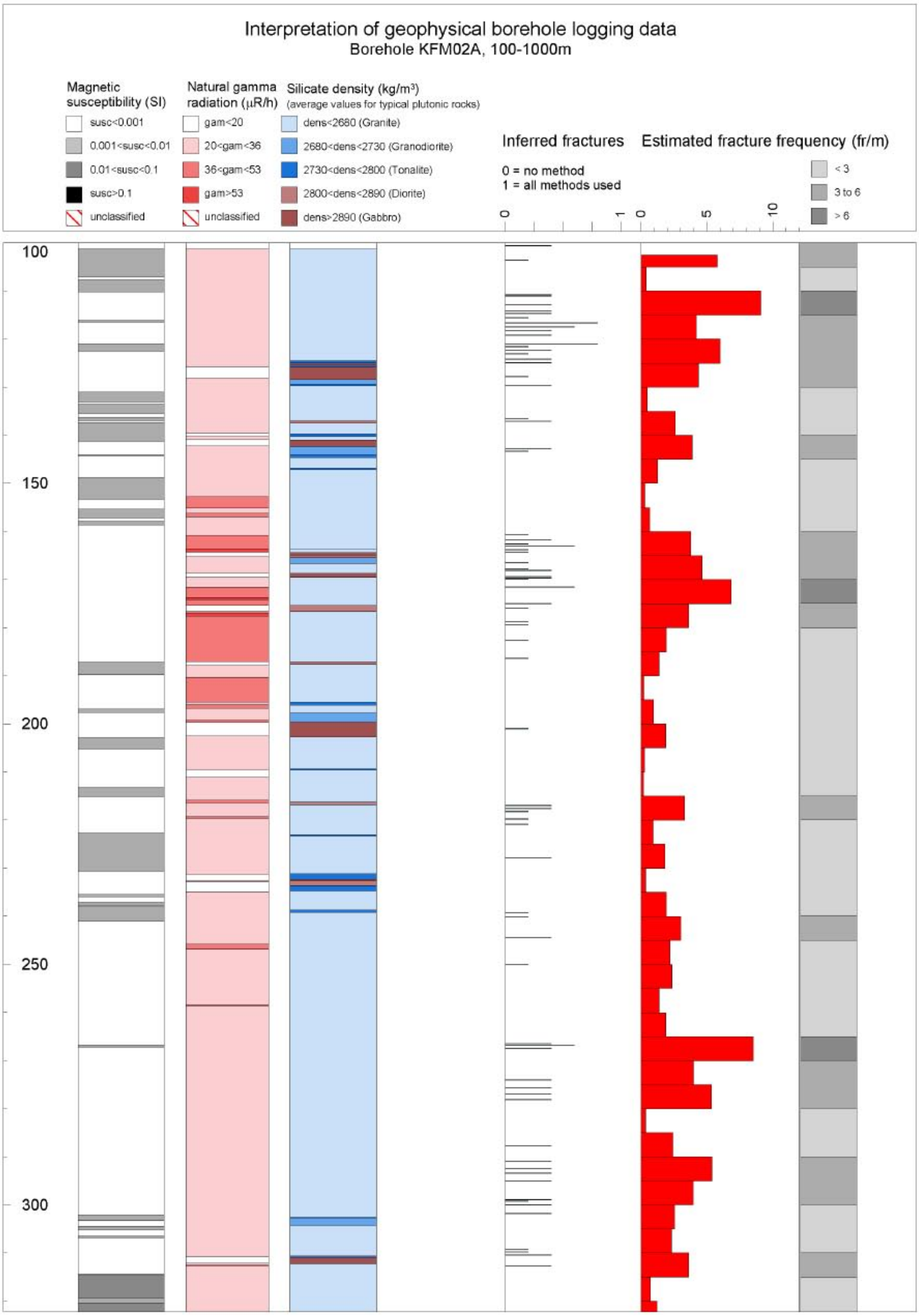
Appendix 1

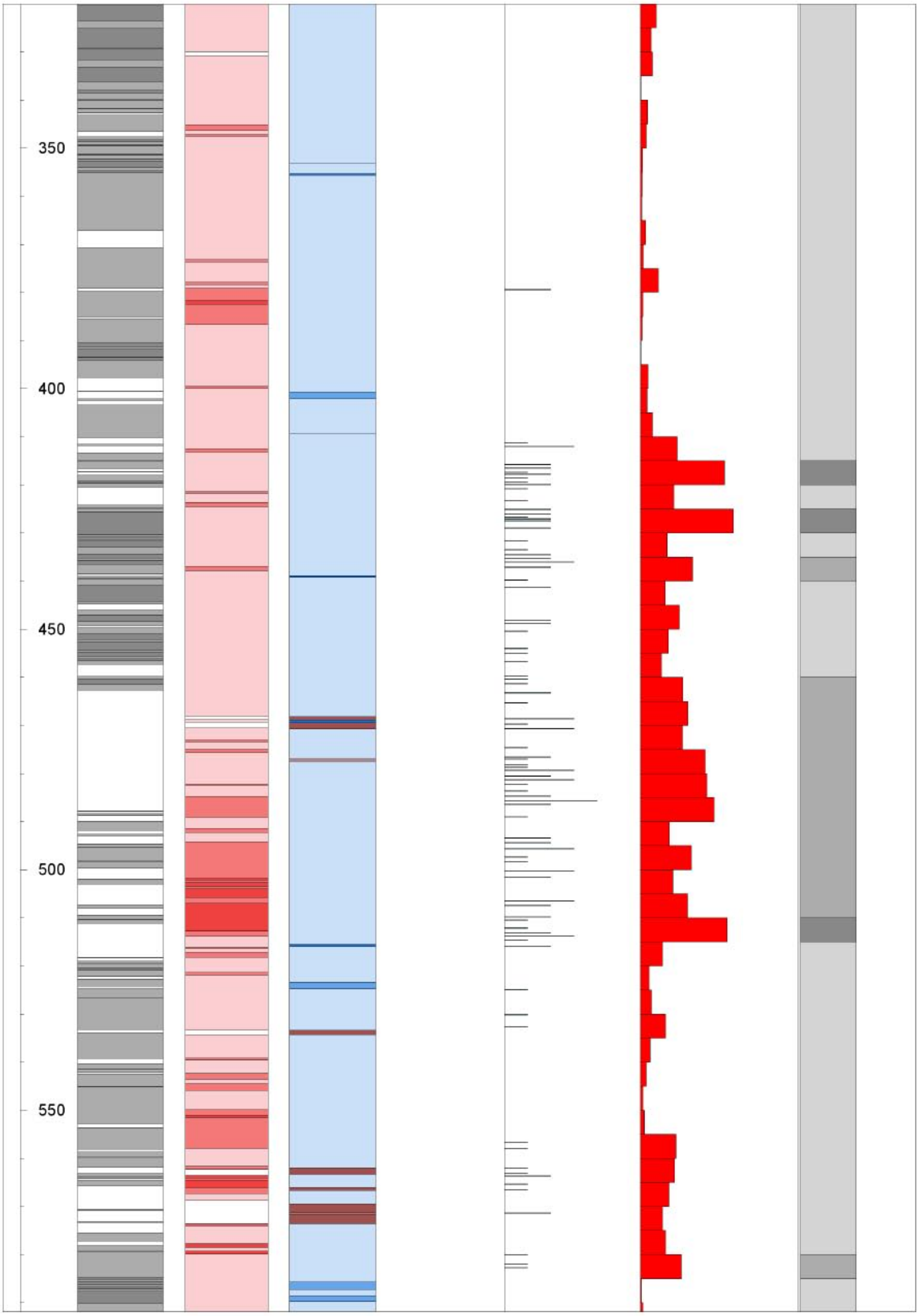
Generalized geophysical logs for the borehole KFM02A (0 to 100 m)



Appendix 2

Generalized geophysical logs for the borehole KFM02A (below 100 m)

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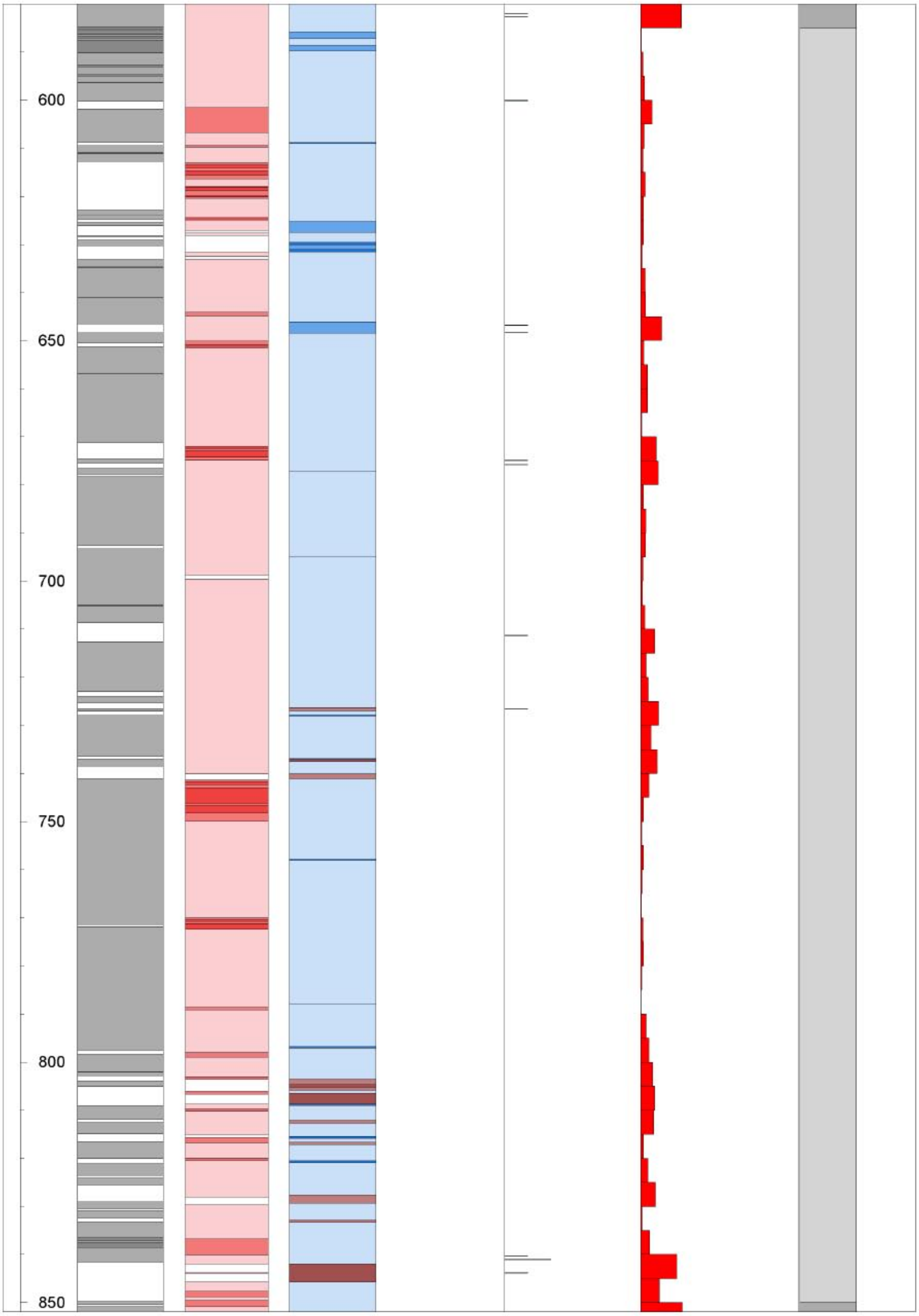
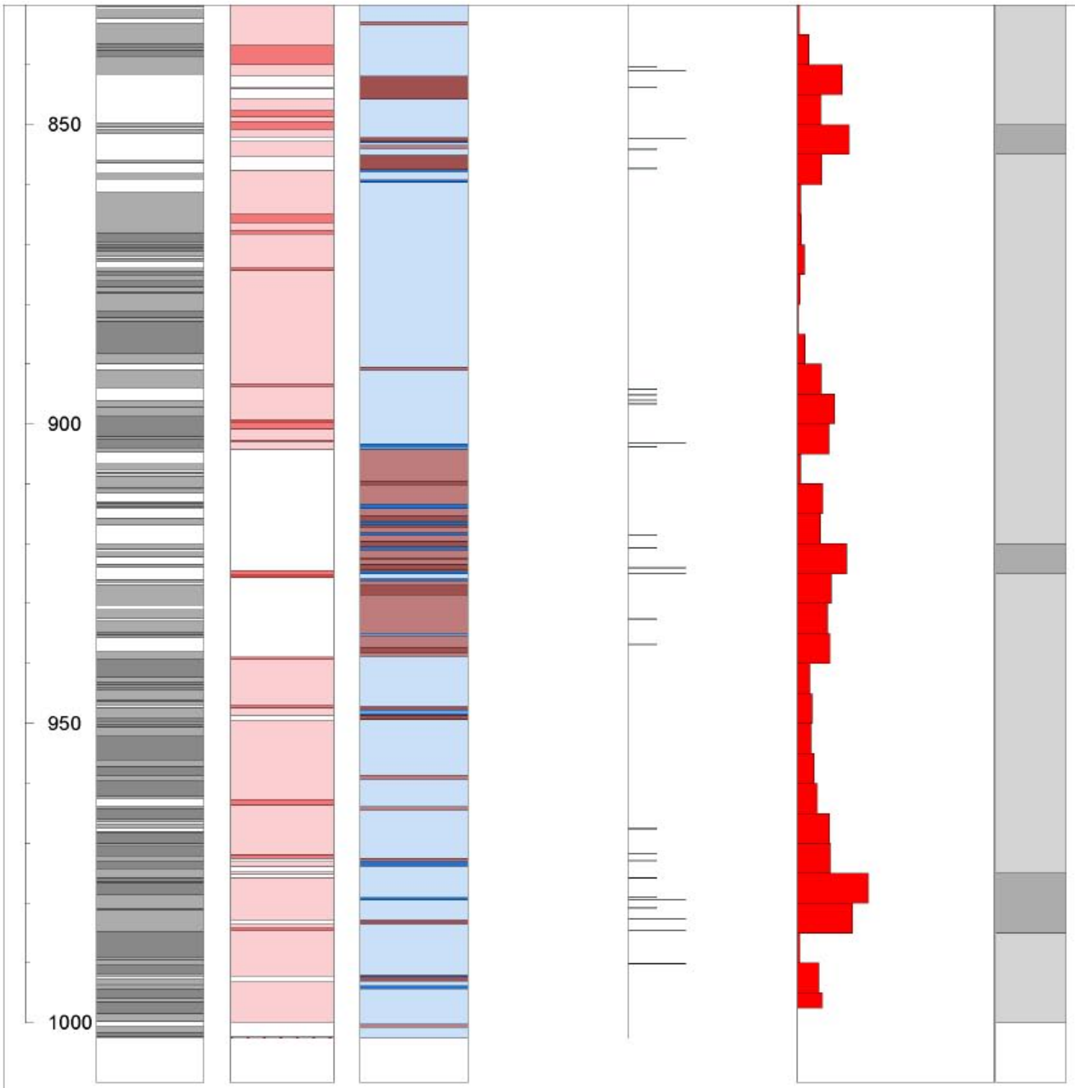
400
450
500
550

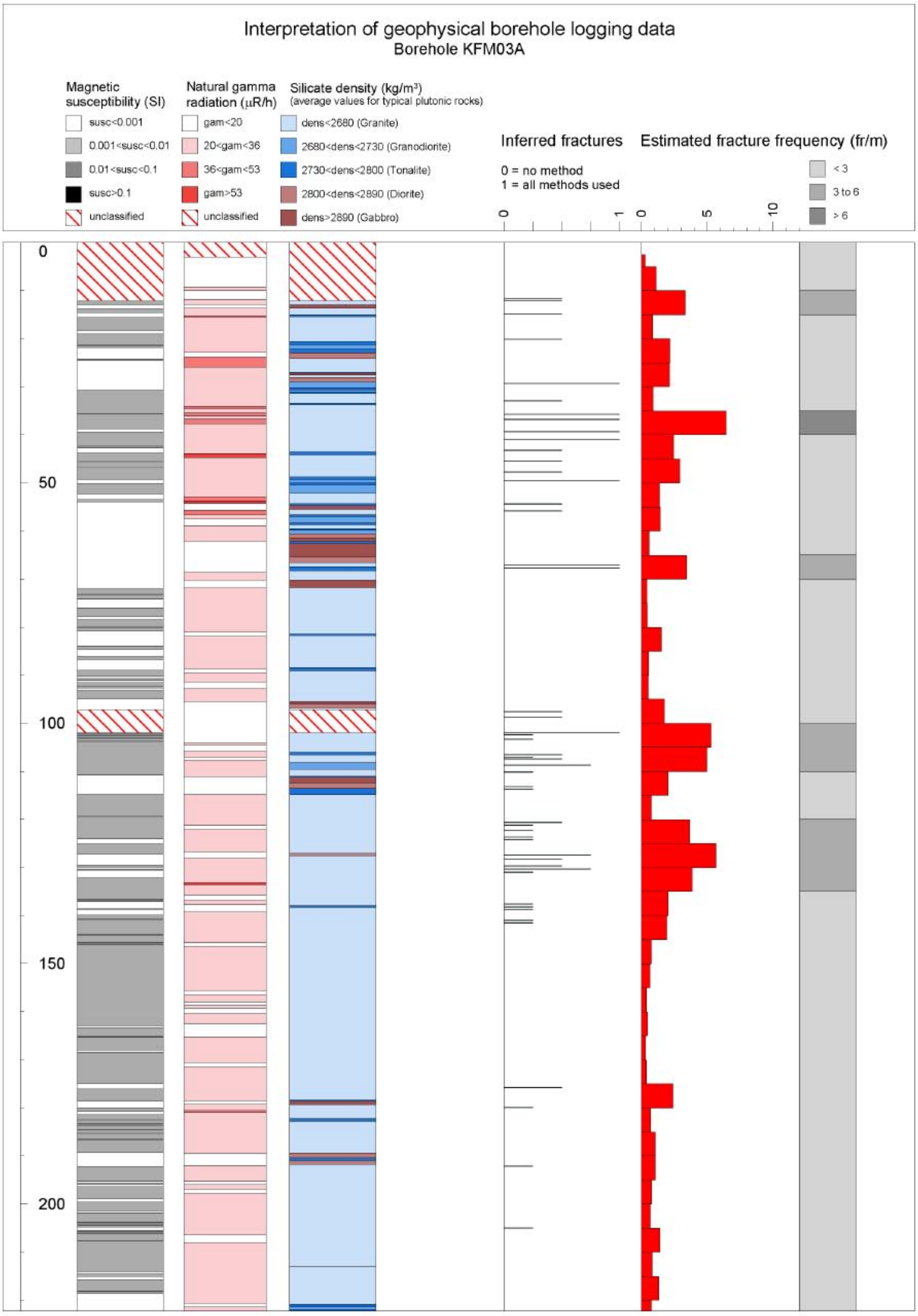

600
650
700
750
800
850

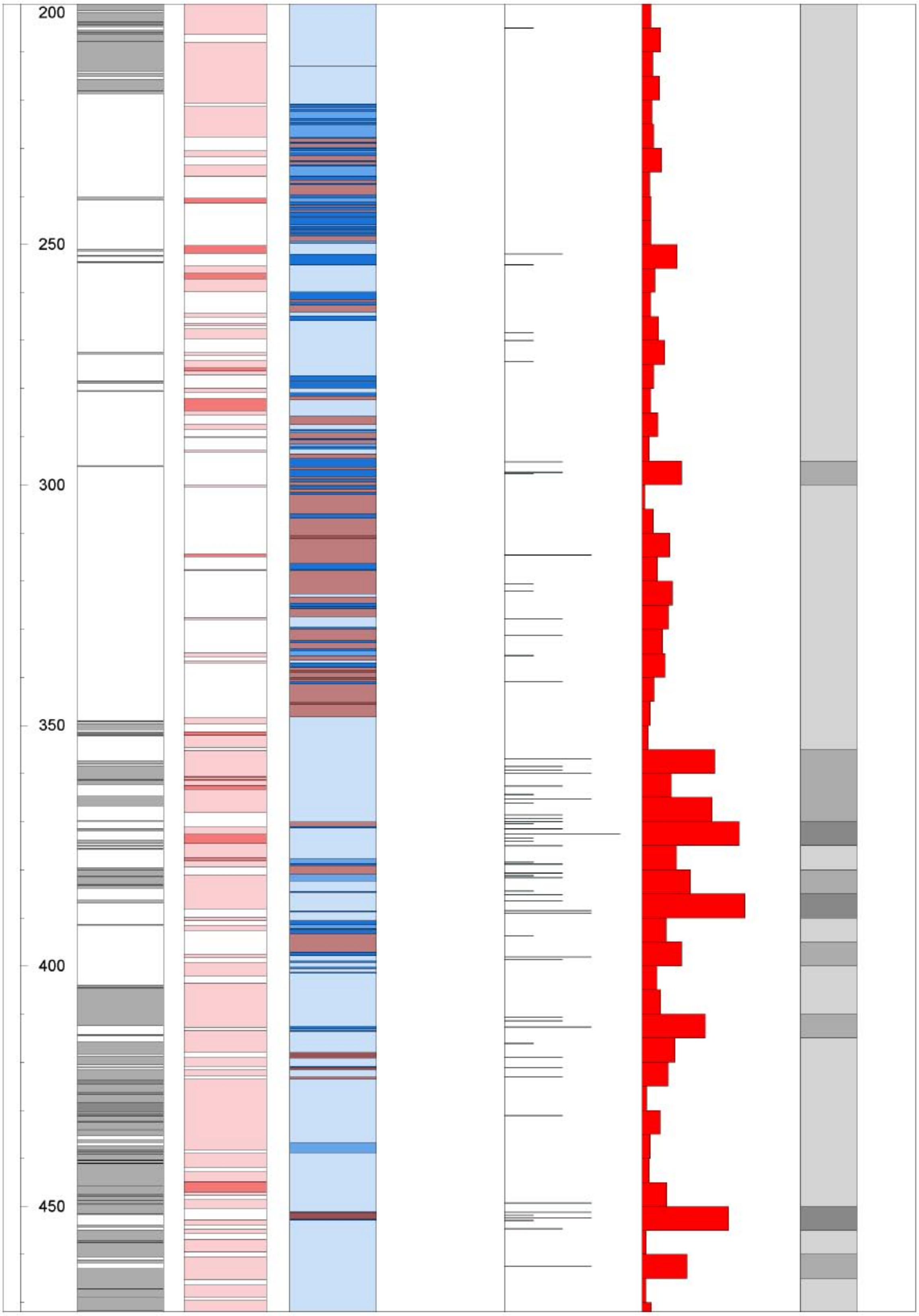


850
900
950
1000

Appendix 3

Generalized geophysical logs for the borehole KFM03A

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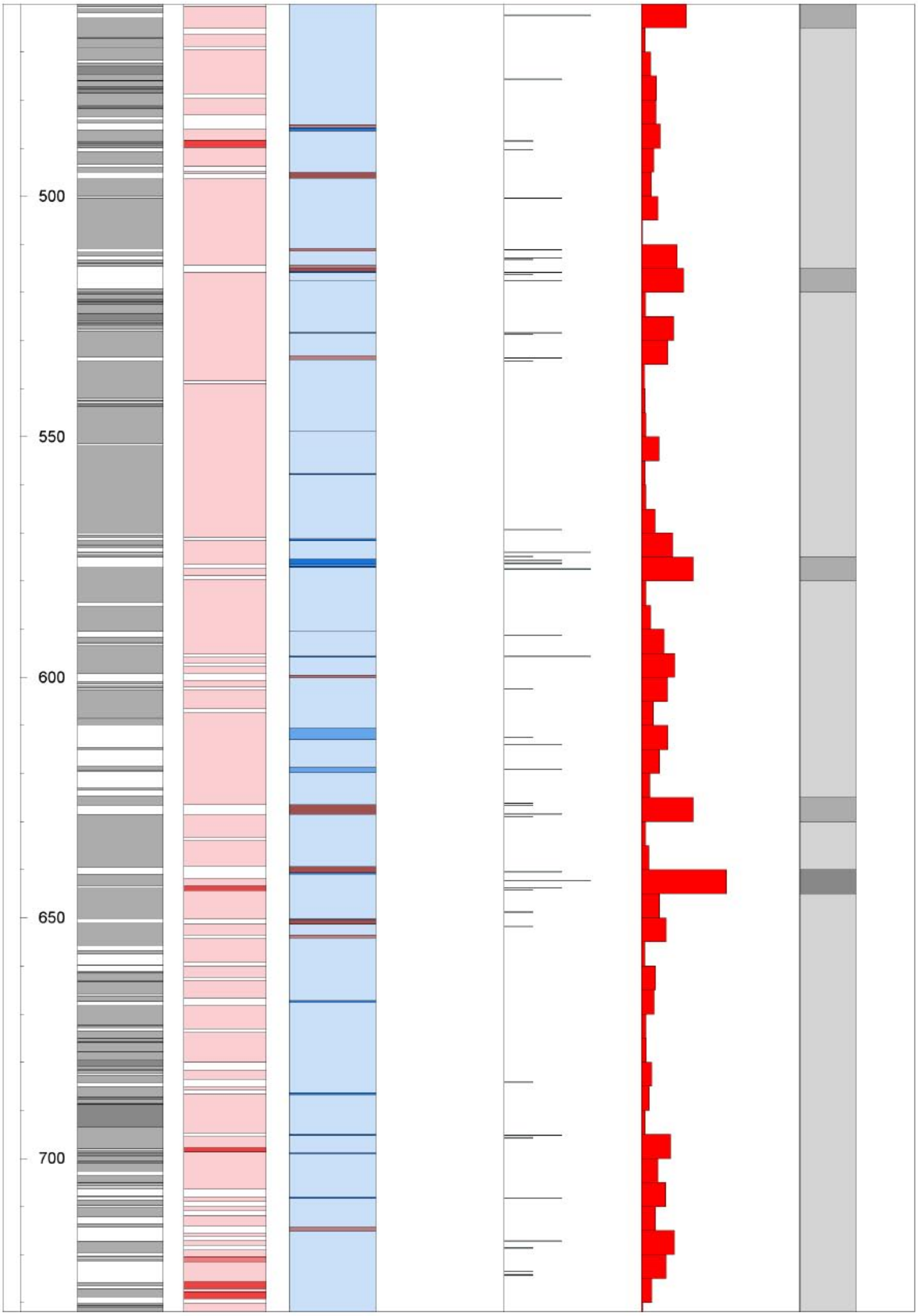

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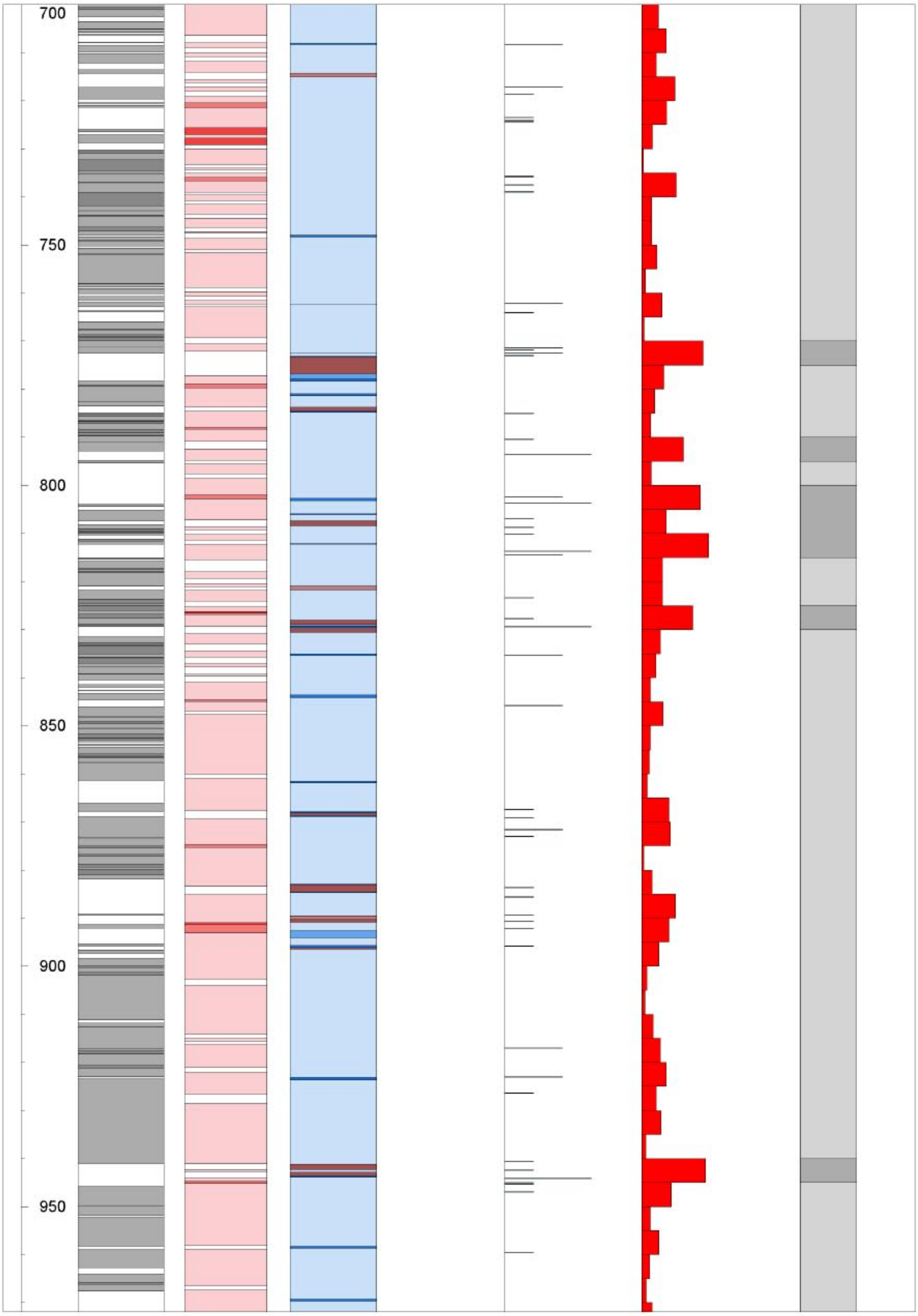
700
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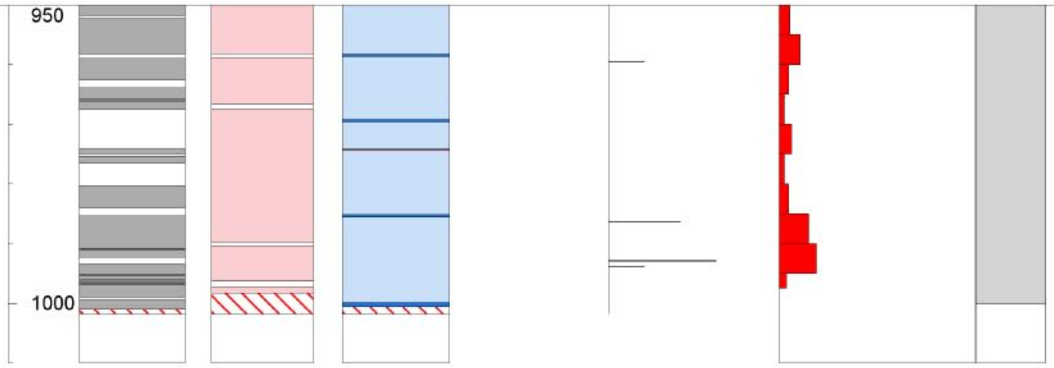
950
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