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Forsmark site investigation

Interpretation of borehole geophysical measurements in KFM04A, KFM06A (0–100 m), HFM10, HFM11, HFM12, HFM13, HFM16, HFM17 and HFM18

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Abstract

This report presents the compilation and interpretation of geophysical logging data from the cored borehole KFM04A, the percussion drilled part (0–100 m) of KFM06A and the percussion drilled boreholes HFM10–13 and HFM16–18.

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

In general, the rock in the vicinity of the investigated boreholes is dominated by silicate densities indicating a mineral composition corresponding to granite. At drill site 4 (KFM04A and HFM10) the uppermost c 150 m of the bedrock seems to by dominated by denser rocks, mainly with an indicated tonalitic composition. In KFM04A, the section 725–745 m is entirely dominated by silicate densities corresponding to gabbro. High density rocks (indicated tonalite, diorite and gabbro composition) also occur rather abundantly at 80–180 m depth in HFM11 and at 90–150 m in HFM12. The geophysical logging data also indicate the occurrences of rocks with an increased level of natural gamma radiation (pegmatite or fine-grained granite) often as thin veins or dykes. In the boreholes KFM04A, HFM10, HFM11, HFM12 and HFM16 there are several sections with very low magnetization, possibly related to alteration of the rock.

The fracture frequency is generally low in the boreholes. Sections of increased fracturing (possibly indicating larger deformation zones) occur at c 100–350 m depth in KFM04A, c 70–120 m in HFM10, c 15–75 m in HFM16 and possibly also at c 110–150 m in HFM17. Anomalies in the vertical temperature gradient data and in the estimated salinity data clearly indicate that several fractures are water bearing.

Sammanfattning

Denna rapport presenterar tolkningen av geofysiska loggningsdata från kärnborrhålet KFM04A, den hammarborrade delen (0–100 m) av KFM06A samt hammarborrhålen HFM10–13 och HFM16–18.

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

Berggrunden som omger de undersökta borrhålen domineras av bergarter med en silikatdensitet motsvarande granit. Data från borrplats 4 (KFM04A och HFM10) visar att de översta ca 150 m av berggrunden har en silikatdensitet motsvarande tonalit. I KFM04A domineras sektionen 725–745 m helt av silikatdensiteter som indikerar gabbro. Relativt hög densitet (motsvarande tonalit, diorit och gabbro) är även vanligt förekommande i sektionerna 80–180 m i HFM11 och 90–150 m i HFM12. Korta sektioner med förhöjd naturlig gammastrålning, troligen orsakade av pegmatitgångar eller finkorniga granitgångar, finns i alla undersökta borrhål. I KFM04A, HFM10, HFM11, HFM12 och HFM16 finns ett flertal relativt långa sektioner med mycket låg magnetisk susceptibilitet, vilket kan vara en indikation på att berget är omvandlat.

Sprickfrekvensen är generellt sett låg. Längre sektioner med förhöjd sprickfrekvens, vilka kan indikera större deformationszoner, är 100–350 m i KFM04A, 70–120 m i HFM10, 15–75 m i HFM16 och möjligen 110–150 m i HFM17. Flera tydliga sprickindikationer sammanfaller med kraftiga anomalier i den vertikala temperaturgradienten och språng i borrhålsvätskans salinitet, vilket tydligt indikerar att dessa sprickor är vattenförande.

Contents

1 Introduction

SKB performs site investigations for localization of a deep repository for high level radioactive waste. The site investigations are performed at two sites, Forsmark and Simpevarp. This document reports the results gained from the interpretation of borehole geophysical logging data from the cored borehole KFM04A, the percussion drilled part (0–100 m) of KFM06A and the percussion drilled boreholes HFM10–13 and HFM16–18 at Forsmark (Figure 1-1).

Generalized geophysical logs related to lithological variations are presented together with indicated fracture logs (including estimated fracture frequency). Vertical temperature gradient and estimated salinity logs are also calculated. The measurements were conducted by Rambøll.

The interpretation presented in this report is performed by GeoVista AB in accordance with the instructions and guidelines presented by SKB in the method description MD 221.003 and activity plan AP PF 400-03-90 (SKB internal controlling document).

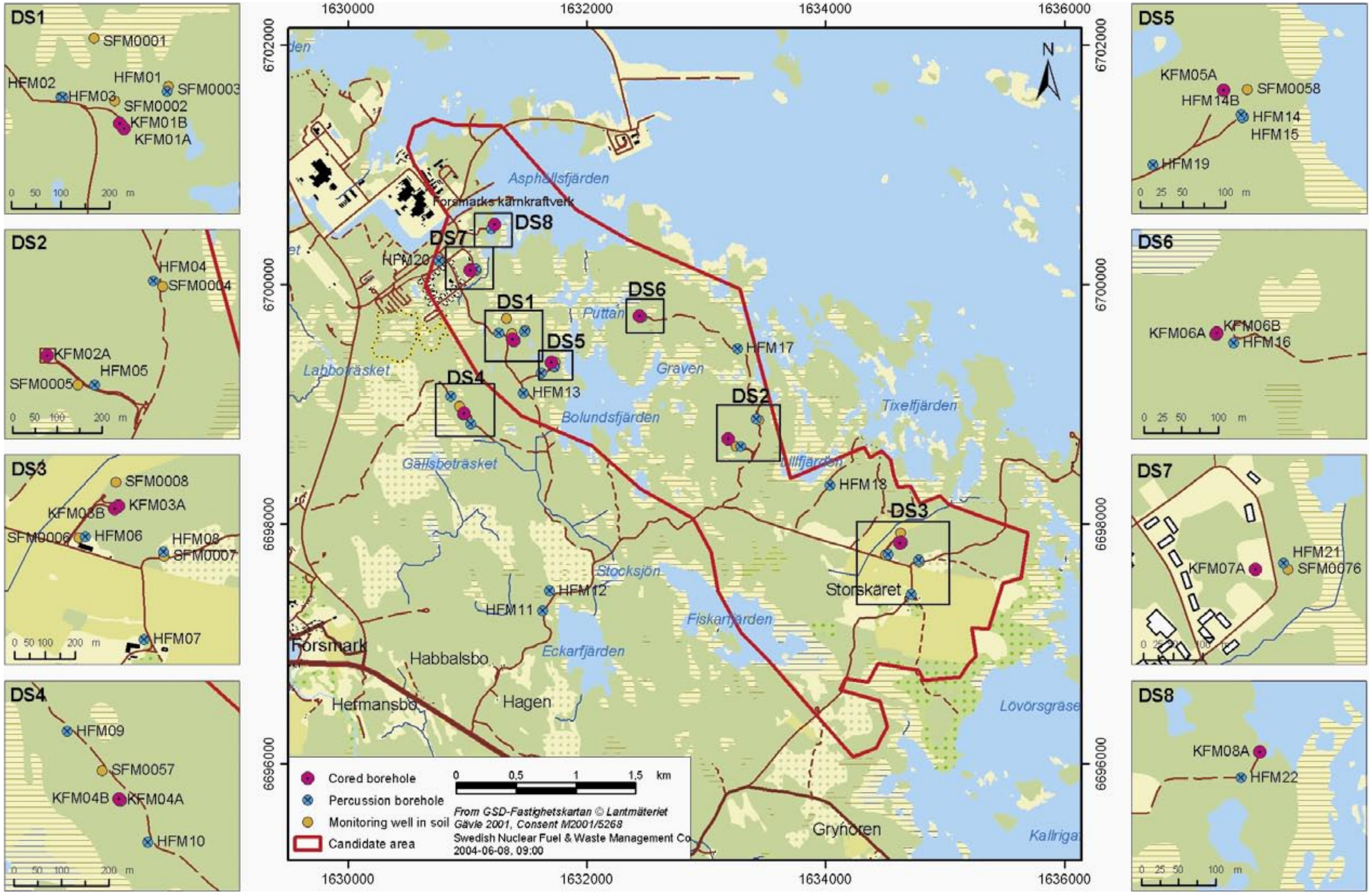


Figure 1-1. *Drill sites in the Forsmark area.*

2 Objective and scope

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

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

3 Execution

The software used for the interpretation are WellCad v3.2 (ALT) and Strater v1.0 (Golden Software), mainly used for plotting, Grapher 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.

The logging data were directly retrieved from Rambøll in order to speed up the interpretation process and make the interpretation available for the geological core mapping without unnecessary delay.

3.1 Logging data

Cored boreholes

The data sets used for interpretation are:

Density (gamma-gamma)
Magnetic susceptibility
Natural gamma radiation
Short normal resistivity
SPR (Single-point-resistance)
Focused resistivity (140 cm and 300 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 long normal, lateral resistivity measurements were performed in the boreholes.

Percussion drilled boreholes

The logging data used for interpretation are:

Density (gamma-gamma)
Magnetic susceptibility
Natural gamma radiation
Short normal resistivity
SPR (Single-point-resistance)
Focused resistivity (140 cm and 300 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 long normal, lateral resistivity measurements were performed in the boreholes.

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 5 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 metre sections /1/:

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

where z = depth co-ordinate (m), t = fluid temperature (ºC) and φ = borehole inclination.

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

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

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

It should be noted that the borehole temperature and salinity might be affected by non-equilibrium with the surrounding rock at the time of logging.

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 /2/ and the data are then divided into 5 intervals indicating a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to /3/. The intervals are bounded by the threshold values

granite <2,680 kg/m^3
2,680 kg/m^3 <granodiorite <2,730 kg/m^3
2,730 kg/m^3 <tonalite <2,800 kg/m^3
2,800 kg/m^3 <diorite <2,890 kg/m^3
2,890 kg/m^3 <gabbro

The magnetic susceptibility logging is subdivided into steps of decades and the natural gamma radiation is divided into "low", "medium", "high" or "very high" radiation by setting threshold values at 20.5, 36.3 and 52.8 μR/h respectively. The threshold values for each level have been adjusted with respect to the geological environment in the candidate area.

3) ***Interpretation of large fractures and estimated fracture frequency*** (classification based on analyses focused resistivity, short normal resistivity, caliper mean, SPR and sonic logs for both cored boreholes and percussion drilled holes).

The position of large fractures is estimated by applying a second derivative filter (convolution 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 metres sections. The weighted sum has been calibrated to the core mapped frequency of natural fractures in KFM01A and KFM02A. Estimated fracture frequencies have also been classified into three classes corresponding to <3, 3 to 6 and >6 fractures per metre.

Table 3-1 shows the threshold values used for the interpretation of fractures and fracture frequency. The threshold values refer to the output of the filters above. These outputs have also been normalised with respect to their mean and standard deviation in order to make different logging methods more comparable. The thresholds have been set by a trial-and-error procedure with the aim of locating possible fractures that produce significant geophysical anomalies but avoiding those anomalies that might be due to instrumental noise or very narrow fractures. The same threshold values will most likely be used for other holes in the investigation area. The weights in Table 3-1 refer to the calibration to core mapped frequency as described above.

A comparison between core and percussion holes has not indicated any diameter dependence /4/.

Table 3-1. Threshold values, in GeoVista in-house programs fract_det and fract_normres, and weights used for estimating position of fractures and calculation of estimated fracture frequency, respectively.

	Borehole	Sonic	Focused res 300	Focused res 140	Caliper	SPR	Short normal resist
Threshold	KFM04A	0.5	0.4	0.02	–	1.0	2.5
Weight	KFM04A	1	1	1	–	1	1
Threshold	KFM06A	0.4	0.9	0.9	0.7	0.7	2.5
Weight	KFM06A	1	1	1	1	1	1
Threshold	HFM10	0.4	0.6	–	0.7	0.7	2.5
Weight	HFM10	1	1	–	1	1	1
Threshold	HFM11	0.4	0.7	–	0.7	0.7	2.5
Weight	HFM11	1	1	–	1	1	1
Threshold	HFM12	0.4	0.9	–	0.7	0.7	2.5
Weight	HFM12	1	1	–	1	1	1
Threshold	HFM13	0.4	0.9	–	0.7	0.7	2.5
Weight	HFM13	1	1	–	1	1	1
Threshold	HFM16	0.4	0.6	0.6	0.7	–	2.5
Weight	HFM16	1	1	1	1	–	1
Threshold	HFM17	0.4	1.0	1.0	0.7	–	2.5
Weight	HFM17	1	1	1	1	–	1
Threshold	HFM18	0.4	1.0	1.0	0.7	–	2.5
Weight	HFM18	1	1	1	1	–	1

4 Results

4.1 Control of the logging data

4.1.1 Noise levels and qualitative control

Noise levels of the raw data for each log method are presented in Table 4-1. Noise levels are only presented for the data used in the interpretation. For a majority of the log data the noise is lower, or only 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. However, the noise levels of the density and the natural gamma radiation logs of HFM11, 12 and 13 are much higher than what is recommended. To reduce the influence of the noise, the logs are average filtered. The higher than recommended noise levels will have the effect that a subtle anomaly with short wave-length will be insignificant.

A qualitative inspection of the logs was performed. The data were checked for spikes and/or other obvious incorrect data points. Sonic data have been rejected for KFM06A in section 19–32 m. For HFM10 the short normal resistivity and SPR are affected by the fluid resistivity from 111 m depth and below. In HFM11 the short normal resistivity and SPR are strongly affected by the fluid resistivity from 137 m depth and below. The short normal resistivity in HFM16 is strongly influenced by the fluid resistivity from 72 m depth and below. The contribution from short normal resistivity and SPR in the estimation of fractures is therefore delimited to fewer geophysical logging methods in the above described boreholes and sections.

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

Logging method	KFM04A (below 110 m)	KFM06A (0–100 m)	HFM10	HFM11	HFM12	HFM13	HFM16	HFM17	HFM18	Recommended max noise level
Density (kg/m^3)	9	9	7	62	52	60	10	9	10	3–5
Magnetic susceptibility (SI)	$0.6 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$0.2 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$0.5 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$0.9 \cdot 10^{-4}$	$0.8 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$	$1 \cdot 10^{-4}$
Natural gamma radiation (μR/h)	0.69	0.4	0.2	2.2	1.9	2.5	0.2	0.2	0.2	0.3
Fluid resistivity (%)	0.05	0.016	0.02	0.10	0.06	0.03	0.05	0.03	0.55	2.0
Fluid temperature (ºC)	0.0011	0.0012	0.008	0.007	0.002	0.006	0.002	0.001	0.001	0.01
Caliper (mm)	–	0.10	0.02	0.17	0.17	0.10	0.13	0.11	0.12	0.5
Focused resistivity 300 (%)	10.8	12.3	15.4	20.9	18.6	17.9	15.5	9.3	12	–
Focused resistivity 140 (%)	2.3	5.4	–	–	–	–	9.8	5.2	5.8	–
Sonic (%)	13.4	10.1	18	20	21	13	22	20	18	20
Short normal resistivity (%)	0.15	0.17	0.19	0.52	0.18	0.24	0.41	0.14	0.50	2.0
SPR (%)	0.14	0.16	0.17	0.38	0.17	0.22	–	–	–	–

4.2 Interpretation of the logging data

The presentation of the processed logs and their interpretation products includes:

- Classification of silicate density.
- Classification of natural gamma radiation.
- Classification of magnetic susceptibility.
- Position of inferred fractures (0 = no fracture, 1 = fracture inferred from 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 KFM04A

Vertical temperature gradient and salinity

The median vertical temperature gradient in KFM04A is 6.6°C/km (Figure 4-1). The gradient data show a large positive anomaly at c 112 m depth (possibly related to the shift of drilling technique from the percussion drilled upper 100 m to the core drilled part of the borehole). Between c 200 and 800 m depth there are several moderate anomalies most likely related to water bearing fractures. The most predominate ones occur at 250–500 m depth. The estimated salinity varies between c 5,500 and c 7,500 ppm NaCl (Figure 4-1), which is high compared to KFM01A but in the same range as for KFM05A.

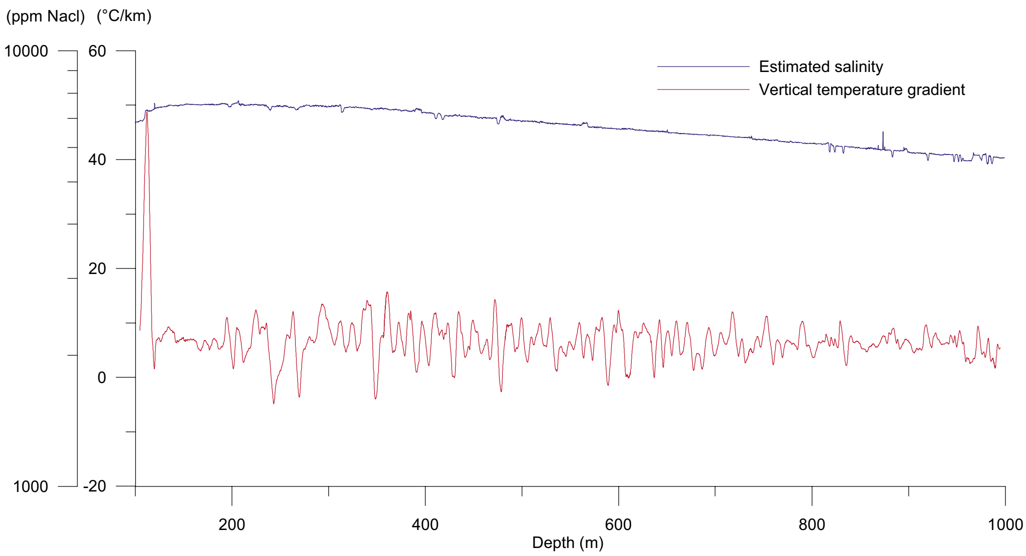


Figure 4-1. *Estimated salinity and vertical temperature gradient for KFM04A.*

Correction of resistivity logs and calculation of apparent porosity

The correction procedure involving estimation of apparent porosity does not work satisfactory for the short normal resistivity data from KFM04A. This may indicate that the borehole fluid was not in chemical equilibrium with the pore fluid of the rock surrounding the borehole at the time of the measurements.

Interpretation of rock types and fractures

The results of the generalized data and fracture estimations for the borehole KFM04A are presented in Figure 4-2 (coarse scale) and Appendix 1 (fine scale).

A majority of the rocks along the borehole have silicate densities indicating a mineral composition corresponding to granite. Between c 110 and 137 m depth there are several minor sections, of which all except one are shorter than 2 m, with a silicate density that corresponds to granodiorite or tonalite. At c 148–175 m there is a higher frequency of minor sections classified as tonalite or gabbro. The sections c 724–742 m and c 990–999 m are dominated by high densities (>2,800 kg/m^3), most likely corresponding to amphibolites since the magnetic susceptibility is low along these sections. Between c 945 and 967 m depth, the silicate density indicates a dominant occurrence of granodiorite rock.

The natural gamma radiation generally varies between 20 and 36 μR/h. Low radiation levels generally coincide with high density rocks. Short sections with high and very high natural gamma radiation occur at irregular intervals along the borehole. These anomalies probably correspond to pegmatite veins or dykes. A concentration of high radiation anomalies seems to occur along parts of the sections c 264–268 m, c 370–390 m, c 436–451 m, c 460–463 m, c 697–701 m and c 875–879 m.

The rocks in KFM04A have a magnetic susceptibility mainly ranging from 0.001 to 0.1 SI. Rocks of low magnetic susceptibility (sometimes related to rock alteration) however dominate the sections c 419–436 and c 939–967 m.

The geophysical logs indicate that the fracture frequency along KFM04A is generally low. In the section 100–340 m, the estimated fracture frequency is however partly increased. For the remaining part, except one short section at 360 m depth, the fracture frequency is estimated to <3 fractures/m.

Figure 4-2. *Generalized geophysical logs and estimated fracture frequency for KFM04A.*

4.2.2 Interpretation of KFM06A (0–100 m)

Vertical temperature gradient and salinity

The median vertical temperature gradient of KFM06A is 5.5°C/km. Apart from the large negative anomaly at c 13 m depth, which is probably related to the soil-rock boundary, there are only minor anomalies (Figure 4-3). The borehole fluid salinity increase stepwise with depth, starting at c 500 ppm NaCl, and ending at c 2,500 ppm NaCl.

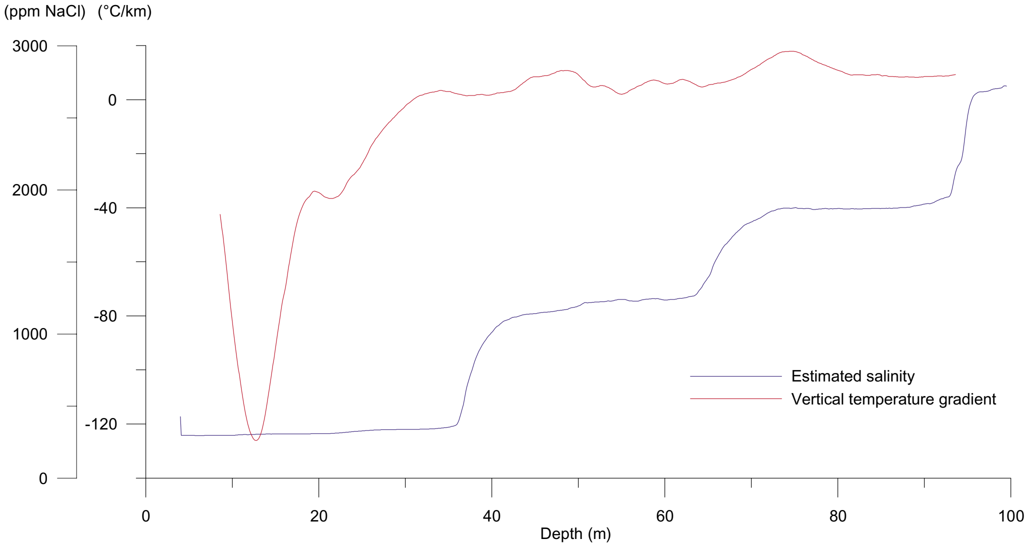


Figure 4-3. *Estimated salinity and vertical temperature gradient for KFM06A.*

Interpretation of rock types and fractures

Generalized geophysical logs and estimated fractures are presented in Figure 4-4.
A majority of the rocks along the borehole have a silicate density indicating a mineral composition corresponding to granite. Between c 25 and 27 m and c 82 and 84 m, the silicate density corresponds to gabbro. The natural gamma radiation along the borehole is generally between 20 and 36 µR/h. In the section c 67–71 m, high and very high radiation occur, probably corresponding to pegmatite or aplite dykes. The susceptibility is generally 0.001–0.01 SI, apart from a few shorter sections of very low susceptibility, which are possibly related to rock alteration.

The geophysical logs indicate that the fracture frequency along KFM06A is generally low, i.e. <3 fractures/m. In the sections c 15–30 m and 50–55 m, the estimated fracture frequency is slightly increased.

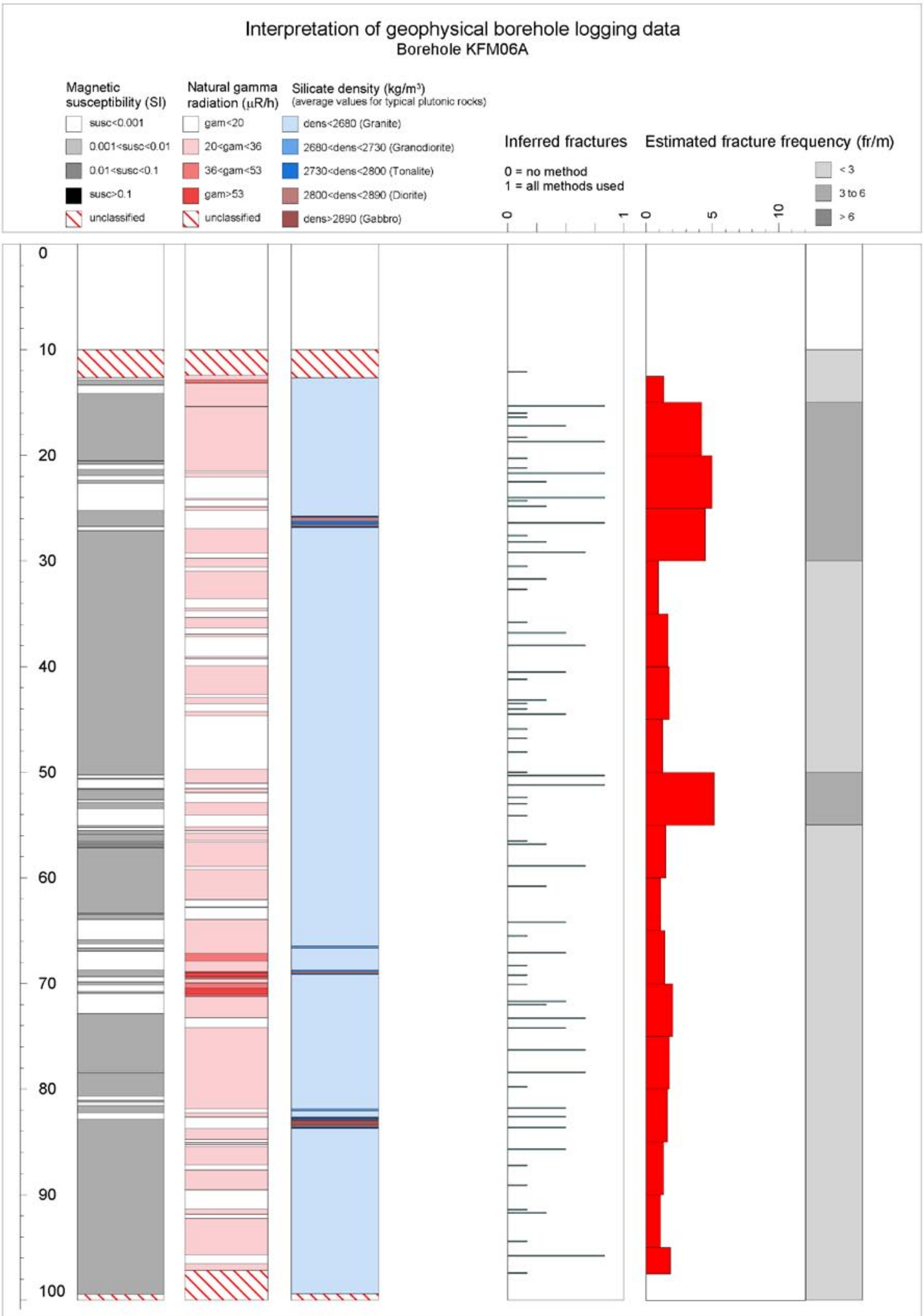


__Figure 4-4.__ Generalized geophysical logs and estimated fracture frequency for KFM06A.

4.2.3 Interpretation of HFM10

Vertical temperature gradient and salinity

The median vertical temperature gradient in HFM10 is 4.6°C/km (Figure 4-5). A few positive anomalies are found at depths of c 45 m and c 115 m, and a large negative anomaly at c 13 m depth, which is probably related to the soil-rock boundary. The positive anomalies are likely to correspond to water bearing fractures. The larger anomaly, which peaks at c 115 m depth, coincides with a major stepwise increase in the estimated borehole fluid salinity. Note that increased fracturing at 115 m depth is also indicated by the fracture logging, see Figure 4-6.

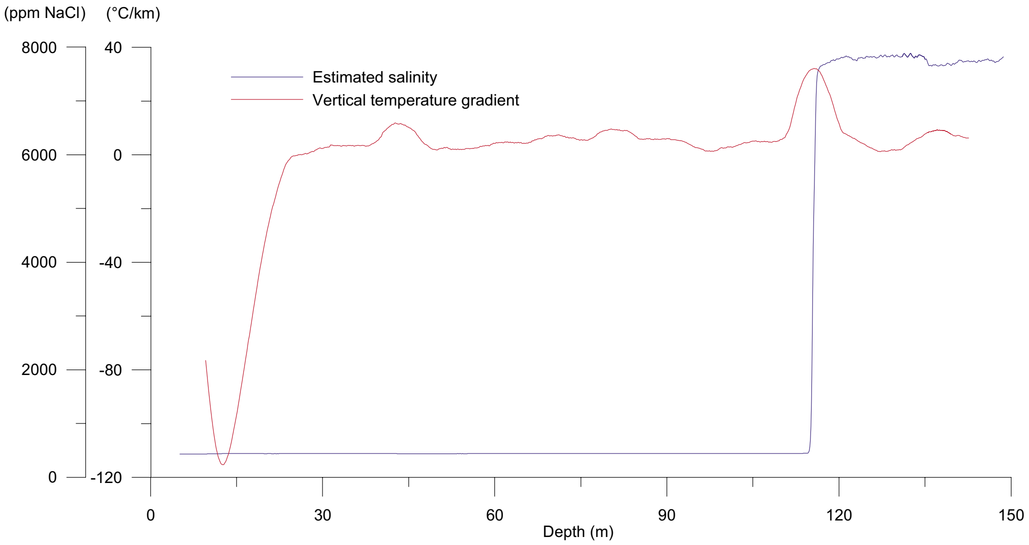


Figure 4-5. *Estimated salinity and vertical temperature gradient for HFM10.*

Correction of resistivity logs and calculation of apparent porosity

The correction procedure involving estimation of apparent porosity does not work satisfactory for the short normal resistivity data from HFM10. This may indicate that the borehole fluid was not in chemical equilibrium with the pore fluid of the rock surrounding the borehole at the time of the measurements.

Interpretation of rock type and fractures

Generalized geophysical logs and estimated fractures are presented in Figure 4-6. The silicate density indicates a large variation in rock composition throughout the entire borehole. 36% of the borehole length is classified as "tonalite", 31% as "granite", 16% as "granodiorite", 12% as "diorite" and 5% as "gabbro". Most classes occur as short sections. The natural gamma radiation is generally low or moderate, which corresponds to the more basic rock composition indicated by the silicate density. Low radiation coincides with high density rocks. The susceptibility varies greatly, and large sections between 40 and 120 m depth are dominated by very low magnetization levels. High susceptibility occurs in some minor sections at the depths c 20 m, 35 m, 67 m, 130 m and 145 m.

The geophysical logs indicate that the fracture frequency along HFM10 is generally <3 fractures/m. In the sections c 15–20 m, 70–75 m and 85–95 m, the estimated fracture frequency is slightly increased. Between c 105 and 120 m depth the estimated fracture frequency is >6 fractures/m, possibly indicating the presence of a deformation zone.

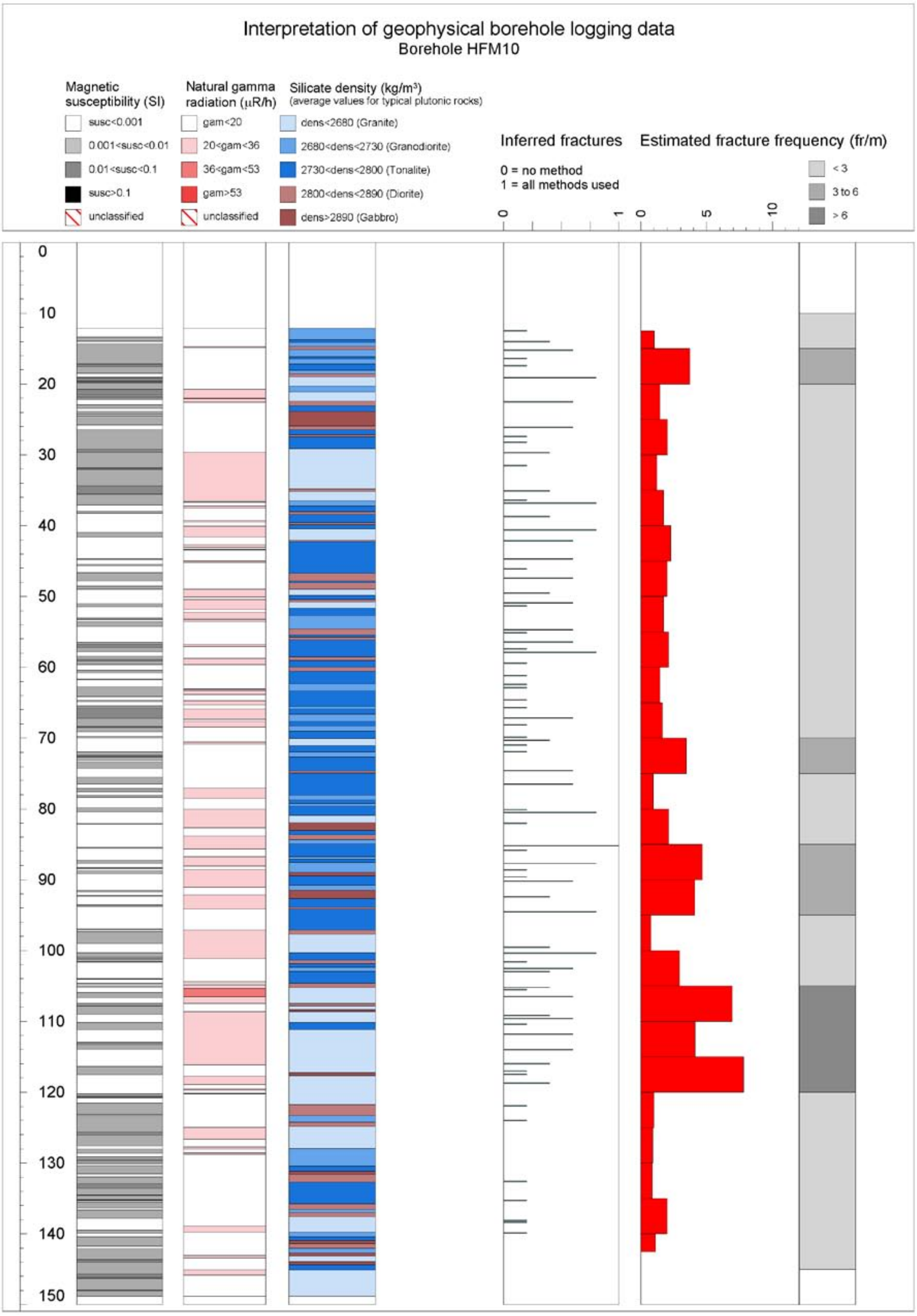


Figure 4-6. Generalized geophysical logs and estimated fracture frequency for HFM10.

4.2.4 Interpretation of HFM11

Vertical temperature gradient and salinity

The vertical temperature gradient and the estimated salinity for HFM11 are presented in Figure 4-7. The median vertical temperature gradient is 3.7°C/km. One large negative anomaly is located at 20 m depth and positive anomalies occur at 67 and 110 m depth. These anomalies most likely correspond to water bearing fractures. The large positive anomaly at c 110 m depth coincides with a suggested increase in the fracture frequency, see Figure 4-8. From c 2 m to c 141 m depth, the estimated salinity varies between 200 and 1,000 ppm NaCl. At c 141 m there is a large and rapid increase in the salinity up to c 6,500 ppm NaCl.

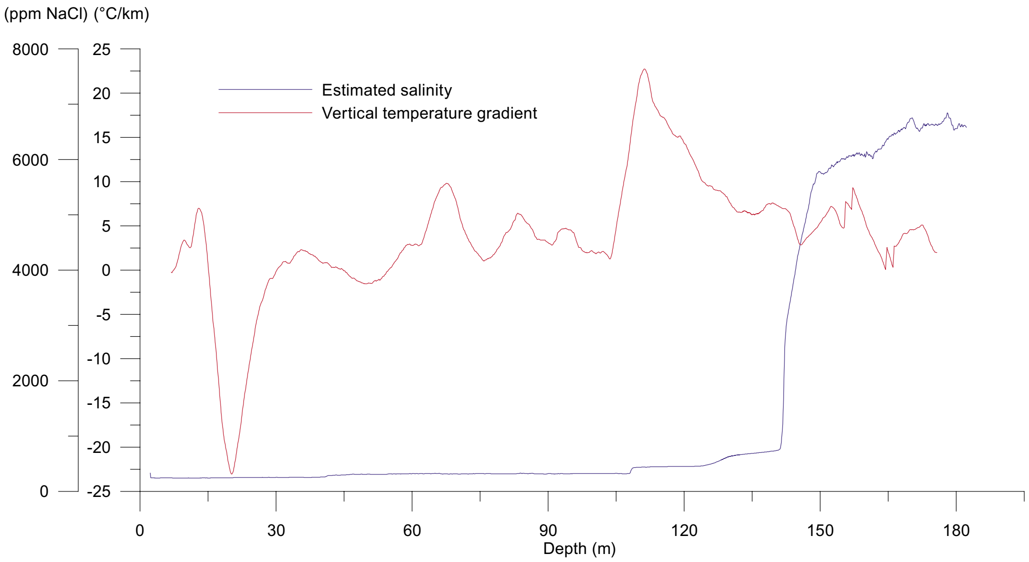


Figure 4-7. *Estimated salinity and vertical temperature gradient for HFM11.*

Correction of resistivity logs and calculation of apparent porosity

The correction procedure involving estimation of apparent porosity does not work satisfactory for the short normal resistivity data from HFM11. This may indicate that the borehole fluid was not in chemical equilibrium with the pore fluid of the rock surrounding the borehole at the time of the measurements.

Interpretation of rock types and fractures

Generalized geophysical logs and estimated fractures are presented in Figure 4-8. A majority of the rocks along the borehole shows silicate densities indicating a mineral composition corresponding to granite. Between c 28–34, c 84–90, c 112–116 and c 151–162 m depth, there are longer sections where the silicate density indicates a mineral composition corresponding to diorite and gabbro. The natural gamma radiation generally varies between 20 and 36 μR/h along the borehole. High and very high radiations occur along short sections at c 124–129 m and c 169–178 m depth. These anomalies probably correspond to pegmatite or aplite veins or dykes

Along the uppermost c 85 m of the borehole, and from c 150–190 m depth, the susceptibility is generally 0.001–0.1 SI. Very low susceptibility, possibly related to rock alteration, dominates the section c 85–150 m. The resistivity is low at 80–115 m depth, which also indicates rock alteration.

The geophysical logs indicate that the fracture frequency along HFM11 is low. In the section c 105–110 m, the estimated fracture frequency is slightly increased.

__Figure 4-8.__ Generalized geophysical logs and estimated fracture frequency for HFM11.

4.2.5 Interpretation of HFM12

Vertical temperature gradient and salinity

The vertical temperature gradient and the estimated salinity for HFM12 can be seen in Figure 4-9. The median vertical temperature gradient is 2.6°C/km. One large negative anomaly is located at 17 m depth (probably related to the soil-rock boundary) and positive anomalies occur at 129 m, 161 m and 196 m depth. The positive anomalies most likely correspond to water bearing fractures. From c 2–21 m, the salinity increases from c 2,000 to c 3,500 ppm NaCl. At c 162 m depth there is a rapid increase in the salinity up to c 4,500 ppm NaCl. Observe that the salinity anomalies coincide with temperature gradient anomalies, which supports the interpretation of water bearing fractures. The anomalies at 129 m and 162 m are also indicated in the fracture logs (Figure 4-10).

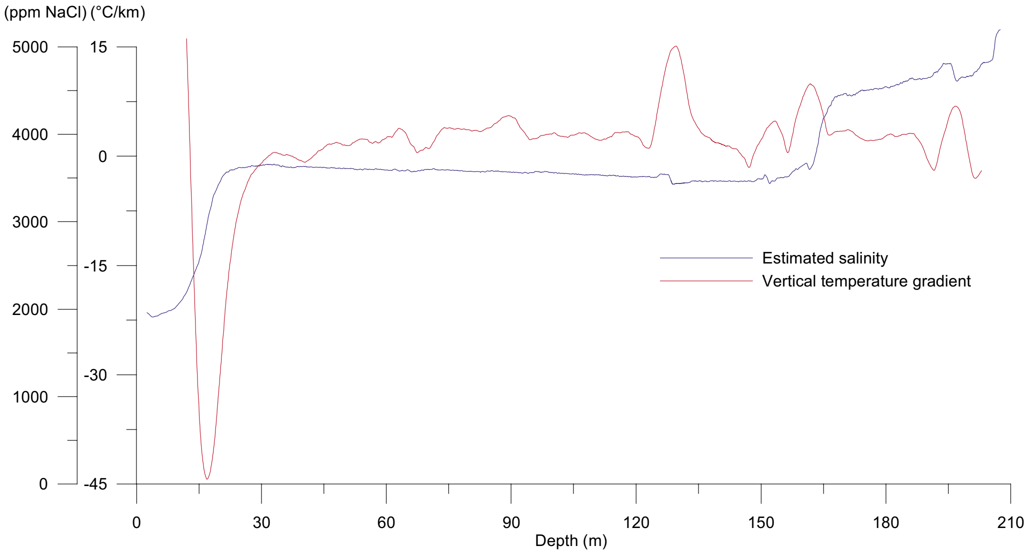


***Figure 4-9.** Estimated salinity and vertical temperature gradient for HFM12.*

Correction of resistivity logs and calculation of apparent porosity

The correction procedure involving estimation of apparent porosity does not work satisfactory for the short normal resistivity data from HFM12. This may indicate that the borehole fluid was not in chemical equilibrium with the pore fluid of the rock surrounding the borehole at the time of the measurements.

Interpretation of rock types and fractures

Generalized geophysical logs and estimated fractures are presented in Figure 4-10. A majority of the rocks along the borehole have silicate densities indicating a mineral composition that corresponds to granite. Between c 106 and 116 m, there are longer sections where the silicate density corresponds to a tonalitic mineral composition. Short sections classified as gabbro, probably related to amphibolite dykes, also occur. The natural gamma radiation generally varies between 20 and 36 μR/h, but sections with low gamma radiation occur at c 70–100 m and c 120–160 m. The magnetic susceptibility is mainly moderate or low.

The geophysical logs indicate that the fracture frequency along HFM12 is low. In the sections c 120–125 m and 150–155 m the estimated fracture frequency is slightly increased.

Figure 4-10. *Generalized geophysical logs and estimated fracture frequency for HFM12.*

4.2.6 Interpretation of HFM13

Vertical temperature gradient and salinity

The vertical temperature gradient and the estimated salinity for HFM13 are presented in Figure 4-11. The median vertical temperature gradient is 3.6°C/km. Several negative and positive anomalies appear, and they are most likely related to water bearing fractures. The largest anomaly is located at c 163 m depth and coincides with a large and rapid increase of the fluid water salinity. At this depth there is also an increase in the estimated fracture frequency (see Figure 4-12). From c 30 to c 163 m the estimated salinity of the borehole fluid shows moderate variations between c 250 and c 750 ppm NaCl.

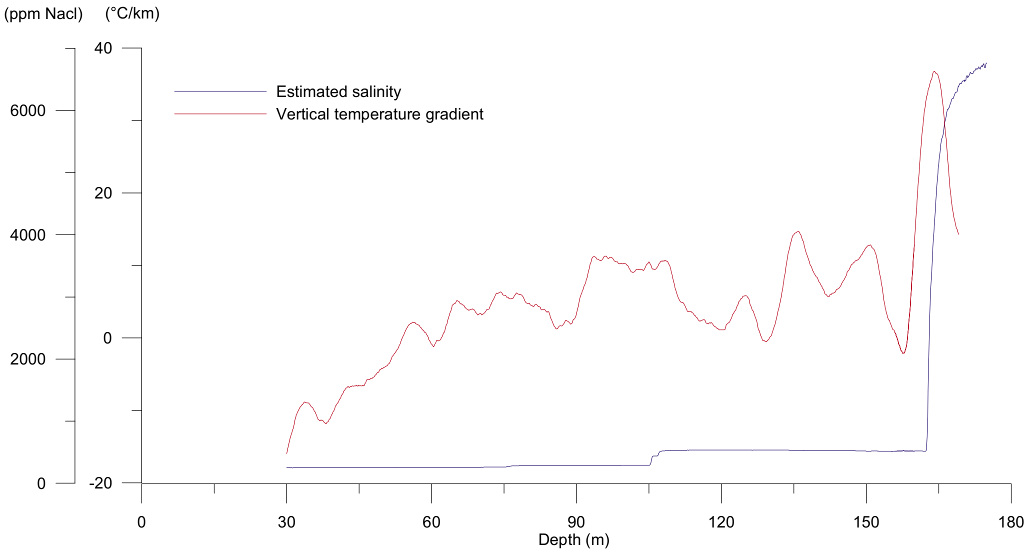


Figure 4-11. *Estimated salinity and vertical temperature gradient for HFM13.*

Correction of resistivity logs and calculation of apparent porosity

The correction procedure involving estimation of apparent porosity does not work satisfactory for the short normal resistivity data from HFM13. This may indicate that the borehole fluid was not in chemical equilibrium with the pore fluid of the rock surrounding the borehole at the time of the measurements.

Interpretation of rock types and fractures

Generalized geophysical logs and estimated fractures are presented in Figure 4-12. A majority of the rocks along the borehole have a silicate density indicating a mineral composition that corresponds to granite. Minor sections of silicate densities corresponding to granodiorite and tonalite occur throughout the entire borehole. A few minor sections classified as gabbro also occur. The natural gamma radiation generally varies between 20 and 36 μR/h. High and very high radiation occur as short sections at the depths c 125 m, 145 m and 160 m. The susceptibility is generally 0.001–0.01 SI, apart from a few low magnetic sections at the depths c 55–80 m and 145–165 m. The geophysical logs indicate that the fracture frequency along HFM12 is generally low. In section c 20–25 m, 100–110 and 160–170 m, the estimated fracture frequency is slightly increased.

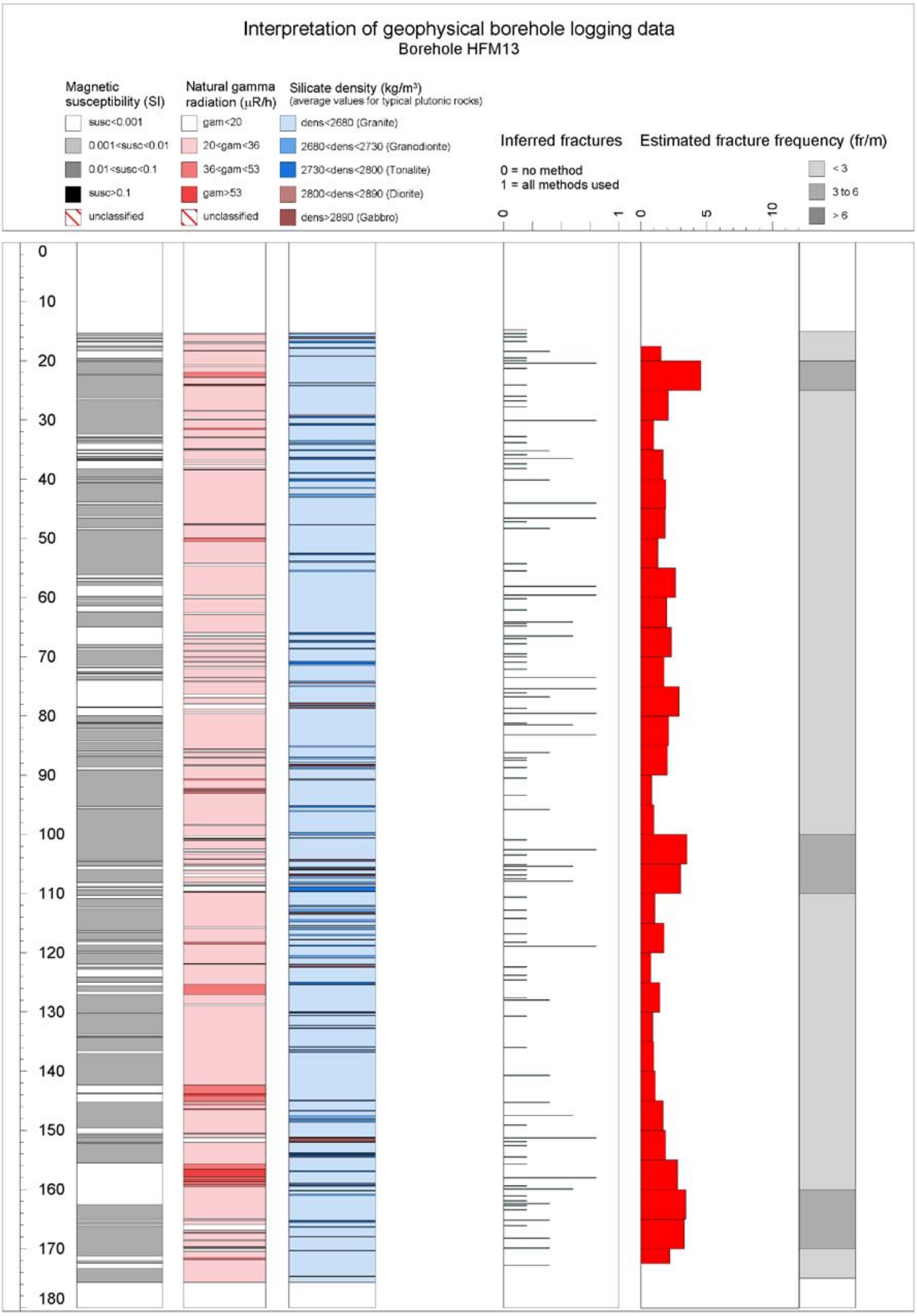


Figure 4-12. *Generalized geophysical logs and estimated fracture frequency for HFM13.*

4.2.7 Interpretation of HFM16

Vertical temperature gradient and salinity

The vertical temperature gradient and the estimated salinity for HFM16 are presented in Figure 4-13. The median vertical temperature gradient is 10°C/km. There is one large positive temperature anomaly at c 70 m depth which most likely indicates the presence of a water bearing fracture (or fracture zone). The anomaly coincides with a large and rapid increase in the fluid water salinity and increased fracturing is also indicated at this depth in the fracture logging data (see Figure 4-14).

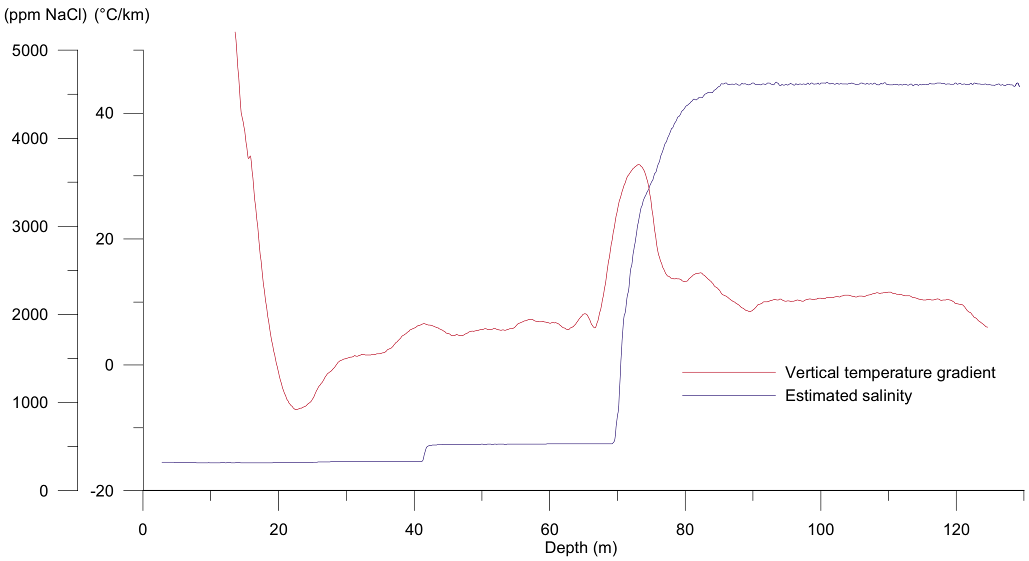


***Figure 4-13.** Estimated salinity and vertical temperature gradient for HFM16.*

Correction of resistivity logs and calculation of apparent porosity

The median short normal resistivity prior to correction is 2,100 Ωm, and the median of the corrected short normal resistivity is 4,300 Ωm. The median apparent porosity is c 0.50%.

Interpretation of rock types and fractures

Generalized geophysical logs and estimated fractures are presented in Figure 4-14. A majority of the rocks along the borehole have silicate densities indicating a mineral composition corresponding to granite. Four minor high density sections occur between 75 m and 90 m depth. The natural gamma radiation generally varies between 20 and 36 µR/h. Four minor sections with high radiation occur between c 19 to 35 m. Low radiation coincides with high density rocks. The magnetic susceptibility is mainly low for the uppermost c 90 m of the borehole and moderate for the remaining c 40 m (section 90–130 m). The low susceptibility coincides with increased fracturing, which may indicate that the rocks along these sections are affected by alteration.

The geophysical logs indicate that the fracture frequency below 75 m depth in HFM16 is low. In the sections 15–45 m and 55–65 m the estimated fracture frequency is slightly increased. Between c 65 and 75 m the estimated fracture frequency is >6 fractures/m.

Figure 4-14. Generalized geophysical logs and estimated fracture frequency for HFM16.

4.2.8 Interpretation of HFM17

Vertical temperature gradient and salinity

The vertical temperature gradient and the estimated salinity for HFM17 are presented in Figure 4-15. The median vertical temperature gradient of the borehole fluid is 9.5°C/km. Minor temperature anomalies occur throughout the entire borehole. One large negative anomaly peaks at c 20 m depth, close to a rapid increase in the estimated fluid water salinity. Anomalies at c 30 m depth are also indicated in the fracture logs (Figure 4-15).

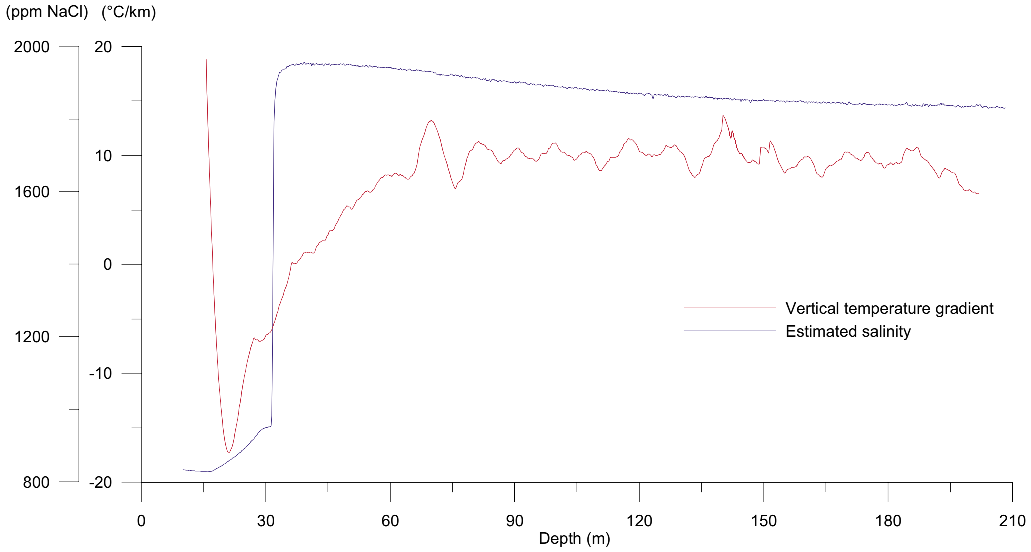


Figure 4-15. *Estimated salinity and vertical temperature gradient for HFM17.*

Correction of resistivity logs and calculation of apparent porosity

The median short normal resistivity prior to correction is 3,000 Ωm, and the median of the corrected short normal resistivity is 6,000 Ωm. The median apparent porosity is c 0.50%.

Interpretation of rock types and fractures

Generalized geophysical logs and estimated fractures are presented in Figure 4-16. A majority of the rocks along the borehole have silicate densities indicating a mineral composition that corresponds to granite. A minor high density section occurs at 116 m depth. The natural gamma radiation generally mainly varies between 20 and 36 μR/h. The magnetic susceptibility is generally moderate (0.001–0.01 SI), but continuous low magnetic sections, possibly related to rock alteration, occur at c 15–35 m, 75–90 m and 140–150 m depth.

The geophysical logs indicate that the fracture frequency in HFM17 is generally low. In the sections 105–110 m, 120–135 m and 140–145 m the estimated fracture frequency is slightly increased. For one short section between 30 and 35 m the estimated fracture frequency is >6 fr/m.

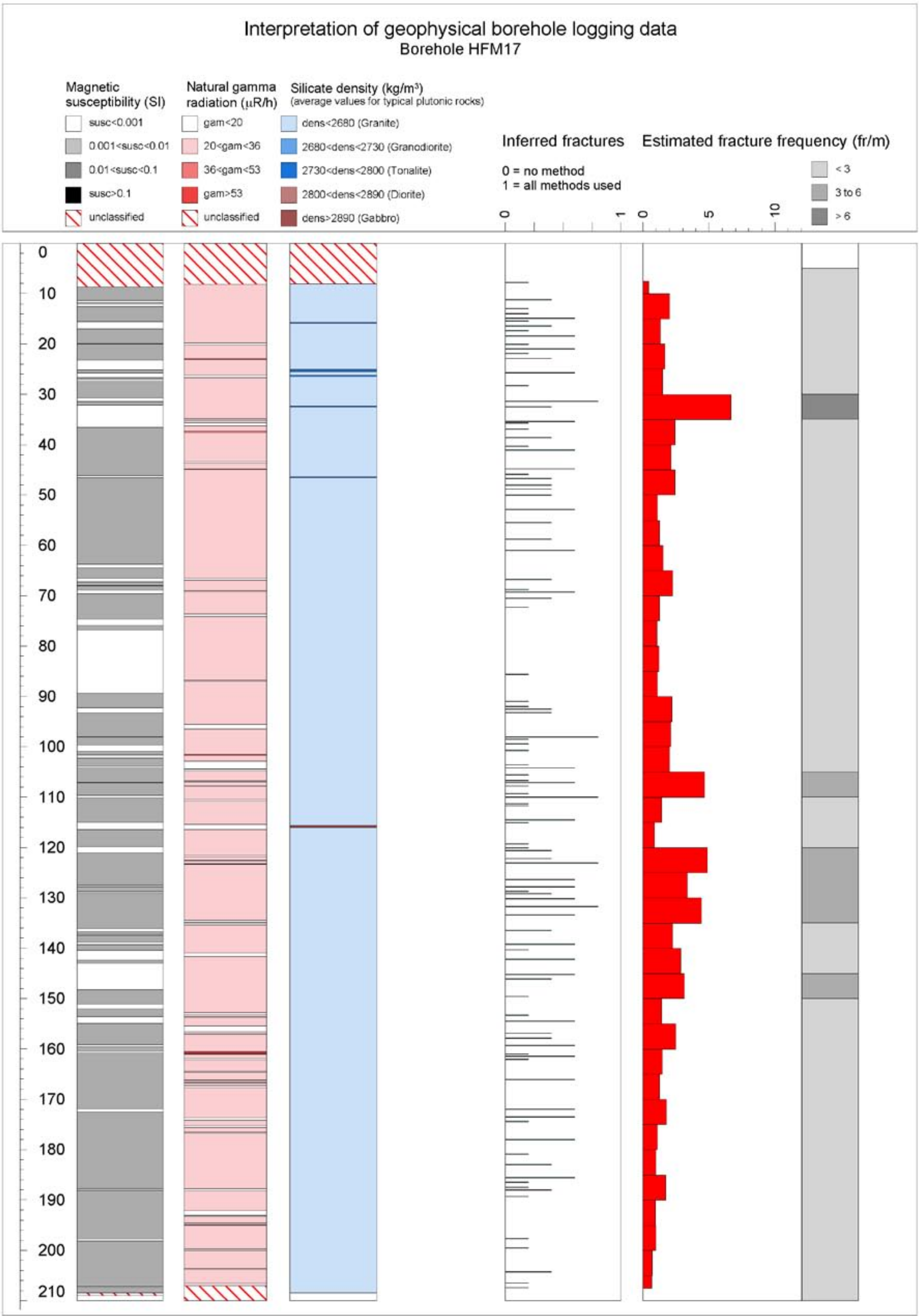


Figure 4-16. *Generalized geophysical logs and estimated fracture frequency for HFM17.*

4.2.9 Interpretation of HFM18

Vertical temperature gradient and salinity

The fluid temperature and the fluid resistivity logs are presented in Figure 4-17. The median vertical temperature gradient of HFM18 is 4.5°C/km. One negative anomaly occurs at c 20 m depth, and two positive anomalies are located at c 80 m and 100 m respectively. A third smaller positive anomaly peaks at c 140 m depth. The three positive anomalies most likely correspond to water bearing fractures, whereas the negative anomaly could be related to the soil-rock boundary. The two largest positive temperature gradient anomalies coincide with a rapid increase in the fluid water salinity, which varies greatly along the borehole, with an increase of almost 3 decades.

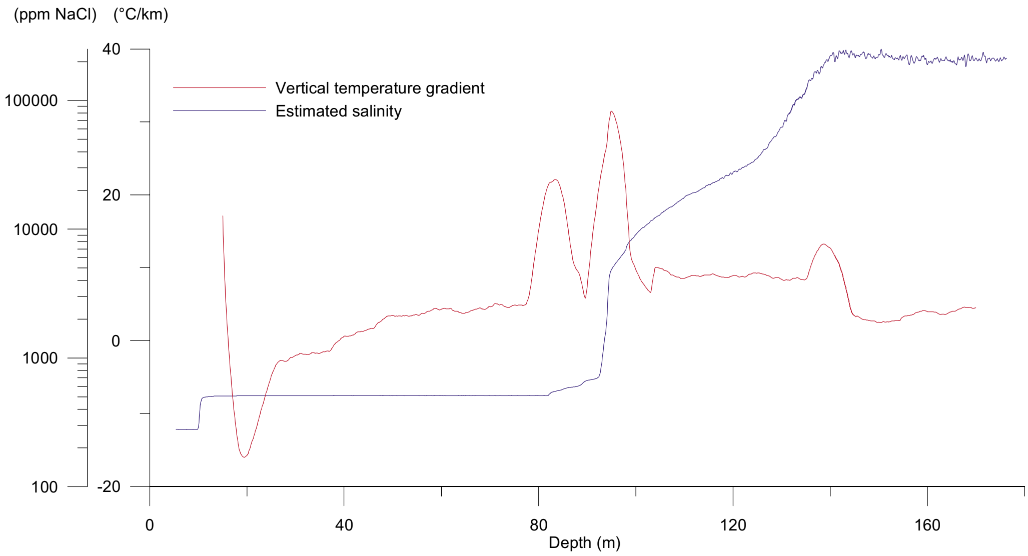


***Figure 4-17.** Estimated salinity and vertical temperature gradient for HFM18.*

Correction of resistivity logs and calculation of apparent porosity

The correction procedure involving estimation of apparent porosity does not work satisfactory for the short normal resistivity data from HFM18. This may indicate that the borehole fluid was not in chemical equilibrium with the pore fluid of the rock surrounding the borehole at the time of the measurements.

Interpretation of rock types and fractures

Generalized geophysical logs and estimated fractures are presented in Figure 4-18. A majority of the rocks along the borehole have silicate densities indicating a mineral composition that corresponds to granite. Between c 13 and 24 m depth there are several minor sections of indicated tonalite, whereas from 24 to 28 m there are indications of diorite and gabbro. The natural gamma radiation is mainly moderate, varying between 20 and 36 μR/h, or low. Nine short sections of high or very high radiation occur between 19 and 53 m. The magnetic susceptibility is most often 0.001–0.01 SI, but low magnetic sections, possibly related to alteration, occur at c 10–50 m, 95–100 m, 140–150 m and 165–170 m.

The geophysical logs indicate that the fracture frequency of HFM18 is generally low. In the sections 35–50 m, 75–80 m, 120–125 m and 160–165 m, the estimated fracture frequency is slightly increased. Along a short section in the bottom of the borehole the estimated fracture frequency is >6 fractures/m.

Figure 4-18. Generalized geophysical logs and estimated fracture frequency for HFM18.

5 Data delivery

The following data have been delivered to SKB for KFM04A, KFM06A (0–100 m), HFM10–13, HFM16–18: Re-sampled, filtered and calibrated data, calculated silicate density, salinity and temperature gradient, generalized logs and logs of inferred fractures and estimated fracture frequency. Apparent porosity and corrected resistivity (when calculated). The generalized logs have also been delivered as WellCAD-files.

The reference to SICADA is field note no 344.

6 References

/1/ **Sehlstedt S, 1988.** Description of geophysical data on the SKB data base GEOTAB. SKB TR-88-05, Svensk Kärnbränslehantering AB.

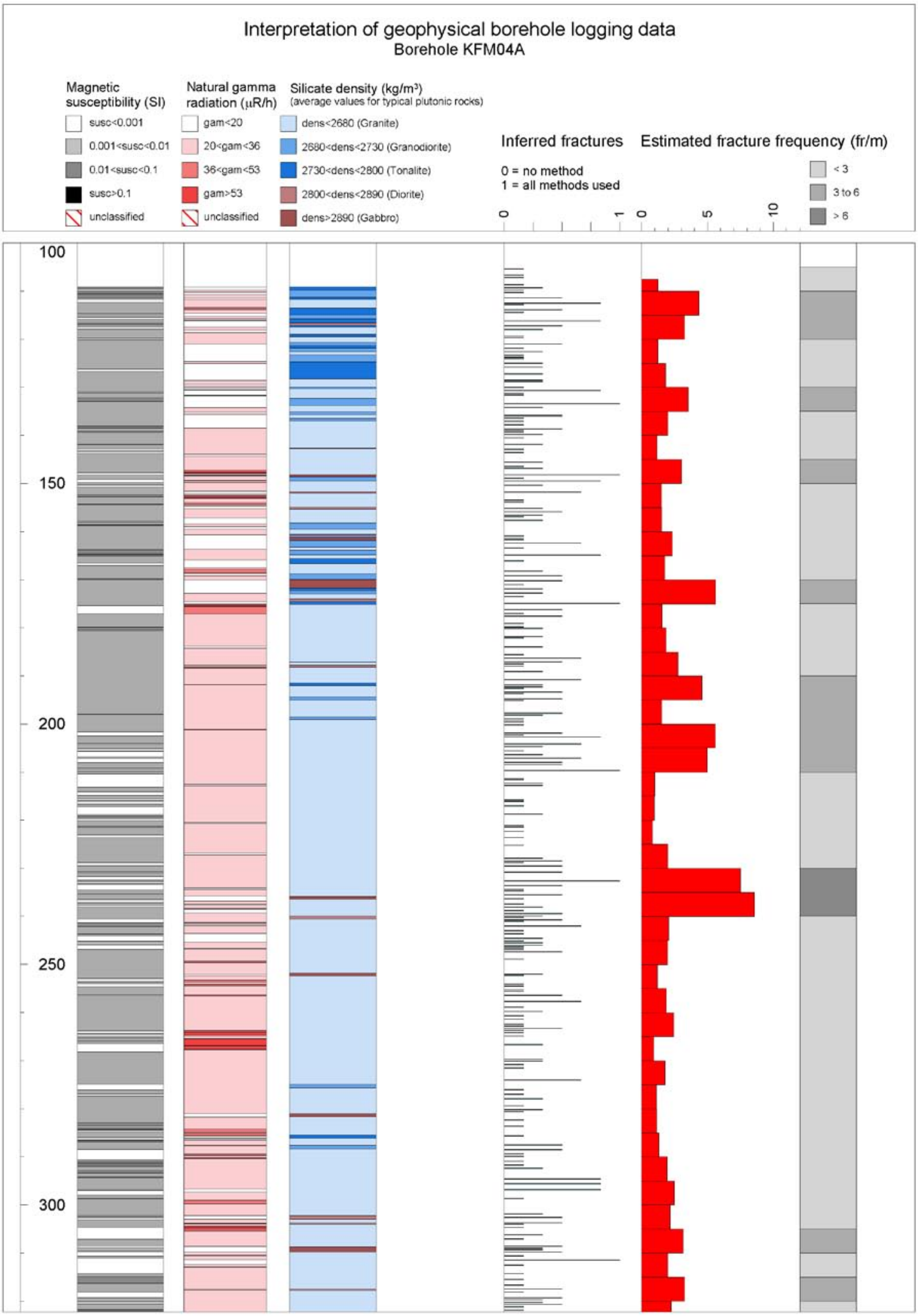
/2/ **Henkel H, 1991.** Petrophysical properties (density and magnetization) of rock from the northern part of the Baltic Shield. Tectonophysics 192, 1–19.

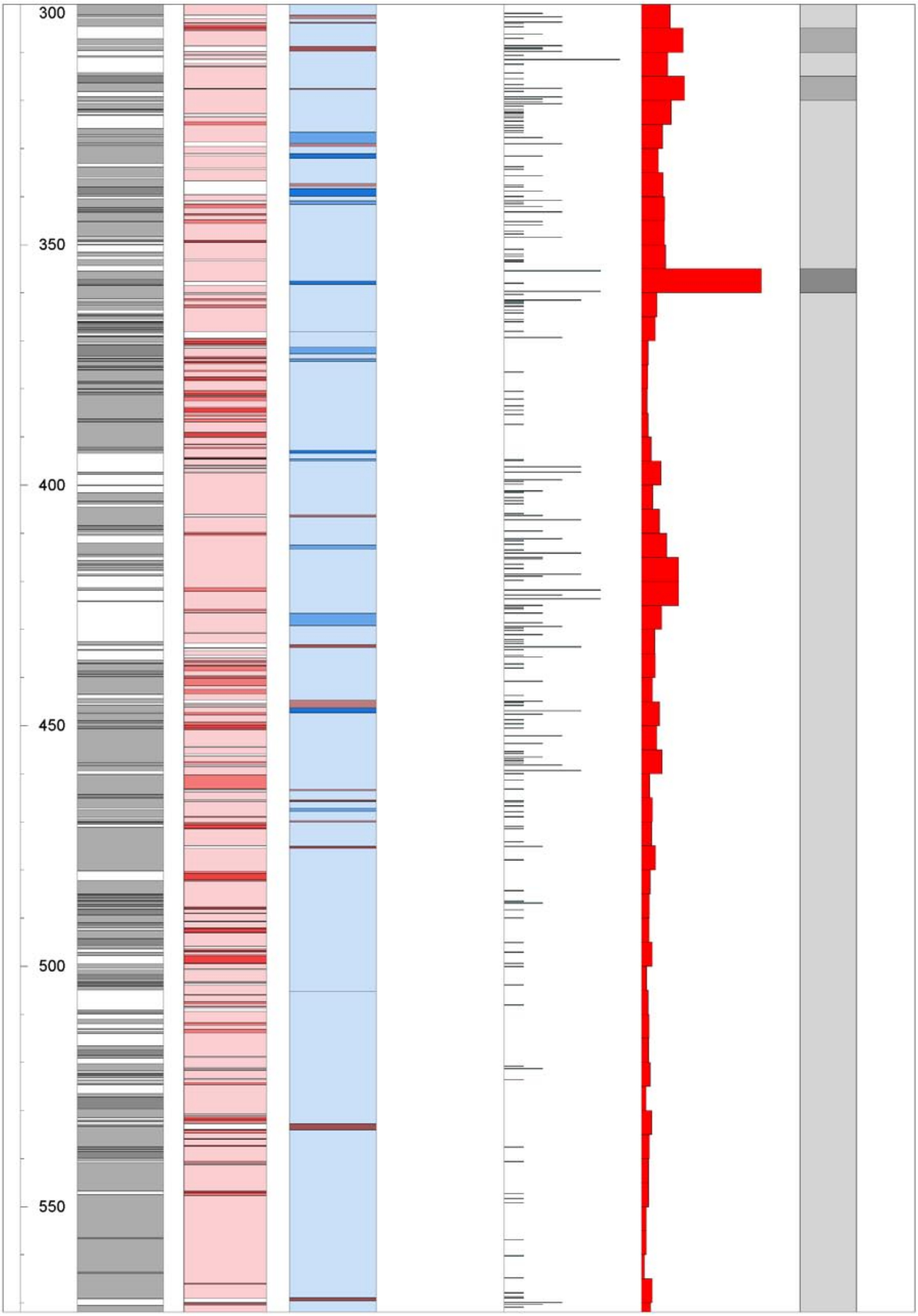
/3/ **Puranen R, 1989.** Susceptibilities, iron and magnetite content of Precambrian rocks in Finland. Geological survey of Finland, Report of investigations 90, 45 pp.

/4/ **Mattsson H, Thunehed H, Keisu M, 2004.** Interpretation of geophysical measurements in KFM01A, HFM01, HFM02 ans HFM03. SKB P-04-89, Svensk Kärnbränslehantering AB.

Appendix 1

Generalized geophysical logs of KFM04A

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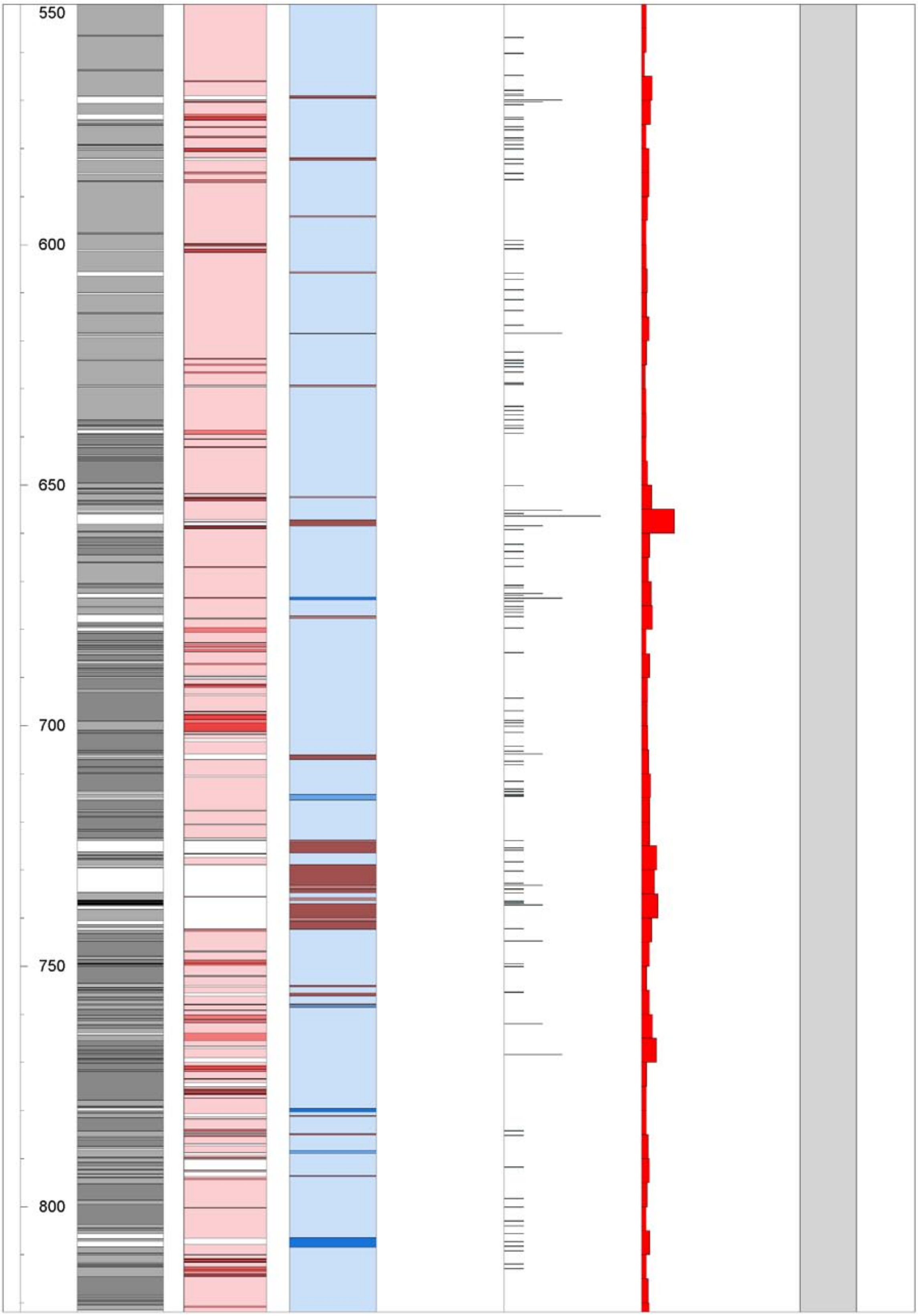

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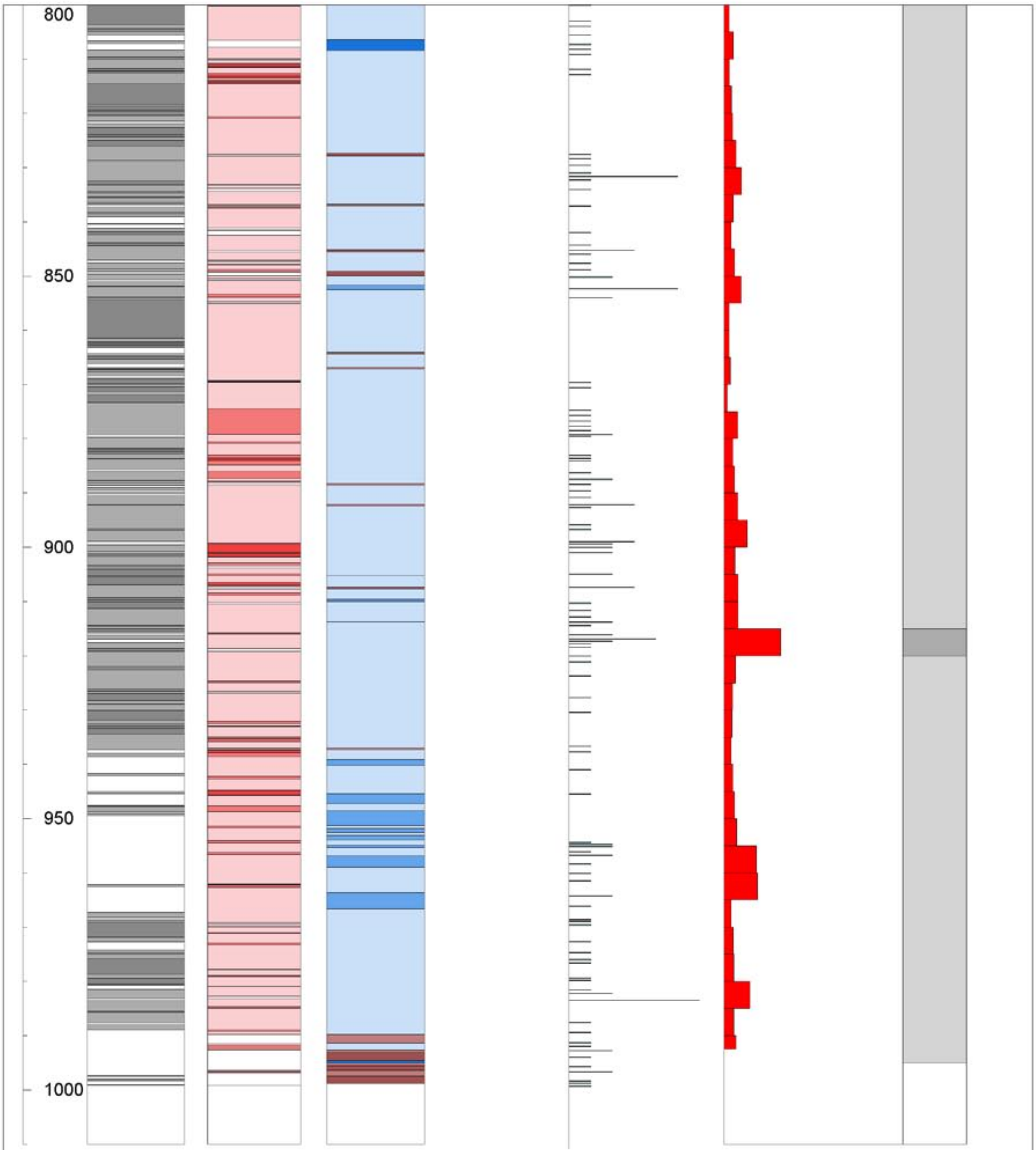
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