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Oskarshamn site investigation

Interpretation of geophysical borehole measurements from KLX07A, KLX07B, HLX20, HLX32, HLX34 and HLX35

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Abstract

This report presents the compilation and interpretations of geophysical logging data from the cored boreholes KLX07A and KLX07B, and the percussion drilled boreholes HLX20, HLX32, HLX34 and HLX35.

The main objective of the investigation is to use the results as supportive information during the geological core and drill bit mappings and as supportive information during the single-hole interpretations.

Approximately 95% of the rocks in the vicinity of KLX07A have a silicate density < 2,730 kg/m^3 and a natural gamma radiation of 20–30 μR/h, and this most likely indicates that Ävrö granite with a granitic to granodioritic mineral composition dominates the rock occurrence close to this borehole. The silicate density distribution of the rocks in the vicinity of KLX07B clearly differs from the distribution in KLX07A. There is a dominance of densities in the intervals 2,680–2,730 kg/m^3 and 2,730–2,800 kg/m^3, indicating greater occurrences of more rocks with increased density in KLX07B compared to KLX07A. A corresponding lower natural gamma radiation level is also identified in KLX07B. In the four percussion drilled boreholes there is a general dominance of silicate density in the two lowest density groups, silicate density < 2,680 kg/m^3 and 2,680 kg/m^3 < silicate density < 2,730 kg/m^3. Sections with silicate density < 2,680 kg/m^3 generally coincide with natural gamma radiation in the interval 20–30 μR/h, whereas sections with silicate density in the range 2,680–2,730 kg/m^3 generally coincide with natural gamma radiation in the interval 10–20 μR/h.

Sections of high density (> 2,850 kg/m^3) and low natural gamma radiation (< 10 μR/h) are extremely rare in KLX07A, which suggests that there are no, or negligible, occurrences of diorite to gabbro rocks close to the borehole. Indications of high density rocks are generally rare in all 6 investigated boreholes, but a few 5–10 m long sections of possible fine-grained diorite to gabbro rock are identified in KLX07B, HLX34 and HLX35. Indications of dykes of fine-grained granite and/or pegmatite (generally < 1 m section length) occur rather commonly in KLX07A, KLX07B, HLX20 and HLX32, but are rare in HLX34 and HLX35.

In KLX07A and KLX07B the estimated fracture frequency is mainly moderate. Possible deformation zones are identified in KLX07A at 110–145 m, 385–390 m, 450–455 m, 635–650 m, and 760–785 m. In KLX07B one possible minor deformation zone is identified at c 125–130 m. The sections with high fracture frequency are generally characterized by low P-wave velocity, major decrease in the electric resistivity, increased borehole diameter and low magnetic susceptibility. In the section 550–800 m of KLX07A there are 5 or 6 significant temperature gradient anomalies that indicate water bearing fractures and the apparent rock porosity shows anomalously high values in the sections c 100–150 m and c 600–650 m and 740–785 m. Long sections (> 20 m) with high fracture frequency are also indicated in HLX32 (100–125 m) and in HLX35 (115–145 m).

In KLX07B and HLX35 there are indications of a spatial relation between the occurrence of fine-grained granite and fine-grained diorite to gabbro in combination with increased fracture frequency.

Sammanfattning

Föreliggande rapport presenterar en sammanställning och tolkning av geofysiska borrhålsmätningar från kärnborrhålen KLX07A och KLX07B samt hammarborrhålen HLX20, HLX32, HLX34 och HLX35.

Syftet med undersökningen 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 borrkärne- och borrkaxkarteringen samt som underlag vid enhålstolkningen.

Ungefär 95 % av bergarterna i närheten av KLX07A har en silikatdensitet < 2 730 kg/m^3 och en naturlig gammastrålning 20–30 µR/h, och dessa värden är typiska för Ävrögranit med en granit till granodioritisk mineralsammansättning. Fördelningen på silikatdensiteten i KLX07B skiljer sig från den i KLX07A. I KLX07B finns en dominans av densitetsvärden i intervallet 2 680–2 800 kg/m^3, vilket indikerar större förekomst av tyngre bergarter i KLX07B jämfört med KLX07A. En lägre nivå på den naturliga gammastrålningen i KLX07B stödjer detta. I de fyra hammarborrade hålen finns en klar dominans av silikatdensitet i intervallen < 2 680 kg/m^3 och 2 680–2 730 kg/m^3. Sektioner med densitet < 2 680 kg/m^3 har generellt en naturlig gammastrålning i intervallet 20–30 µR/h medan sektioner med silikatdensitet i intervallet 2 680–2 730 kg/m^3 har en naturlig gammastrålning i intervallet 10–20 µR/h.

Sektioner med hög densitet (> 2 850 kg/m^3) och låg naturlig gammastrålning (< 10 µR/h) är mycket ovanliga i KLX07A, vilket indikerar att andelen diorit till gabbro runt borrhålet är mycket låg. I allmänhet finns få sektioner med hög densitet i alla de undersökta borrhålen, med undantag av några enstaka 5–10 m långa intervall med tolkad finkornig diorit till gabbro som kan identifieras i KLX07B, HLX34 och HLX35. Indikationer på förekomst av gångar av pegmatit och/eller finkornig granit (< 1 m sektionslängd) är vanliga i KLX07A, KLX07B, HLX20 och HLX32, och är relativt ovanliga i HLX34 och HLX35.

Den uppskattade sprickfrekvensen i KLX07A och KLX07B är mestadels medelhög. Möjliga deformationszoner kan identifieras i intervallen 110–145 m, 385–390 m, 450–455 m, 635–650 m och 760–785 m av KLX07A. I KLX07B finns en trolig mindre deformationszon vid 125–130 m. De möjliga deformationszonerna karaktäriseras generellt av låg P-vågshastighet, kraftigt sänkt resistivitet, utökad borrhålsdiameter och låg magnetisk susceptibilitet. Längs sektionen 550–800 m i KLX07A finns 5 eller 6 kraftiga anomalier i temperaturgradienten som troligen indikerar förekomst av vattenförande sprickzoner. Dessutom indikerar den skenbara porositetsloggen förhöjd porositet längs intervallen 100–150 m, 600–650 m och 740–785 m av KLX07A. I två av de undersökta hammarborrhålen, HLX32 (sektion 100–125 m) och HLX35 (115–145 m), kan långa sektioner (> 20 m) identifieras med kraftigt förhöjd uppskattad sprickfrekvens.

I KLX07B och i HLX35 finns två tydliga indikationer på ett rumsligt samband mellan förekomst av finkornig diorit till gabbro och finkornig granit i kombination med förhöjd sprickfrekvens.

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 Oskarshamn. This document reports the results gained from the interpretation of geophysical borehole logging data from the cored boreholes KLX07A and KLX07B, and the percussion drilled boreholes HLX20, HLX32, HLX34 and HLX35, all located in Laxemar, Oskarshamn.

Generalized geophysical loggings related to lithological variations are presented together with indicated fracture loggings, including estimated fracture frequency. Calculations of the vertical temperature gradient, salinity and apparent porosity are presented for the cored boreholes. The logging measurements were conducted in 2005 by Rambøll.

The interpretation presented in this report is performed by GeoVista AB in accordance with the instructions and guidelines from SKB (activity plan AP PS 400-05-054 and method description MD 221.003, SKB internal controlling documents), Table 1-1.

Figure 1-1 shows the location of boreholes KLX07A, KLX07B, HLX20, HLX32, HLX34 and HLX35 in Laxemar. The interpreted results are stored in the primary data base SICADA and are traceable by the activity plan number.

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

Activity plan	Number	Version
Tolkning av borrhålsgeofysiska data från KLX07A, KLX07B, HLX32, HLX34 OCH HLX35.	AP PS 400-05-054	1.0
Tillägg avseende tolkning av borrhålsgeofysiska data från HLX20.	Tillägg till AP PS 400-05-054 avseende HLX20	
Method descriptions	**Number**	**Version**
Metodbeskrivning för tolkning av geofysiska borrhålsdata.	SKB MD 221.003	2.0

Figure 1-1. *Location of the boreholes KLX07A, KLX07B, HLX20, HLX32, HLX34 and HLX35.*

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.

The vertical temperature gradient, an estimation of the salinity and the apparent porosity are presented for the cored borehole. These parameters indicate the presence of water bearing fractures, saline water and the transportation properties of the rock volume in the vicinity of the borehole.

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

3 Equipment

3.1 Description of equipment for analyses of logging data

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

4 Execution

4.1 Interpretation of the logging data

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

1. Preparations of the logging data (calculations of noise levels, 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 section co-ordinates (0.1 m point distance).

The density and magnetic susceptibility logging data are calibrated with respect to petro-physical data. The logging data were calibrated by use of a combination of petrophysical data from the boreholes KLX02, KLX03, KLX04, KSH01A, KSH02, KSH03A and KAV04A, see /1, 2, 3, 4, 5/.

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

The silicate density is calculated with reference to /6/ and the data are then divided into 5 sections **indicating** a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to /7/. 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" (< 10μR/h), "medium" (10 μR/h < gamma < 20 μR/h), "high" (20 μR/h < gamma < 30 μR/h) and "very high" (> 30 μR/h).

3. For the cored borehole 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 /8/; $\sigma = a\, \sigma_w\, \varphi^m + \sigma_s$ 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" and "m" are constants. Since "a" and "m" vary significantly 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 vertical temperature gradient (in degrees/km) is calculated from the fluid temperature logging for 9 m sections according to the following equation /9/:

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

where z = depth co-ordinate (m), t = fluid temperature (°C) and φ = borehole inclination (°). The vertical temperature gradient 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 logging for each method respectively, and then calculating the total sum of all power functions. Parameters for the power functions were estimated by correlating the total weighted sum to the mapped fracture frequency in the cored boreholes KLX03 and KLX04 /1/. The powers and linear coefficients (weights) used are presented in Table 4-1.

5. Report evaluating the results.

Table 4-1. Threshold values, powers 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	KLX07A	2.0	1.5	1.5	0.5	3.0	–	7.0	–
Power	KLX07A	1.0	1.0	1.6	1.0	0.5	–	0.6	–
Weight	KLX07A	1.0	7.1	6.7	1.0	5.0	–	5.0	–
Threshold	KLX07B	1.3	1.5	1.5	0.5	3.0	4.0	5.8	–
Power	KLX07B	1.0	1.0	1.6	1.0	0.5	0.5	0.6	–
Weight	KLX07B	1.0	7.1	6.7	1.0	5.0	2.9	5.0	–
Threshold	HLX20	1.4	1.4	1.4	0.5	1.0	4.0	4.0	–
Power	HLX20	1.0	1.0	1.6	1.0	0.5	0.5	0.6	–
Weight	HLX20	1.0	7.1	6.7	1.0	5.0	2.9	5.0	–
Threshold	HLX32	1.8	1.4	1.4	0.5	1.0	4.0	4.0	–
Power	HLX32	1.0	1.0	1.6	1.0	0.5	0.5	0.6	–
Weight	HLX32	1.0	7.1	6.7	1.0	5.0	2.9	5.0	–
Threshold	HLX34	1.7	1.2	1.2	0.4	1.0	4.0	4.0	–
Power	HLX34	1.0	1.0	1.6	1.0	0.5	0.5	0.6	–
Weight	HLX34	1.0	7.1	6.7	1.0	5.0	2.9	5.0	–
Threshold	HLX35	1.3	1.2	1.2	0.5	1.0	4.0	4.0	–
Power	HLX35	1.0	1.0	1.6	1.0	0.5	0.5	0.6	–
Weight	HLX35	1.0	7.1	6.7	1.0	5.0	2.9	5.0	–

4.2 Preparations and data handling

The logging data were delivered as Microsoft Excel files via email from Rambøll. The data of each logging method is saved separately as an ASCII-file. The data processing is performed on the ASCII-files. The data used for interpretation are:

- Density (gamma-gamma).
- Magnetic susceptibility.
- Natural gamma radiation.
- Focused resistivity (300 cm).
- Focused resistivity (140 cm).
- Sonic (P-wave).
- Caliper mean.
- SPR.
- 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 vertical temperature gradient, salinity and apparent porosity help identifying water bearing fractures, saline ground water and porous rocks.

4.4 Nonconformities

The long normal resistivity log of KLX07A was not used in the interpretation at all due to its abnormal behavior. Apparent porosity calculations and corrections for the borehole diameter and fluid resistivity are not presented for the long normal resistivity loggings of KLX07A or KLX07B since the logging data show dubious values. Apart from this, no nonconformities are reported.

5 Results

5.1 Quality controll of the logging data

Noise levels of the raw data for each logging method are presented in Table 5-1. Noise levels are close to or above the recommended levels for the density log, the magnetic susceptibility log and the natural gamma radiation log for all borehoels with the exception of the magnetic susceptibility log of HLX32 that is 10 times below the recommended level. However, the levels are in most cases low enough to allow a meaningful interpretation of the data, apart from the noise of 18 kg/m^3 for the density data of HLX34, which reduces the reliability of this log. Also the sonic log of HLX32 is noisier than what is recommended, but the level is low enough to allow a meaningful interpretation of these 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. Sections with null values are indicated by red and white stripes in the presentation of the generalized loggings (see for example Figure 5-8).

Table 5-1. Noise levels in the investigated geophysical logging data of KLX07A, KLX07B, HLX20, HLX32, HLX34 and HLX35.

Logging method	KLX07A	KLX07B	HLX20	HLX32	HLX34	HLX35	Recommended max noise level
Density (kg/m^3)	8	9	10	13	18	10	35
Magnetic susceptibility (SI)	$2.5\cdot10^{-4}$	$2.7\cdot10^{-4}$	$2.0\cdot10^{-4}$	$0.1\cdot10^{-4}$	$3.0\cdot10^{-4}$	$3.0\cdot10^{-4}$	$1\cdot10^{-4}$
Natural gamma radiation (μR/h)	0.3	0.3	0.3	0.5	0.5	0.3	0.3
Long normal resistivity (%)	Not used	0.9	0.3	0.3	0.4	0.3	2.0
Short normal resistivity (%)	0.3	0.8	0.3	0.2	0.4	0.2	2.0
Fluid resistivity (%)	0.06	0.006	0.01	0.01	0.01	0.06	2
Fluid temperature (°C)	$8\cdot10^{-4}$	$6\cdot10^{-4}$	$6\cdot10^{-4}$	$2\cdot10^{-4}$	$6\cdot10^{-4}$	$1\cdot10^{-3}$	0.01
Lateral resistivity (%)	Not used	Not used	Not used	Not used	Not used	Not used	2
Single point resistance (%)	0.2	0.6	0.3	0.3	0.3	0.2	No data
Caliper (m)	$0.3\cdot10^{-4}$	$0.2\cdot10^{-4}$	$0.2\cdot10^{-3}$	$0.7\cdot10^{-4}$	$3.0\cdot10^{-4}$	$1.4\cdot10^{-4}$	$5\cdot10^{-4}$
Focused resistivity 300 (%)	9.8	12.0	8.9	10.8	11.0	7.7	No data
Focused resistivity 140 (%)	17.1	12.8	7.1	8.7	11.3	5.5	No data
Sonic (m/s)	13	6	7	34	10	11	20

5.2 Interpretation of the logging data

The presentation of interpretation products presented below, in chapter 5.2.1–5.2.6 includes:

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

5.2.1 Interpretation of KLX07A

The results of the generalized logging data and fracture estimations of KLX07A are presented in Figure 5-1 below, and in a more detailed scale in Appendix 1.

A majority of the rocks in the vicinity of KLX07A have a silicate density < 2,680 kg/m^3 (Figure 5-1 and Table 5-2). In these sections with silicate density < 2,680 kg/m^3 the natural gamma radiation is generally 20–30 μR/h, and this combination of low density and fairly high natural gamma radiation is typical for Ävrö granite with a granitic mineral composition. In the section 200–600 m there are several > 10 m long subsections with silicate density in the interval 2,680–2,730 kg/m^3, generally with a corresponding decrease in the natural gamma radiation. The most prominent high density interval occurs at c 454–587 m, and in this section there are also a number of intervals with silicate density in the range 2,730–2,800 kg/m^3. Note the complete lack of silicate density > 2,890 kg/m^3, which indicates that there is no, or very little, occurrence of diorite to gabbro rock in KLX07A.

The magnetic susceptibility is in the range 0.01–0.04 for the majority of the borehole length, which is normal compared to the other cored boreholes in the Laxemar area. Two major low magnetic sections occur at c 110–180 m and 605–655 m, and in these sections the magnetic susceptibility is c 0.0005–0.003 SI. The low magnetic susceptibility is probably related to oxidation or destruction of magnetite caused by alteration of the rock.

Short intervals (< 1 m) with high natural gamma radiation anomalies (> 30 μR/h) occur in the entire borehole, but they are most frequent in the upper 100–500 m. In the upper part of the borehole there are also a few longer sections, 5–15 m, with anomalously high natural gamma radiation. Natural gamma radiation > 30 μR/h most likely indicates the occurrence of fine grained granite and/or pegmatite.

Table 5-2. Distribution of silicate density classes with borehole length of KLX07A.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
2,680 > dens	516	71
2,680 < dens < 2,730	176	24
2,730 < dens < 2,800	35	5
2,800 < dens < 2,890	3	0
dens > 2,890	0	0

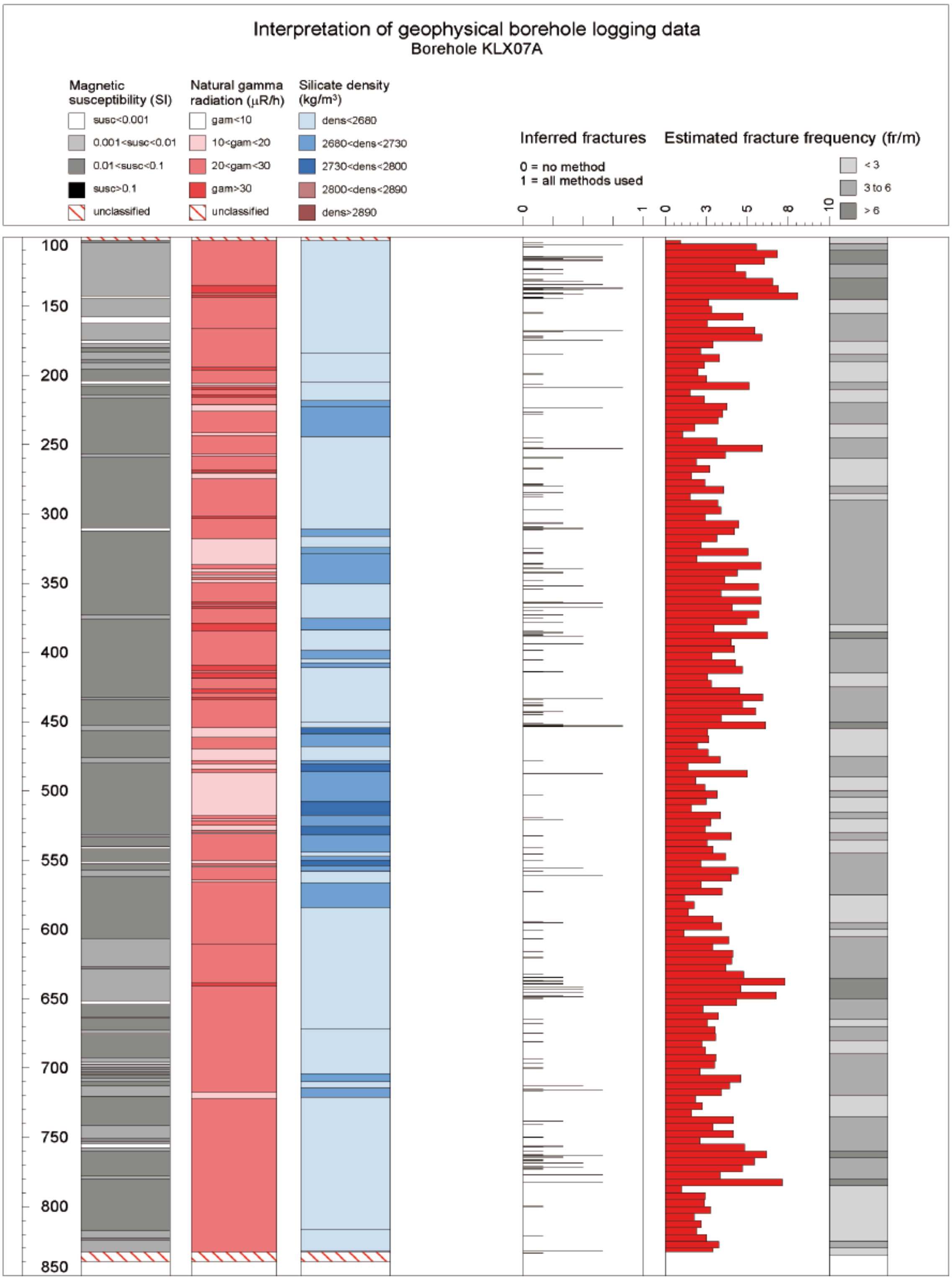

Figure 5-1. Generalized geophysical logs of KLX07A.

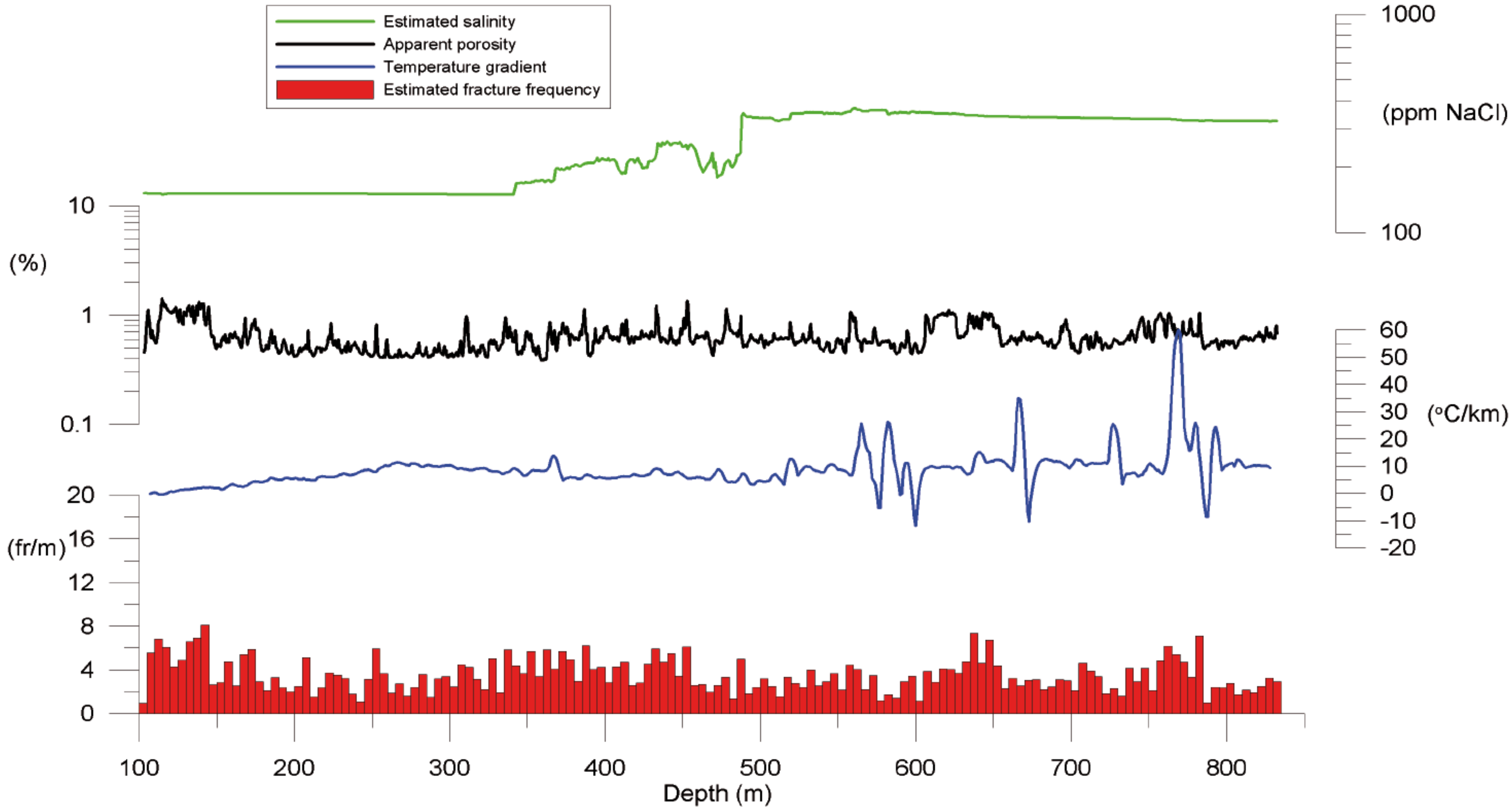

Figure 5-2. *Estimated salinity, apparent porosity, vertical temperature gradient and estimated fracture frequency of KLX07A.*

The estimated fracture frequency of KLX07A is mainly moderate (indicated at 3–6 fractures/m). Sections of indicated high fracture frequency are identified at 110–145 m, 385–390 m, 450–455 m, 635–650 m, and 760–785 m. These sections are characterized by low P-wave velocity, major decrease in the electric resistivity and increased borehole diameter. Note that the two low magnetic sections discussed above coincide with sections of increased fracturing and they also coincide with a major decrease in the bulk resistivity, the latter which is most likely caused by a large number of fractures and/or crushed rock.

The fluid temperature gradient data shows no major anomalies in the section 100–550 m, which indicates that fractures in this section of the borehole do not carry water. In the section 550–800 m there are 5 (or possibly 6) significant temperature gradient anomalies that may indicate the presence of water bearing fractures in these sections. The estimated fluid water salinity is fairly constant at 60–80 ppm NaCl in the section c 100–350 m, between 350 m and 500 m the salinity shows large variations, and in the lower most 550–840 m the salinity is fairly stable at c 300 ppm NaCl.

The apparent rock porosity (estimated from the short normal resistivity logging) indicates a "background level" of c 0.4–0.8%, which is normal for unaltered rocks in this area. However, there are two long sections with anomaously high apparent porosity (> 1%), c 100–150 m and c 600–650 m, and these are coincident with low magnetic susceptibility as noted above. Increased rock porosity is also indicated in the section c 740–785 m.

5.2.2 Interpretation of KLX07B

The results of the generalized logging data and fracture estimations of KLX07B are presented in Figure 5-3 below.

The silicate density distribution of the rocks in the vicinity of KLX07B differs significantly from the distribution in KLX07A (Figure 5-3, Table 5-3). There is a dominance of densities in the intervals 2,680–2,730 kg/m^3 and 2,730–2,800 kg/m^3, which indicate rocks with increased density in KLX07B compared to KLX07A. A corresponding lower natural gamma radiation level is identified in KLX07B, though this is somewhat difficult to see in the generalized logging in Figure 5-3 due to the limits of the radiation level groups. The sections 10–22 m, 41–62 m and 127–192 m are dominated by high silicate density (2,730–2,800 kg/m^3, with a maximum of c 2,940 kg/m^3) and low natural gamma radiation (5–20 µR/h), and remaining parts of the borehole are dominated by silicate density in the range 2,680–2,730 kg/m^3 and natural gamma radiation in the range 20–30 µR/h. The low-density sections most likely indicate the occurrences of Ävrö granite with a granitic mineral composition. Silicate density above 2,800 kg/m^3 most likely indicates the occurrence of diorite to gabbro rock. The most prominent section with indicated diorite to gabbro rock occurs at c 144–154 m. The low magnetic susceptibility in this interval (< 0.001 SI) suggests that the rock type is fine-grained diorite to gabbro.

At c 128–130 m there is a strong positive natural gamma radiation anomaly in the direct vicinity of a high density anomaly, in combination with low susceptibility, and this combination of physical properties is typical for a dyke of fine-grained granite close to a dyke, or enclave, of fine-grained diorite to gabbro (sometimes denoted composite dykes). Also note the anomalously high fracture frequency indicated along this section, which suggests that the combination of fine-grained granite and fine-grained diorite to gabbro is related to increased fracturing.

Apart from the high fracture frequency indicated at c 130 m, the estimated fracture frequency of KLX07B is mainly moderate, or low. However, in the sections c 40–65 m and 127–170 m there is a general decrease in the bulk resistivity, which possibly could be related to sealed fractures and/or alteration. However, the lack of sonic anomalies in these sections indicates that no, or only few, open fractures occur.

There are no significant anomalies indicating water bearing fractures in the fluid temperature gradient data (Figure 5-4). The estimated pore water salinity is fairly constant at c 160–180 ppm NaCl down to c 170 m section length, where there is a rapid increase of the salinity level up to c 210 ppm NaCl. The general level of the apparent porosity is c 0.5–0.8%, which is normal for unaltered rocks in this area. Three significant porosity highs (> 1%) are identified at c 28–30 m, 40–42 m and 128–134 m. The anomaly at 128–134 m coincides with the section of high fracture frequency discussed in the previous paragraphs.

Table 5-3. Distribution of silicate density classes with borehole length of KLX07B.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
2,680 > dens	24	13
2,680 < dens < 2,730	88	47
2,730 < dens < 2,800	64	34
2,800 < dens < 2,890	9	5
dens > 2,890	2	1

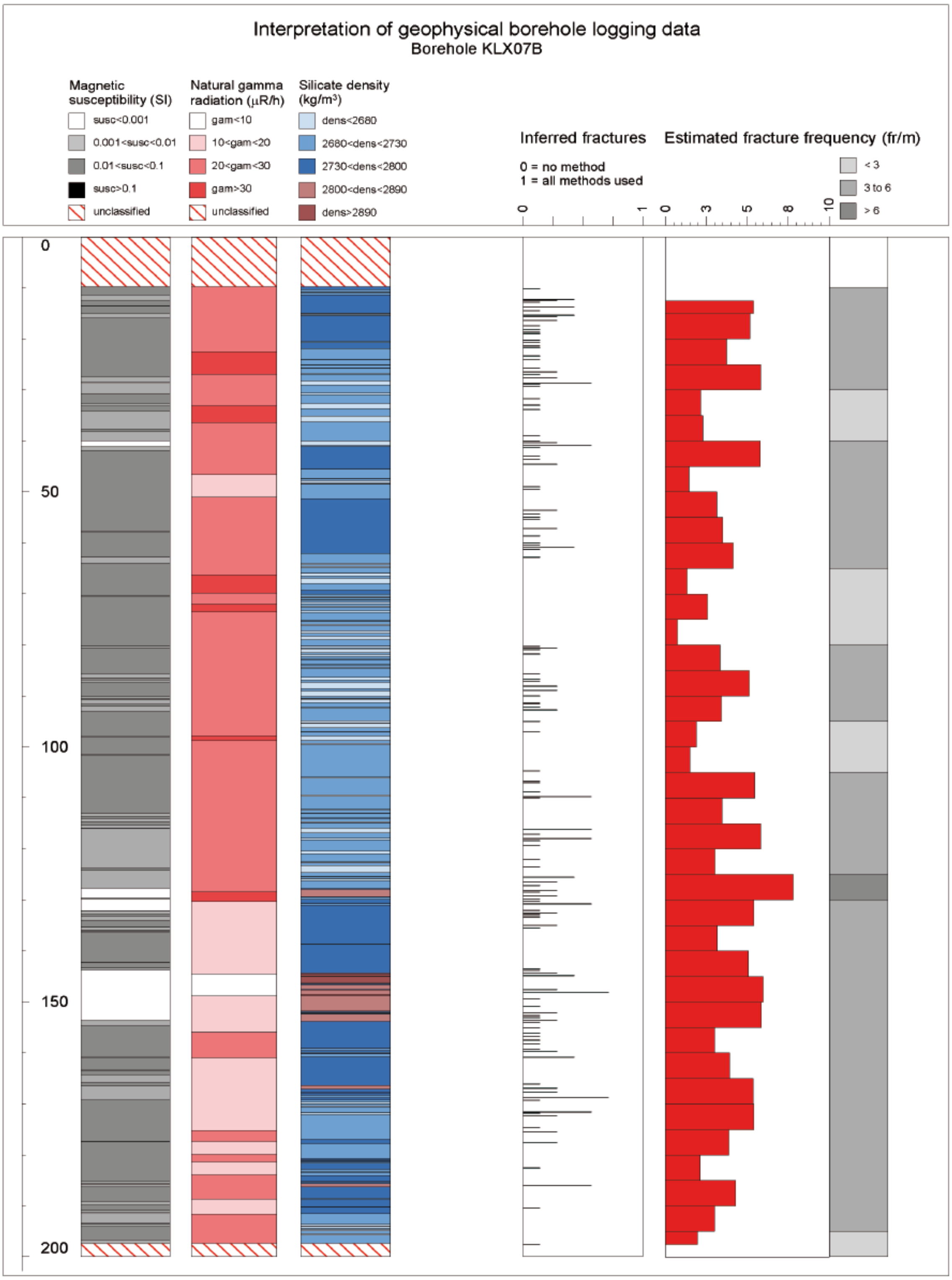

Figure 5-3. *Generalized geophysical logs of KLX07B.*

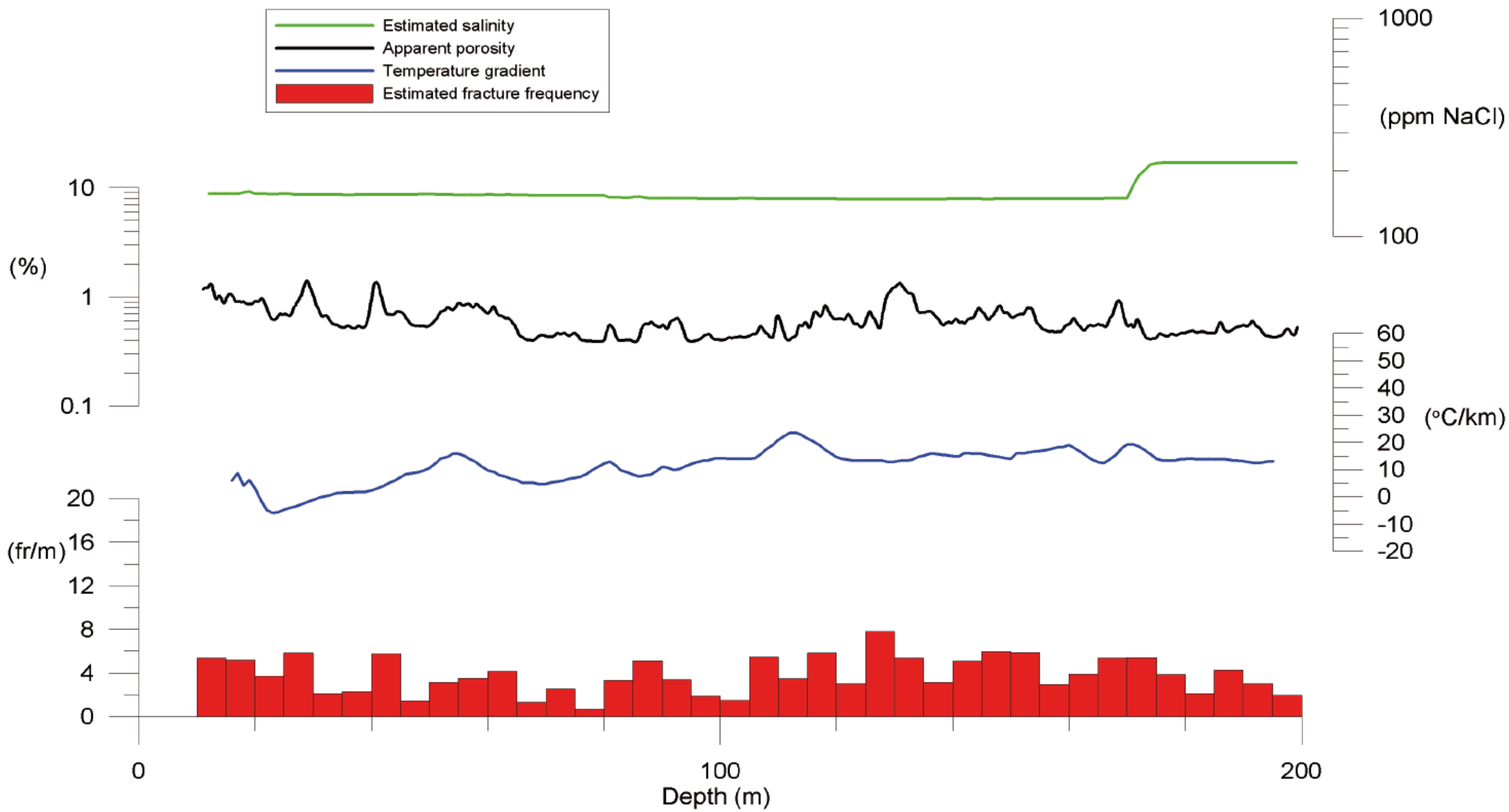

Figure 5-4. Estimated salinity, apparent porosity, vertical temperature gradient and estimated fracture frequency of KLX07B.

5.2.3 Interpretation of HLX20

The results of the generalized logging data and fracture estimations of HLX20 are presented in Figure 5-5 below.

The variation of silicate density and natural gamma radiation of the rocks in the vicinity of HLX20 indicates that the borehole can be divided into three subsections. Subsection 1 (9–135 m) is characterized by silicate density in the range 2,680–2,740 kg/m^3 and a natural gamma radiation in the range of 15–20 µR/h. The magnetic susceptibility in subsection 1 is fairly constant in the interval 0.010–0.025 SI, though with a constant decrease down to c 0.0005 SI along the lower most c 45 m. Subsection 2 (135–188 m) is characterized by density in the range 2,600–2,650 kg/m^3 and natural gamma radiation varying from c 20 µR/h up to c 30 µR/h, which indicates rock with a granitic composition. There are major variations in the magnetic susceptibility in subsection 2. The lowermost 12 m of HLX20, subsection 3 at c 188–200 m, are characterized by low natural gamma radiation (5–10 µR/h), high silicate density (2,800–2,860 kg/m^3) and low magnetic susceptibility (0.001–0.002 SI). This combination of physical properties is typical for fine-grained diorite to gabbro rock.

There are few strong positive anomalies in the natural gamma radiation logging data, which indicates that the number of fine-grained granite dykes and/or pegmatite dykes in HLX20 is low.

The estimated fracture frequency in HLX20 is mainly low or moderate. Three sections of high fracture frequency are indicated in the sections 45–50 m, 90–95 m and 115–125 m. The possible deformation zone at c 45–50 m coincides with a positive anomaly in the natural gamma radiation. All three sections of possible deformation zones are characterized by a major decrease in electric resistivity, a decrease in the P-wave velocity, anomalously low magnetic susceptibility and caliper anomalies. The combination of anomalies in the geophysical logging data strongly suggests that the rocks have suffered from deformation in these sections.

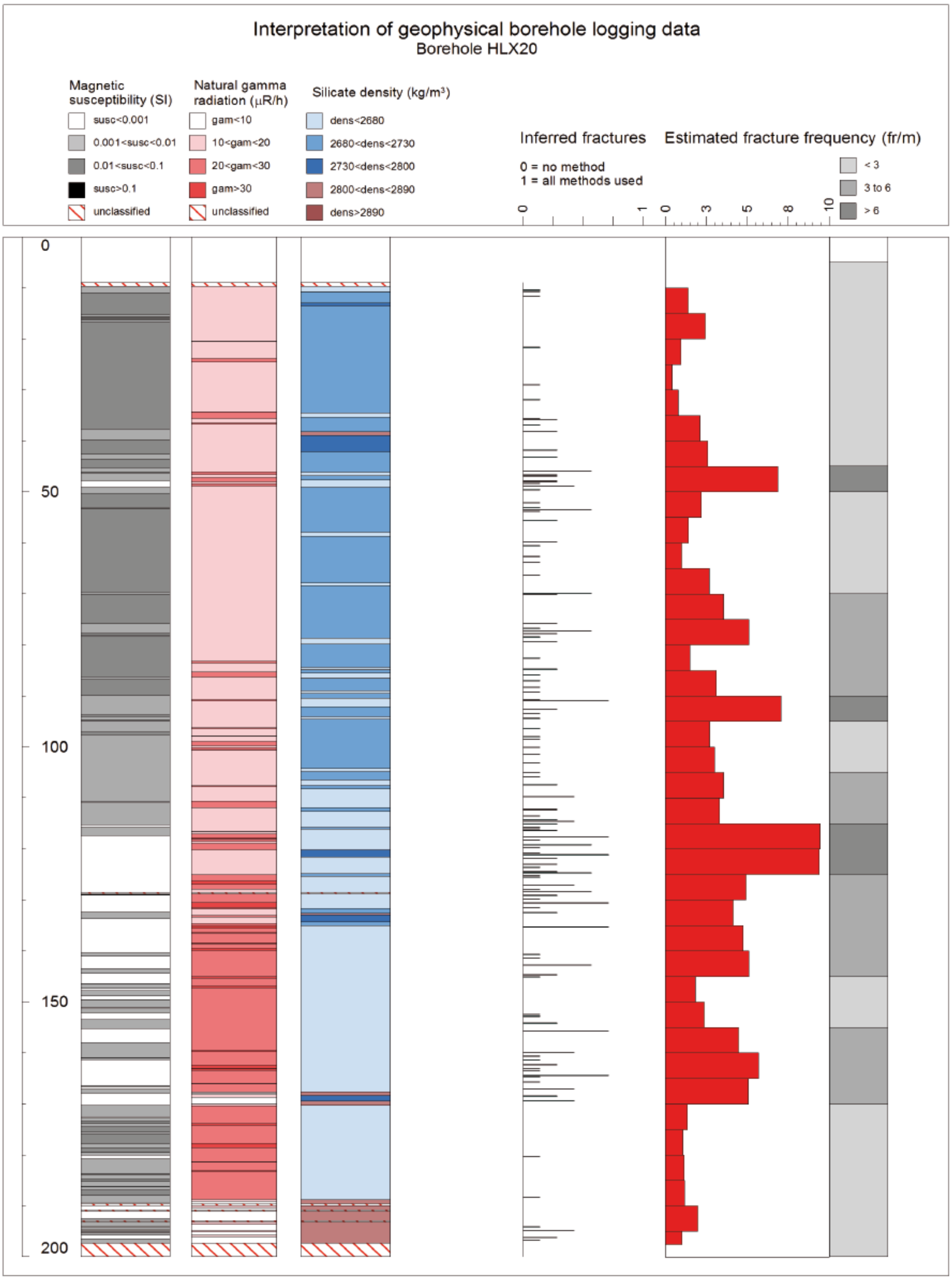

Figure 5-5. Generalized geophysical logs of HLX20.

5.2.4 Interpretation of HLX32

The results of the generalized logging data and fracture estimations of HLX32 are presented in Figure 5-6 below.

There are many and rapid variations in silicate density, magnetic susceptibility and natural gamma radiation with borehole length in HLX32; especially in the section c 12–120 m. For the major part of the borehole the silicate density is in the range 2,630–2,730 kg/m^3 and the natural gamma radiation is c 15–25 µR/h. However, more than 10 strong positive natural gamma radiation anomalies (> 30 µR/h) are identified, most of them with a correspondingly low density anomaly, and these probably indicate the presence of dykes of fine-grained granite and/or pegmatite.

In the lowermost c 40 m (section c 120–160 m) there are only minor variations in the physical properties of the rocks in the vicinity of the borehole. The density is c 2,710–2,740 kg/m^3, the magnetic susceptibility is c 0.012–0.016 SI and the natural gamma radiation is c 16–20 µR/h.

The estimated fracture frequency is mainly moderate or high. Possible deformation zones (sections with indicated fracture frequency > 6 fr/m) are indicated in the sections 20–25 m, 30–35 m, 50–55 m, 85–90 m and 100–125 m. All these sections, except section 85–90 m, are characterized by a major decrease in the electric resistivity, low magnetic susceptibility and clear caliper anomalies (and null values in the sonic log). In the section 85–90 m there are only minor resistivity and caliper anomalies. All the sections mentioned above with indicated increased fracturing, overlap (or partly overlap) with positive anomalies in the natural gamma radiation that most likely indicate the presence of fine-grained granite or pegmatite.

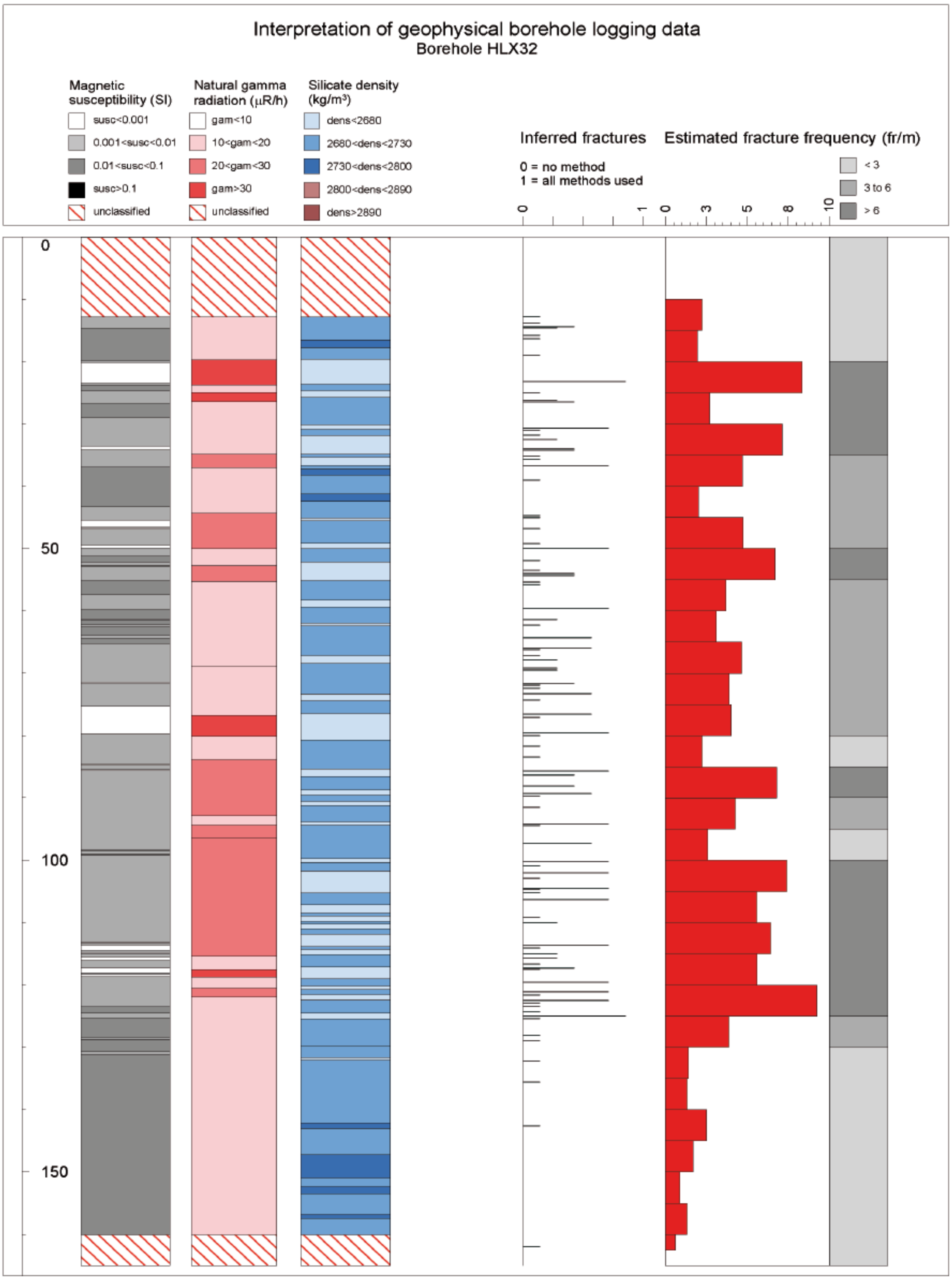

Figure 5-6. Generalized geophysical logs of HLX32.

5.2.5 Interpretation of HLX34

The results of the generalized logging data and fracture estimations of HLX34 are presented in Figure 5-7 below.

The rocks in the vicinity of HLX34 show fairly large variations between the two silicate density classes of density < 2,650 kg/m^3 and 2,650 < density < 2,730 kg/m^3. The silicate density is slightly higher in the upper half of the borehole (c 2,710–2,750 kg/m^3), section 10–86 m, compared to the lower half, section 86–151 m, where it is c 2,610–2,700 kg/m^3. Corresponding general variations of the data clearly occur for the magnetic susceptibility logging as well, and it is also indicated in the natural gamma radiation data. In section 86–151 m the magnetic susceptibility is mainly in the range 0.015–0.025 SI, and in the section 86–151 m it is mainly in the range 0.002–0.015 SI. The interpretation of the general variations in physical properties between the upper and lower halves of HLX34 is that the rocks in the vicinity of the two sections have compositional variations.

High silicate density (> 2,800 kg/m^3), with corresponding low natural gamma radiation (< 10μR/h) and low magnetic susceptibility (< 0.001 SI), occur in the sections c 20–24 m and 42–44 m. The data are typical indicators of fine-grained diorite to gabbro rocks. There are only few minor positive anomalies in the natural gamma radiation logging data, which indicates that the number of dykes of fine-grained granite or pegmatite is low.

The estimated fracture frequency is mainly moderate. Three sections of indicated high fracture frequency (> 6 fr/m) occur at c 20–25 m, 70–75 m and 90–95 m. Section 20–25 m is mainly characterized by low resistivity and only minor decrease in P-wave velocity and minor caliper anomalies, which indicates that the section most likely is dominated by sealed fractures and only few open fractures. Section 70–75 m is characterized by a major decrease in electric resistivity, caliper anomalies and null values in the sonic data. In the third section, 90–95 m, there are many but fairly small variations in the geophysical logging data and there are no significant anomalies. This suggests that the high fracture frequency is wrongly indicated and that this section actually contains sound rock. However, in the section 40–46 m there is a significant decrease in the P-wave velocity (3,600 m/s) and a decrease in the electric resistivity that suggests that the section has suffered from brittle deformation and might correspond to a rather large fracture zone.

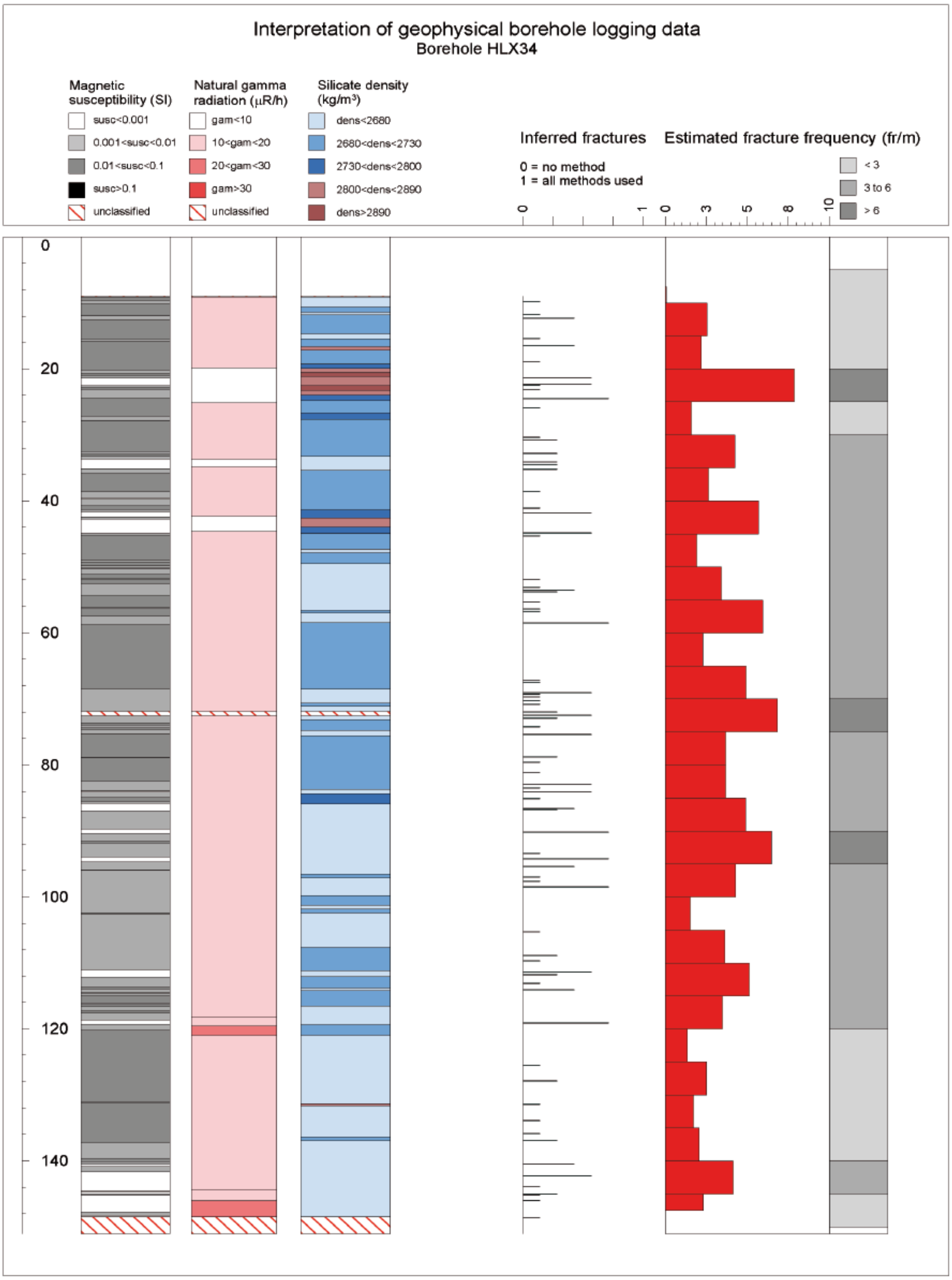

Figure 5-7. Generalized geophysical logs of HLX34.

5.2.6 Interpretation of HLX35

The results of the generalized logging data and fracture estimations of HLX35 are presented in Figure 5-8 below.

Based on the silicate density logging data and the natural gamma radiation data HLX35 can be divided into two subsections. Subsection 1 (c 6–65 m) is characterized by density in the range 2,620–2,670 kg/m^3 and natural gamma radiation varying from c 15 μR/h to c 25 μR/h. Subsection 2 (c 65–149 m) is characterized by density manly in the range 2,685–2,745 kg/m^3 and natural gamma radiation in the range 8–14 μR/h. The magnetic susceptibility is in the interval 0.010–0.025 SI for the major part of HLX35, apart from a few sections of magnetic lows that occur at c 6–16 m, 93–98 m, 116–124 m and 139–145 m. The last three low magnetic sections coincide with positive density anomalies (density > 2,800 kg/m^3), which indicates that the rock in the vicinity of these sections is most likely dominated by fine-grained diorite to gabbro. In direct vicinity of the lowermost high density section there is a distinct positive anomaly in the natural gamma radiation that indicates a dyke of fine-grained granite or pegmatite. This suggests that there is a spatial relation between fine-grained granite and fine-grained diorite to gabbro rocks.

High estimated fracture frequency is indicated in the sections c 10–15 m, 90–95 m and 115–145 m. Section 10–15 m is characterized by a decrease in the P-wave velocity together with a decrease in the electric resistivity. The two lower sections also show anomalously low P-wave velocity, low resistivity and several caliper anomalies. Note that the three possible deformation zones coincide with intervals of low magnetic susceptibility and that the two lowermost indicated zones coincide with sections where fine-grained diorite to gabbro rocks seems to occur.

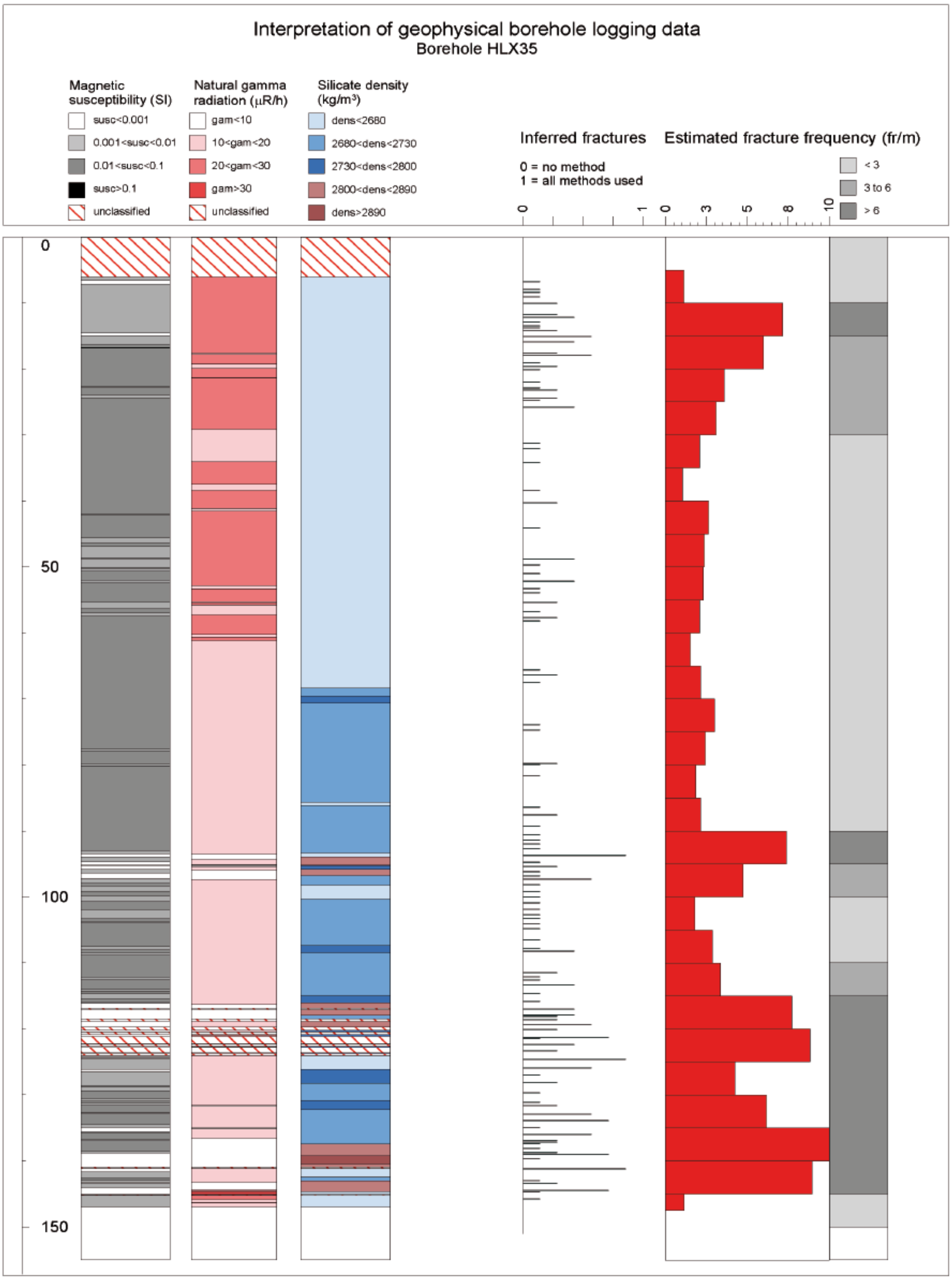

Figure 5-8. *Generalized geophysical logs of HLX35.*

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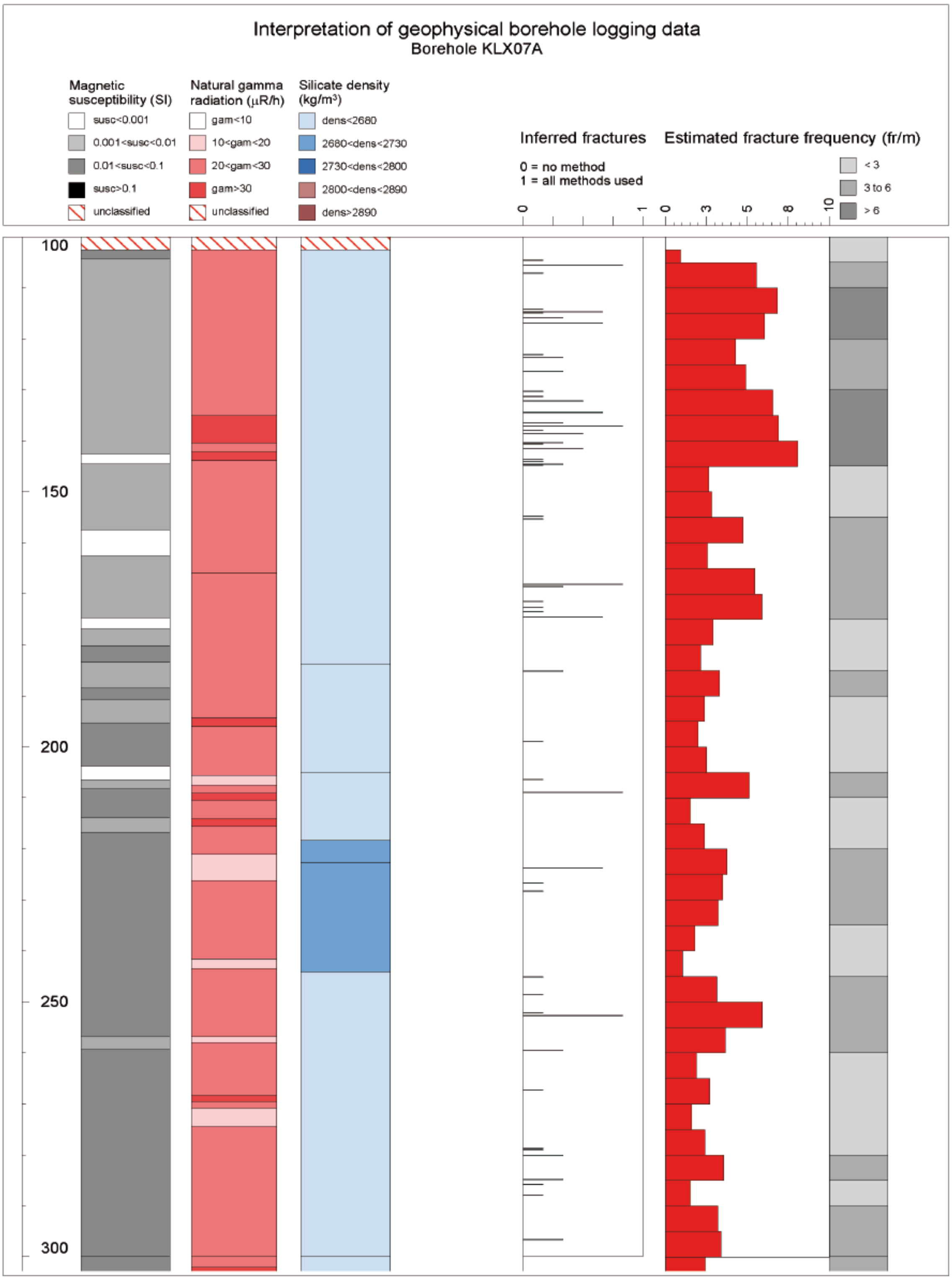

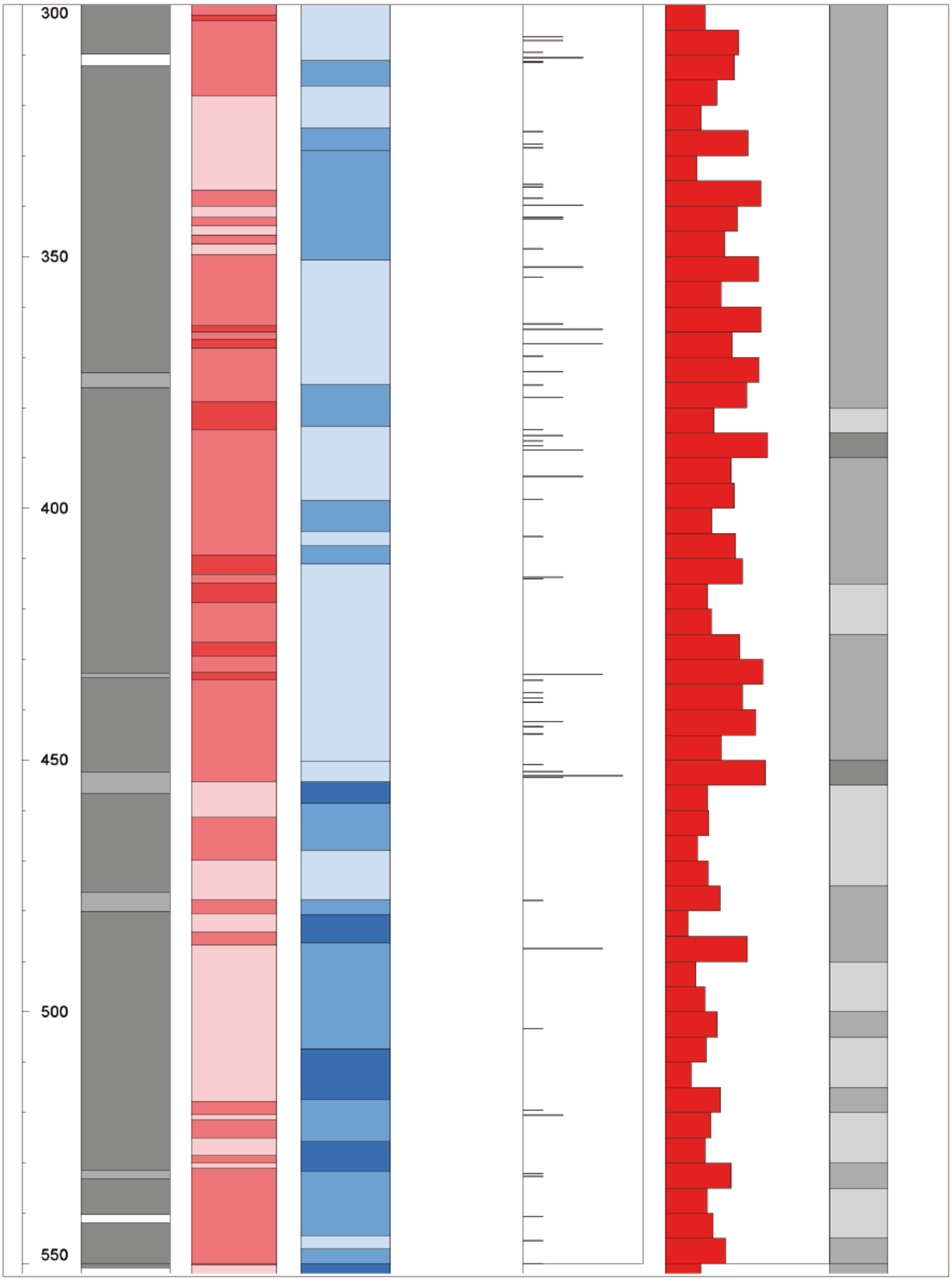
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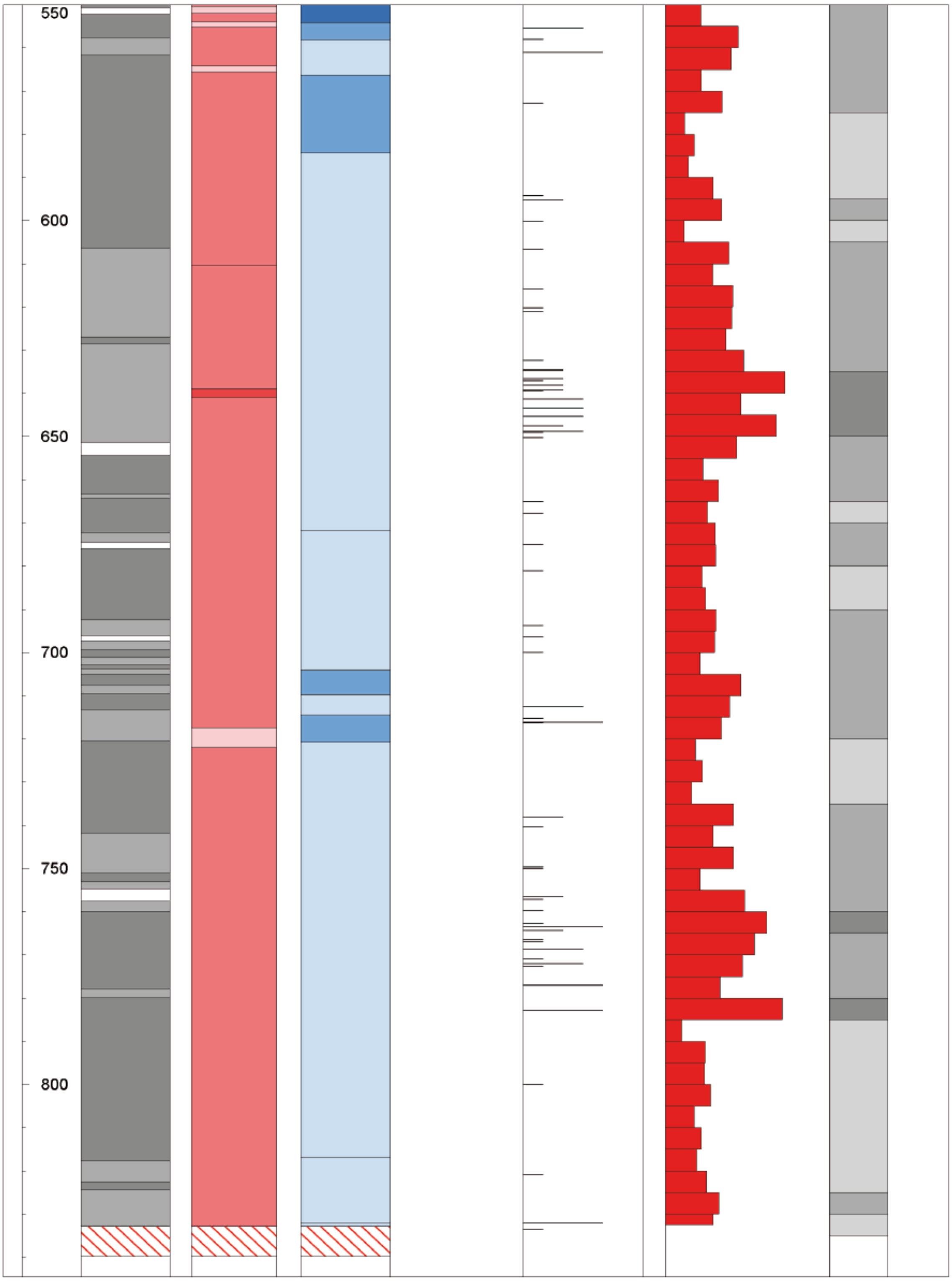

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