P-07-129

Forsmark site investigation

Interpretation of geophysical borehole measurements from KFM12A

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June 2007

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ISSN 1651-4416
SKB P-07-129

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Keywords: Borehole, logging, geophysics, geology, bedrock, fractures, Forsmark, AP PF 400-07-033.

Abstract

This report presents the compilation and interpretations of geophysical logging data from the cored borehole KFM12A.

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 silicate density, natural gamma radiation and magnetic susceptibility logs clearly indicate a heterogeneous distribution of rock types in the vicinity of KFM12A. Rocks with an indicated granitic to granodioritic mineral composition occur most frequent, but there are also rather large occurrences of rocks with higher densities.

The fracture frequency estimated from the geophysical logs indicates an unusually high level of fracturing with reference to the majority of the investigated boreholes in the Forsmark area. In the upper half of the borehole, c 60–370 m, there is a dominance of intervals with partly and significantly increased fracture frequency. In the lower half of the borehole, c 370–600 m, the fracture frequency is mainly low. The increased fracturing along the upper half of KFM12A is clearly reflected in decreased magnetic susceptibility and increased porosity.

Sections with significantly increased estimated fracture frequency (possible deformation zones) occur at c 83–90 m, 212–251 m, 265–277 m, 310–340 m, 356–372 m and 514–524 m. The most prominent possible deformation zone occurs in the section c 212–251 m, and it is characterized by a core at c 230-240 m in which most geophysical logs show major anomalies (such as significantly decreased density, resistivity, P-wave velocity and magnetic susceptibility).

Sammanfattning

Föreliggande rapport presenterar en sammanställning och tolkning av geofysiska borrhålsmätningar från kärnborrhålet KFM12A.

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, dels som underlag vid den geologiska enhålstolkningen.

Silikatdensiteten, den naturliga gammastrålningen och magnetiska susceptibiliteten varierar kraftigt i KFM12A vilket indikerar en heterogen bergartsfördelning i närheten av borrhålet. Det finns en dominans av silikatdensitet som indikerar en mineralsamman-sättning motsvarande den för granit och granodiorit, men högre densiteter är också vanligt förekommande.

Den uppskattade sprickfrekvensen är ovanligt hög i KFM12A jämfört med de flesta andra borrhål i Forsmarksområdet. I borrhålets övre halva, ca 60–370 m, är det en dominans av förhöjd till mycket förhöjd beräknad sprickfrekvens. I den nedre halvan, ca 370-600 m, är dock sprickfrekvensen generellt låg. Den förhöjda sprickigheten i borrhålets övre halva avspeglar sig även i form av förhöjd skenbar porositet samt avvikande låg magnetisk susceptibilitet.

Sektioner med kraftigt förhöjd sprickfrekvens, möjliga deformationszoner, kan identifieras längs ca 83–90 m, 212–251 m, 265–277 m, 310–340 m, 356–372 m och 514–524 m. Den mest prominenta möjliga deformationszonen förekommer vid ca 212–251 m och har en indikerad zonkärna vid ca 230–240 m. Zonkärnan karaktäriseras av kraftigt sänkt resistivitet, P-vågshastighet, magnetisk susceptibilitet och densitet.

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 KFM12A 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 borehole. The logging measurements were conducted in 2007 by Rambøll /1/.

The interpretation presented in this report is performed by GeoVista AB in accordance with the instructions and guidelines from SKB (Table 1-1).

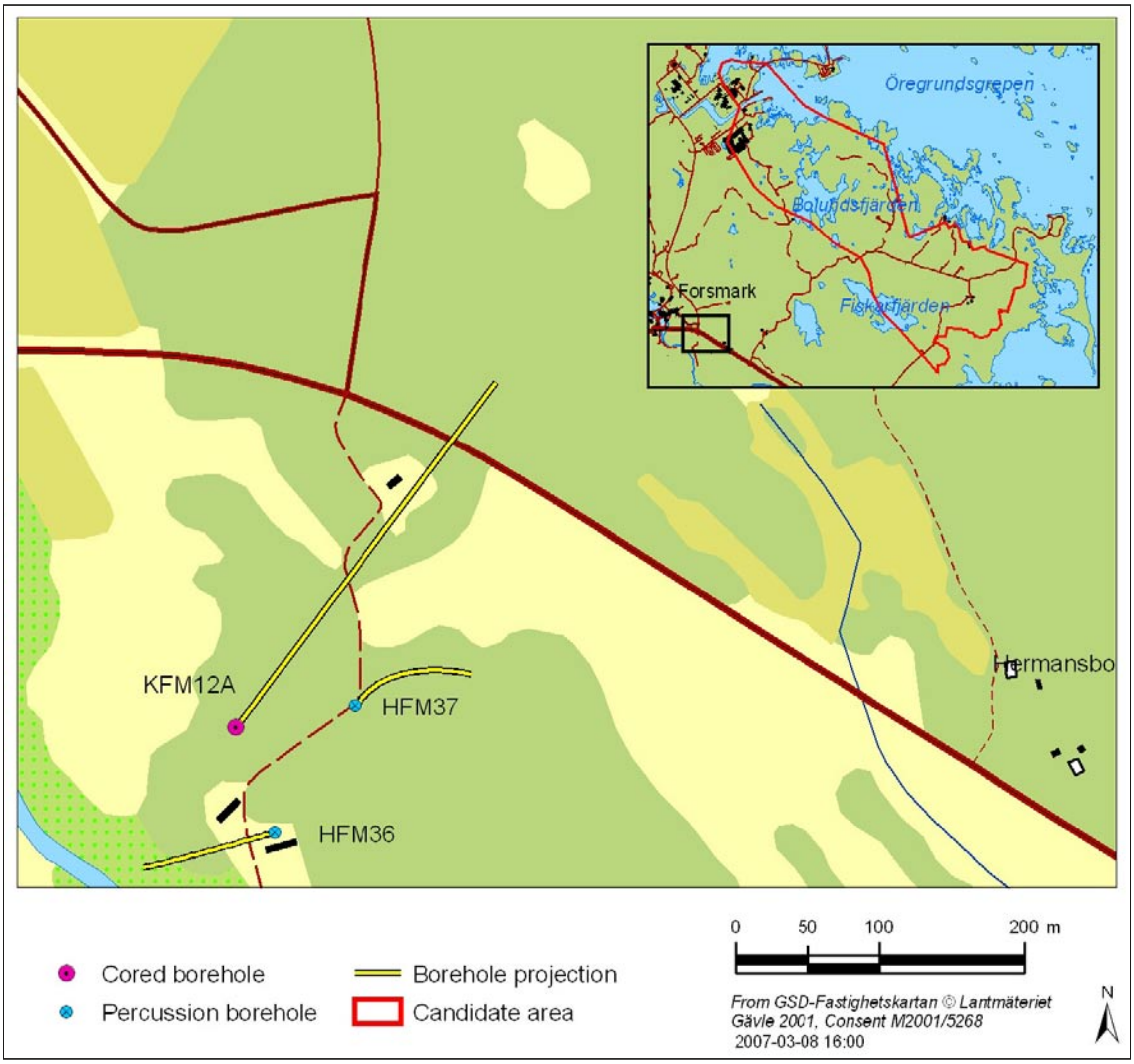

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Figure 1-1. *Map showing the location of the borehole KFM12A.*

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

Activity plan	Number	Version
Tolkning av geofysiska borrhålsdata från KFM12A	AP PF 400-07-033	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för tolkning av geofysiska borrhålsdata	SKB MD 221.003	3.0

Original data from the reported activity are stored in the primary database Sicada, where they are traceable by the Activity Plan number (AP PF 400-07-033). Only data in SKB's databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major data revisions entail a revision of the P-report. Minor data revisions are normally presented as supplements, available at www.skb.se.

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 v 3.2 (ALT) and Strater 1.00.24 (Golden Software), that are mainly used for plotting, Grapher v 5 (Golden Software), mainly used for plotting and some statistical analyses, and a number of in-house software developed by GeoVista AB on behalf of SKB.

4 Execution

4.1 Interpretation of the logging data

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

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

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

The density logging data are calibrated with respect to petrophysical data from KLX20A /2/. The magnetic susceptibility logging data are calibrated with respect to a combination of petrophysical data from the boreholes KFM01A and KFM02A /3 and 4/.

2. Interpretation 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 sections indicating a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to /6/. The sections are bounded by the threshold values

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

The magnetic susceptibility logging is subdivided into steps of decades and the natural gamma radiation is divided into steps of “low” (< 20 μR/h), “medium” (20 μR/h < gamma < 36 μR/h), “high” (36 μR/h < gamma < 53 μR/h) and “very high” (>53 μR/h).

3. For the cored boreholes the normal resistivity loggings are corrected for the influence of the borehole diameter and the borehole fluid resistivity. The apparent porosity is calculated during the correction of the resistivity loggings. The calculation is based on Archie’s law /7/; $\sigma = a\,\sigma_w^k\,\varphi^m + \sigma_s$ 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 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 (°C) 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 4-1) 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 4-1.

5. Report evaluating the results.

4.2 Preparations and data handling

The logging data were delivered as Microsoft Excel files via email from SKB's database Sicada. The data of each logging method were saved separately in ASCII-files. The data processing was performed on the ASCII-files. The data used for interpretation were:

- Density (gamma-gamma).
- Magnetic susceptibility.
- Natural gamma radiation.
- Focused resistivity (300 cm).
- Focused resistivity (140 cm).
- Sonic (P-wave).
- Caliper mean.
- Caliper 1D.
- SPR (Single Point Resistance).
- Short normal resistivity (16 inch).
- Long normal resistivity (64 inch).
- Fluid resistivity.
- Fluid temperature.

4.3 Analyses and interpretations

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

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

4.4 Nonconformities

Apparent porosity calculations and corrections for the borehole diameter and fluid resistivity are not presented for the long normal resistivity loggings since the calculation show unrealistic values.

Table 4-1. 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	KFM12A	1.15	3.5	2.0	0.5	3.0	5.0	6.0	–
Weight	KFM12A	4.0	2.56	4.0	2.0	2.56	0.24	1.75	–

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. The natural gamma radiation data, the magnetic susceptibility, the density and the sonic data have noise levels clearly above the recommended values. Especially the magnetic susceptibility data must be pointed out with a noise that is four times larger than the recommended level. The noise levels of the natural gamma radiation, density and sonic logs are however low enough to fully allow a reliable interpretation of the data. To reduce the influence of the noise, all logs were average 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.

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 metre sections.
- Classification of estimated fracture frequency (0 to 3, 3 to 6 and > 6 fractures/m).

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

Logging method	KFM12A	Recommended max noise level
Density (kg/m^3)	8	3–5
Magnetic susceptibility (SI)	4×10^{-4}	1×10^{-4}
Natural gamma radiation (μR/h)	0.7	0.3
Long normal resistivity (%)	0.2	2.0
Short normal resistivity (%)	0.1	2.0
Fluid resistivity (%)	0.01	2
Fluid temperature (°C)	3×10^{-4}	0.01
Lateral resistivity (%)	Not used	2
Single point resistance (%)	0.1	No data
Caliper (meter)	0.03×10^{-3}	0.5×10^{-3}
Focused resistivity 300 (%)	12	No data
Focused resistivity 140 (%)	2	No data
Sonic (m/s)	34	20

5.2.1 Interpretation of KFM12A

The results of the generalized logging data and fracture estimations of KFM12A are presented in Figure 5-1, and in a more detailed scale in Appendix 1. The distribution of silicate density classes with borehole length is presented in Table 5-2.

The silicate density, natural gamma radiation and magnetic susceptibility logs clearly indicate a heterogeneous distribution of rock types in the vicinity of KFM12A (Figure 5-1). Rocks with an indicated granitic to granodioritic mineral composition occur most frequent but there are also rather large occurrences of rocks with higher densities (Table 5-2).

The section c 60–150 m is dominated by decreased natural gamma radiation and partly increased silicate density. The following section, c 150–290 m, is dominated by silicate density < 2,680 kg/m^3 and natural gamma radiation in the interval 20–36 μR/h, which is typical for granite rock. There are major variations in the physical properties in the section c 290–540 m and all 5 density classes occur frequently, which indicates a large mixture of different rock types. The lowermost part of the borehole, c 540–600 m, is dominated by silicate density that corresponds to that of granodiorite rock and natural gamma radiation < 20 μR/h.

There are several indications of short intervals with high density, occurring side by side with short positive natural gamma radiation anomalies. This suggests that mafic and felsic dykes are spatially related. A majority of the indicated mafic dykes are most likely amphibolites since they have decreased magnetic susceptibility, which indicates that they have suffered from alteration e.g. due to metamorphose.

The fracture frequency estimated from the geophysical logs indicates an unusually high level of fracturing with reference to the majority of the investigated boreholes in the Forsmark area. In the upper half of the borehole, c 60–370 m, there is a dominance of intervals with partly and significantly increased fracture frequency. However, in the lower half, c 370–600 m, the fracture frequency is mainly low. The increased fracturing along the upper half of KFM12A is clearly reflected in the magnetic susceptibility, which shows a general decrease in the section c 60–400 m.

Decreased magnetic susceptibility (when not related to lithological variations) is often related to increased fracturing and/or alteration. Sections with significantly increased estimated fracture frequency (possible deformation zones) occur at c 83–90 m, 212–251 m, 265–277 m, 310–340 m, 356–372 m and 514–524 m. The geophysical characteristics of these possible deformation zones are presented in Table 5-3. The most prominent possible deformation zone occurs in the section c 212–251 m, and it is characterized by a core at c 230–240 m in which most geophysical logs show major anomalies (such as significantly decreased density, resistivity, P-wave velocity and magnetic susceptibility).

Table 5-2. Distribution of silicate density classes with borehole length in KFM12A.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	206	38
2,680 < dens < 2,730 (granodiorite)	157	29
2,730 < dens < 2,800 (tonalite)	90	17
2,800 < dens < 2,890 (diorite)	44	8
dens > 2,890 (gabbro)	39	8

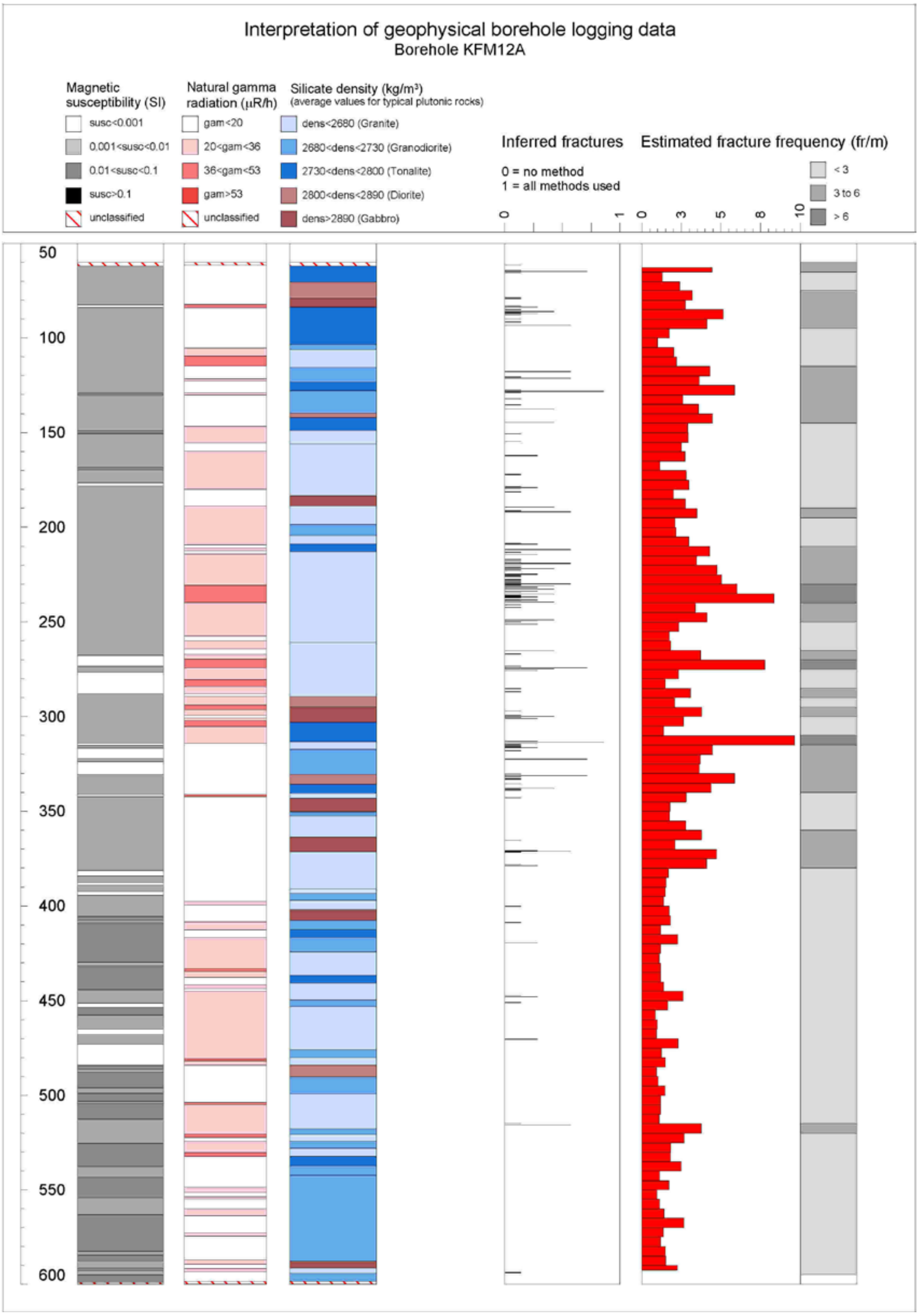

Figure 5-1. *Generalized geophysical logs of KFM12A.*

Table 5-3. Possible deformation zones in KFM12A and their geophysical signature.

Section co-ordinates (m)	Resistivity	P-wave velocity (sonic)	Magnetic susceptibility	Borehole diameter (caliper)
83–90	Significantly decreased	Partly decreased	Significantly decreased	No anomalies
212–251	Significantly decreased	Significantly decreased	Significantly decreased	One major anomaly
265–277	Significantly decreased	No anomaly	Significantly decreased	Major anomalies
310–340	Significantly decreased	Partly decreased	Significantly decreased	Several anomalies
356–372	Significantly decreased	Partly increased (amphibolite?)	Partllly decreased	General increase
514–524	Significantly decreased	Minor anomalies	Partly decreased	No anomalies

The apparent porosity (Figure 5-2) averages at c 0.65% which is normal for rocks in the Forsmark area. The most significant porosity anomaly occurs in the interval c 230–240 m. The section c 60–380 m is characterized by an increased number of high porosity anomalies that generally coincide with the possible deformation zones. This interval also coincides with the indicated increased fracturing and the decreased magnetic susceptibility reported in previous paragraphs.

The vertical temperature gradient (Figure 5-2) averages at c 10.5°C/km. Anomalies in the temperature gradient can be related to in or out flow of water in fractures. The most prominent anomalies in the vertical temperature gradient occur at c 75–90 m, 133–153 m, 313–328 m and 358–382 m.

The estimated fluid water salinity (Figure 5-2) is fairly constant at c 4,000 ppm NaCl in the section c 60–350 m. In the section c 350-530 m the salinity is increased and shows variation in the interval c 4,500–6,000 ppm NaCl. Observe that the start of the salinity increase at c 350 m is spatially related to the most prominent temperature gradient anomaly. At c 530 m and down to the bottom of the borehole the salinity decreases, ending at c 3,500 ppm NaCl.

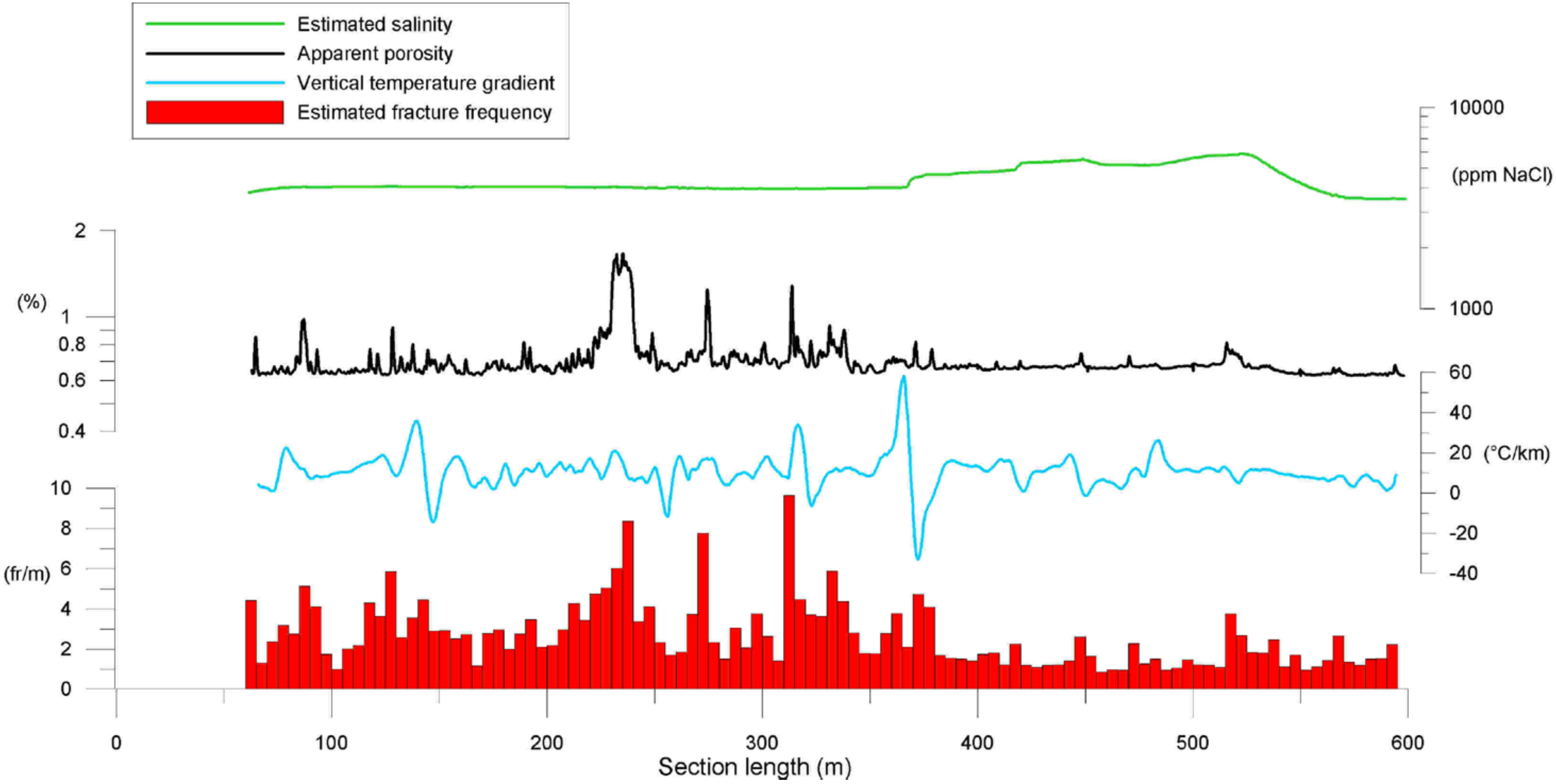

***Figure 5-2.** Estimated salinity, apparent porosity, vertical temperature gradient and estimated fracture frequency of KFM12A.*

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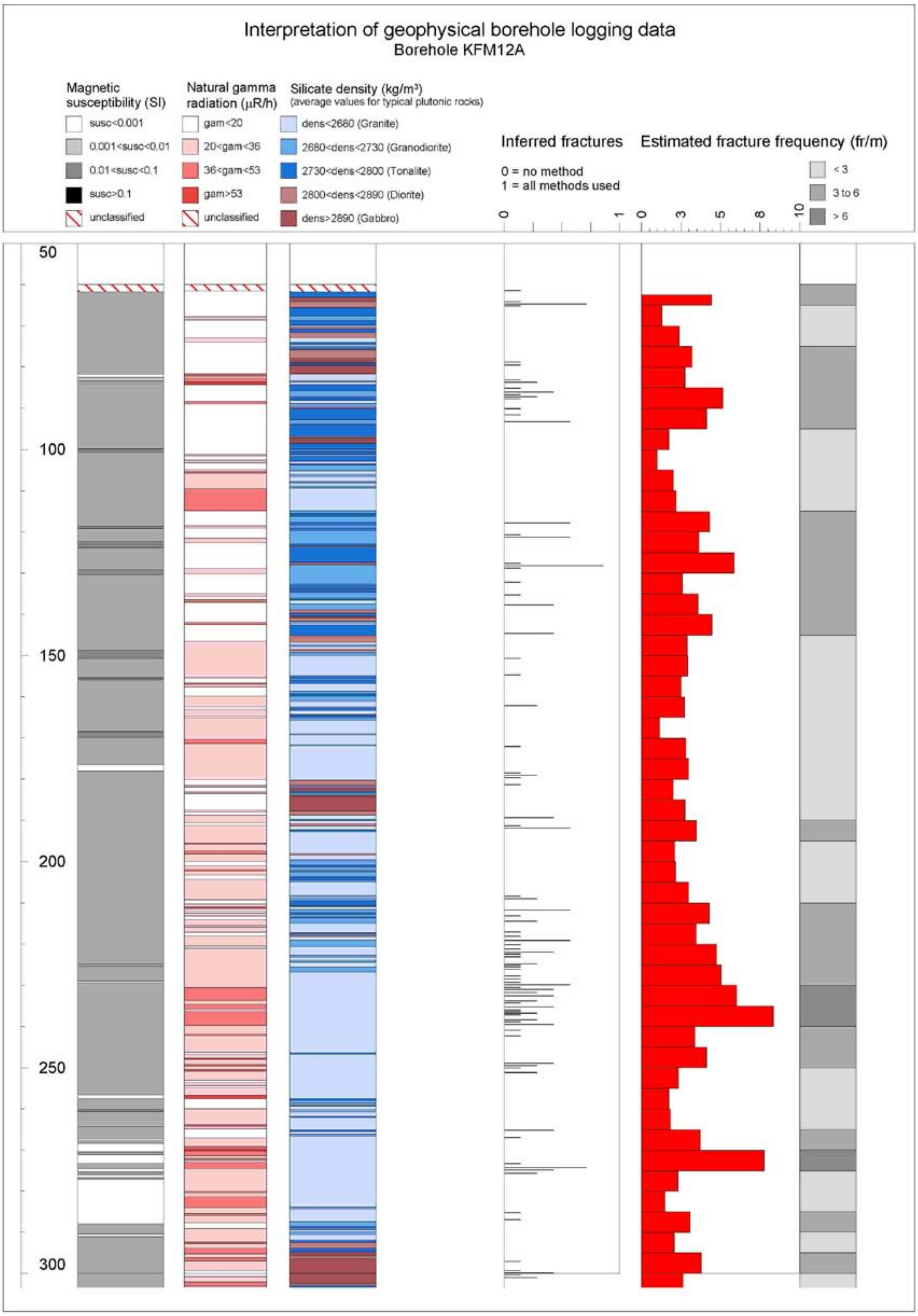
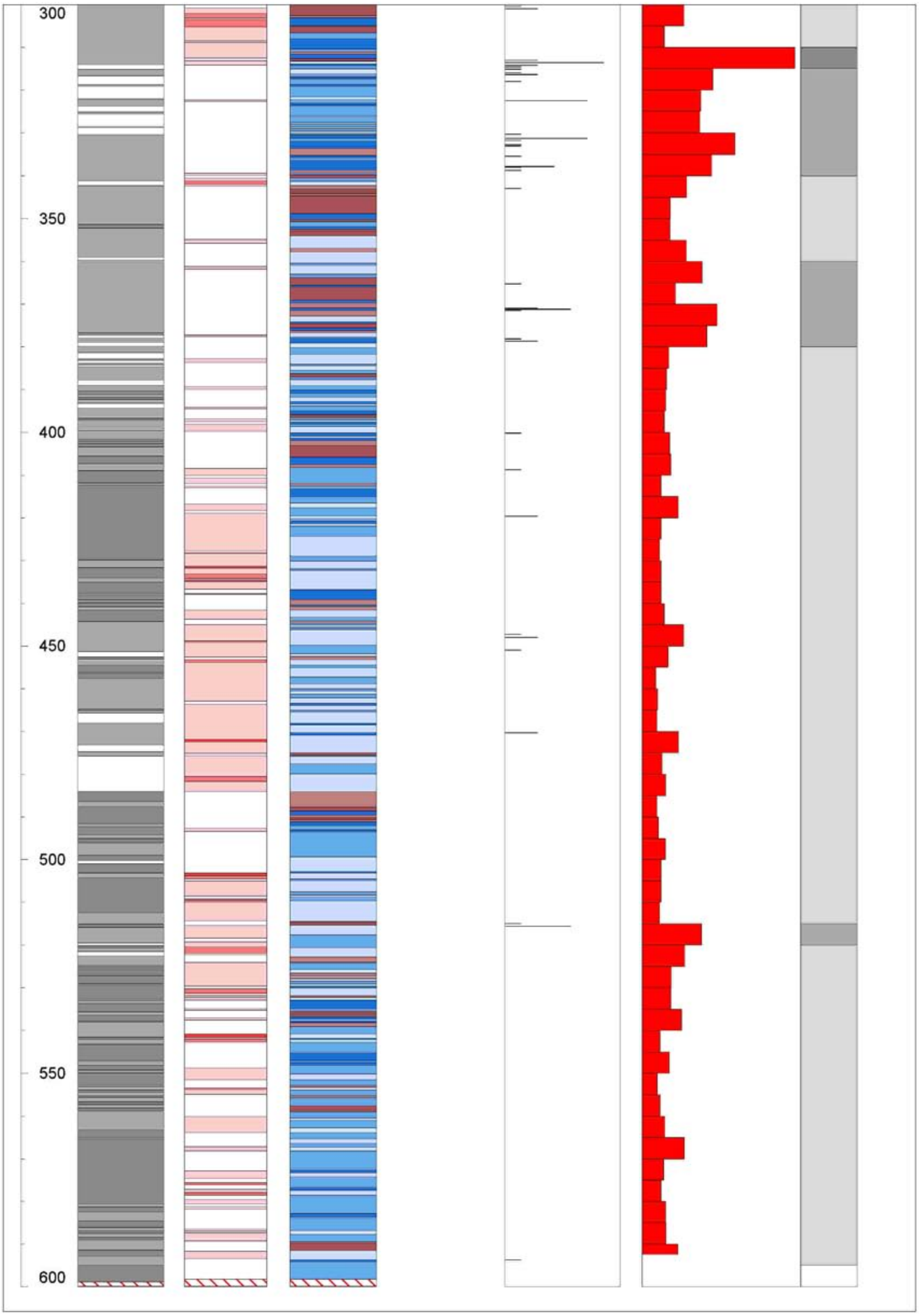
Appendix 1

Generalized geophysical loggings of KFM12A

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