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Oskarshamn site investigation

Interpretation of geophysical borehole measurements from KLX06

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February 2005

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

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

Abstract

This report presents the compilation and interpretations of geophysical logging data from the cored borehole KLX06.

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 single-hole interpretation.

The rocks in the vicinity of KLX06 are dominated by silicate densities in the interval 2,650–2,730 kg/m^3, which indicate a mineral composition corresponding to granite and granodiorite rock.

The borehole can roughly be divided into 5 subsections. Section 1 (c 100–165 m) is dominated by moderate and high density rocks, fairly low natural gamma radiation and high magnetic susceptibility. In subsection 2 (c 165–375 m) the rocks are mainly governed by low to moderate silicate density, moderate natural gamma radiation and moderate to high magnetic susceptibility. Rocks with high density and low natural gamma radiation, most likely diorite to gabbro, occur frequently in large parts of the third subsection, c 375–590 m. In between the sections with high densities there are large occurrences of rocks with a silicate density indicating granitic mineral composition.

The fourth subsection of KLX06 is c 590–845 m. Along this interval the silicate density keeps fairly constant at c 2,700–2,730 kg/m^3, the natural gamma radiation is mainly low and the magnetic susceptibility is stable with an average of c 0.03 SI. The occurrence of diorite to gabbro rocks is indicated at c 635–660 m. Along the lowermost c 145 m of the borehole (subsection 5, c 845–990 m) there is a dominance of low silicate density. The natural gamma radiation is partly low, but shows a markedly high level (45–55 μR/h) along the interval c 910–945 m. In this interval the magnetic susceptibility goes down below 0.004 SI and the data indicate that fine or medium grained (probably red) granite rock dominates this borehole section.

The estimated fracture frequency is low in the section c 100–150 m. Along the section c 150–420 m there are several long intervals with indicated high fracture frequency; the most prominent occurs at c 225–240 m, c 307–315 m and c 340–420 m. These sections are characterized by low P-wave velocity; caliper anomalies, low magnetic susceptibility, a major decrease in the resistivity and increased apparent porosity. The estimated fracture frequency is generally low or moderate in the deeper parts of the borehole (section c 420–990 m).

The fluid temperature gradient log shows an increased number of anomalies in the sections c 150–370 m and c 910–980 m compared to most other sections of the borehole, which suggests that the rocks along these sections contain water bearing fractures.

Sammanfattning

Föreliggande rapport presenterar en sammanställning och tolkning av geofysiska borrhålsmätningar från kärnborrhålet KLX06.

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

Resultaten av undersökningarna visar att berggrunden i närheten av KLX06 i stor utsträckning har en silikatdensitet i intervallet 2 650–2 730 kg/m^3, vilket indikerar en mineralsammansättning motsvarande den för granit till granodiorit.

Borrhålet kan grovt sett delas in i 5 delsektioner. Sektion 1 (ca 100–165 m) domineras av bergarter med medel till hög densitet, relativt låg naturlig gammastrålning och hög magnetisk susceptibilitet. Inom delsektion 2 (ca 165–375 m) har bergarterna låg till medelhög densitet, medelhög naturlig gammastrålning och medel till hög magnetisk susceptibilitet. Bergarter med medelhög till hög silikatdensitet, motsvarande den för diorit till gabbro, förekommer rikligt i den tredje delsektionen, ca 375–590 m. Mellan sektionerna med hög densitet är densiteten markant lägre, motsvarande granitisk mineralsammansättning.

Den fjärde delsektionen är ca 590–845 m. Längs den ligger silikatdensiteten relativt konstant i intervallet ca 2 700–2 730 kg/m^3, den naturliga gammastrålningen är oftast låg och den magnetiska susceptibiliteten ligger på en stabil nivå, ca 0,03 SI. Förekomst av diorit till gabbro indikeras längs 635–660 m. Den femte och sista delsektionen (ca 845–990 m) domineras av låg silikatdensitet och bitvis låg naturlig gammastrålning. Längs ca 910–945 m är dock gammastrålningen mycket hög (45–55 μR/h) och den magnetiska susceptibiliteten är här låg (< 0,004 SI), vilket indikerar förekomst av fin- till medelkornig (troligen röd) granit.

Den tolkade sprickfrekvens är låg i sektionen 100–150 m. Längs med sektionen 150–420 m föreligger det flera långa avsnitt med hög tolkad sprickfrekvens; de mest uppenbara återfinns vid sektionerna 225–240 m, 307–315 m och 340–420 m. Dessa sektioner karaktäriseras av låg P-vågshastighet, caliperanomalier, sänkt magnetisk susceptibilitet, sänkt resistivitet och förhöjd skenbar porositet. Sektionen ca 420–990 m av KLX06 har generellt sett låg eller moderat uppskattad sprickfrekvens. Vertikala temperaturgradientloggen indikerar förhöjd förekomst av vattenförande sprickor längs ca 150–370 m och ca 910–980 m jämfört med övriga delar av borrhålet.

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 geophysical borehole logging data from the cored borehole KLX06, Figure 1-1.

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 also presented. 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 400-05-002 and method description MD 221.003, SKB internal controlling documents, Table 1-1).

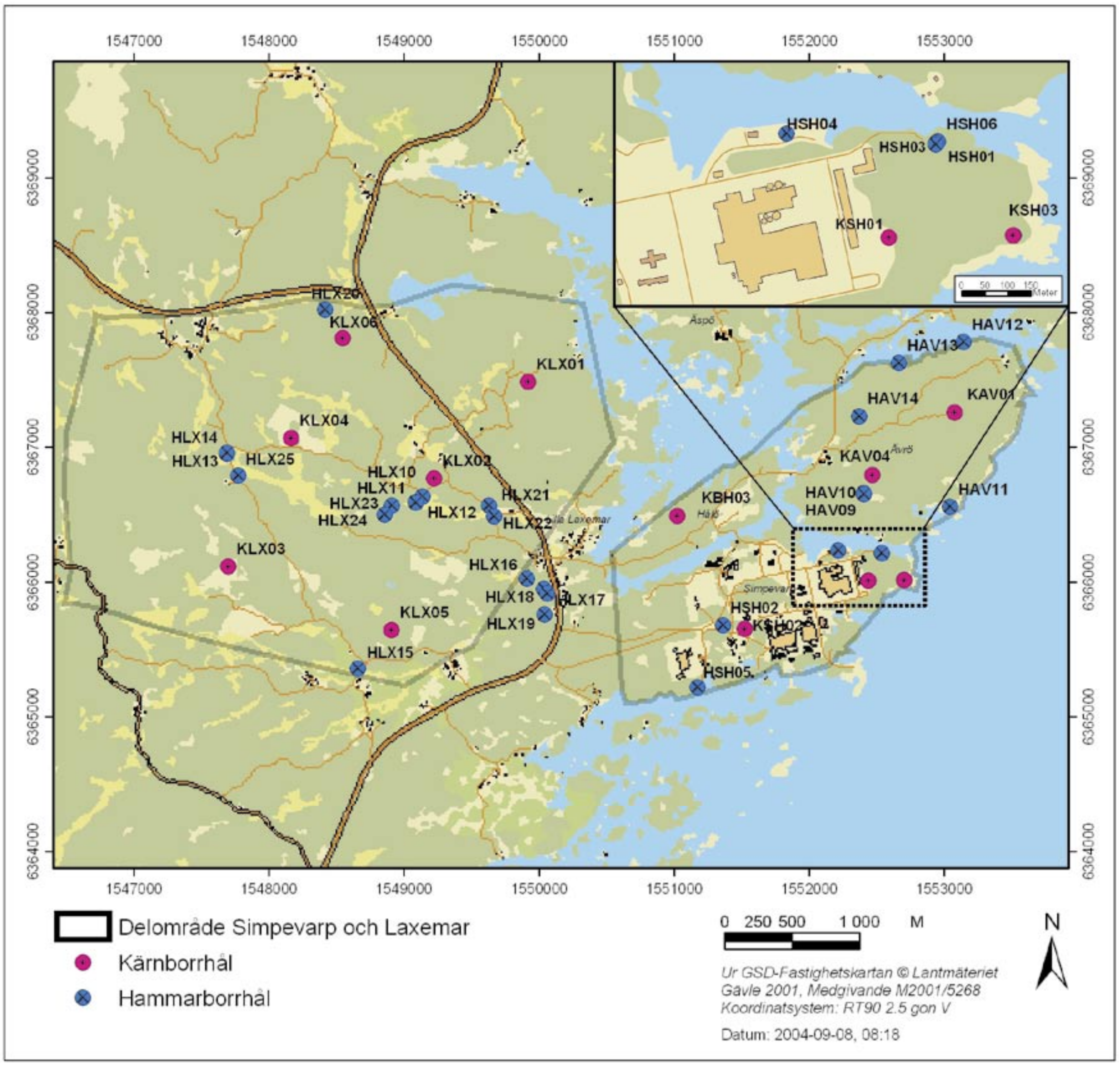

Figure 1-1. *Map showing the location of the investigated borehole KLX06.*

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

Activity plan	Number	Version
Tolkning av borrhålsgeofysiska data från KLX06.	AP PS 400-05-002	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för tolkning av geofysiska borrhålsdata.	SKB MD 221.003	2.0

The original results are stored in the primary data base (SICADA) and the data are traceable by the activity plan numbers.

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 boreholes. 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 mappings and as supportive information during the so called “single-hole interpretation”, which is a combined borehole interpretation of core logging (Boremap) data, geophysical data and radar data.

3 Equipment

3.1 Description of equipment for analyses of logging data

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

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, median filtering, error estimations, re-sampling, drift correction, length adjustment).

The loggings are median 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 and magnetic susceptibility logging data are calibrated with respect to petrophysical data. The logging data of KLX06 were calibrated by use of a combination of petrophysical data from the boreholes KLX03, KSH01A, KSH02, KSH03A and KAV04A, see /1, 2, 3, 4 and 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 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 /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 constants used in this investigation are presented in Table 4-1.

Table 4-1. Values of the constants a and m in Archie's law used in the calculation of the apparent porosity.

Borehole	Average fluid resistivity (Ωm)	a	m
KLX06	19.0	17.5	1.715

The vertical temperature gradient (in °C/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 4-2) 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 4-2.

5. Report evaluating the results.

Table 4-2. 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	KLX06	1.8	2.0	2.0	0.5	4.0	7.0	7.0	–
Power	KLX06	1.0	1.0	1.6	–	0.5	0.5	0.6	–
Weight	KLX06	1.0	7.1	6.7	–	5.0	2.9	5.0	–

4.2 Preparations and data handling

The logging data from KLX06 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)
- Lateral resistivity
- 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 to identify water bearing fractures, 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. Apart from this, no nonconformities are reported.

5 Results

The original results are stored in the primary data base (SICADA). For further interpretation and modelling the data in SICADA must be used. The data is traceable in SICADA by the Activity Plan number (AP PS 400-05-002).

5.1 Quality control of the logging data

5.1.1 Noise levels

Noise levels of the raw data for each logging method are presented in Table 5-1. Noise levels are above the recommended levels for the density log, the magnetic susceptibility log and the natural gamma radiation log. However, the levels are most likely low enough to allow a meaningful interpretation of the data. To reduce the influence of the noise, all logs were average or median filtered prior to the interpretation.

A qualitative inspection was performed on the loggings. The data were checked for spikes and/or other obvious incorrect data points. Erroneous data were replaced by null values (–999) by the contractor Rambøll prior to the delivery of the data, and all null values were disregarded in the interpretation.

Table 5-1. Noise levels in the investigated geophysical logging data of KLX06.

Logging method	KLX06	Recommended max noise level
Density (kg/m^3)	22	3–5
Magnetic susceptibility (SI)	5×10^{-4}	1×10^{-4}
Natural gamma radiation (μR/h)	0.8	0.3
Long normal resistivity (%)	0.4	2.0
Short normal resistivity (%)	0.4	2.0
Fluid resistivity (%)	0.04	2
Fluid temperature (°C)	0.004	0.01
Lateral resistivity (%)	Not used	2
Single point resistance (%)	0.2	No data
Caliper (meter)	0.000002	0.0005
Focused resistivity 300 (%)	11	No data
Focused resistivity 140 (%)	10	No data
Sonic (m/s)	19	20

5.2 Interpretation of the logging data

The presentation of interpretation products presented below, in chapter 5.2.1 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 KLX06

The results of the generalized logging data and fracture estimations of KLX06 are presented in Figure 5-1 below, and in a more detailed scale in Appendix 1.

The rocks in the vicinity of KLX06 are dominated by silicate densities in the interval 2,650–2,730 kg/m^3, which indicate a mineral composition corresponding to granite and granodiorite rock (Table 5-2).

The borehole can roughly be divided into 5 subsections. Section 1 (c 100–165 m) is dominated by moderate and high density rocks, fairly low natural gamma radiation (10–20 µR/h) and high magnetic susceptibility (0.02–0.04 SI). In subsection 2 (c 165–375 m) the rocks are mainly governed by low to moderate silicate density (2,650–2,700 kg/m^3), moderate natural gamma radiation (20–30 µR/h) and moderate to high magnetic susceptibility (0.003–0.02 SI). Rocks with high density and low natural gamma radiation, most likely diorite to gabbro, occur frequently in large parts of the third section, c 375–590 m. The magnetic susceptibility of these high density rocks shows large variations; along some sections the susceptibility is 0.02–0.04 SI and along others it is 0.001–0.003 SI. This might indicate that some of the rocks have suffered from alteration, which has resulted in a transformation of magnetite to hematite, or that the rocks are deformed and that the deformation process lead to a destruction of the magnetite. In between the sections with high densities there are large occurrences of rocks with a silicate density indicating granitic mineral composition.

The fourth subsection of KLX06 is c 590–845 m. Along this interval the silicate density keeps fairly constant at c 2,700–2,730 kg/m^3, the natural gamma radiation is mainly low (10–20 µR/h) and the magnetic susceptibility is stable with an average of c 0.03 SI. However, a high density, low natural gamma radiation and low magnetic susceptibility anomaly occurs at c 635–660 m, which probably corresponds to diorite to gabbro. Along the lowermost c 145 m of the borehole (subsection 5, c 845–990 m) there is a dominance of low silicate density (< 2,680 kg/m^3). The natural gamma radiation is partly low, but shows a markedly high level (45–55 µR/h) along the interval c 910–945 m. In this interval the magnetic susceptibility goes down below 0.004 SI and the data indicate that fine or medium grained granite rock dominates this borehole section.

Table 5-2. Distribution of silicate density classes with borehole length of KLX06.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens < 2,680 (granite)	258	29
2,680 < dens < 2,730 (granodiorite)	351	40
2,730 < dens < 2,800 (tonalite)	144	16
2,800 < dens < 2,890 (diorite)	118	13
dens > 2,890 (gabbro)	16	2

Several short positive natural gamma radiation anomalies occur along the entire borehole, and these correspond most likely to fine-grained granite or pegmatite dykes. Some of these occur close to high density anomalies (probable indications of diorite to gabbro rocks), which suggests that felsic and mafic rocks sometimes are spatially related.

The estimated fracture frequency is low in the section c 100–150 m. Along the section c 150–420 m there are several long intervals with indicated high fracture frequency; the most prominent occurs at c 225–240 m, c 307–315 m and c 340–420 m (Figures 5-1 and 5-2). These sections are characterized by low P-wave velocity; caliper anomalies, low magnetic susceptibility, a major decrease in the resistivity and increased apparent porosity. The estimated fracture frequency is generally low or moderate in the deeper parts of the borehole (section c 420–990 m), though partly increased fracturing is indicated at c 495–550 m.

The results of the estimated salinity, apparent porosity, vertical temperature gradient and estimated fracture frequency of KLX06 are presented in Figure 5-2 below.

The fluid temperature gradient log shows an increased number of anomalies in the section c 150–370 m compared to most other sections of the borehole, which suggests that the rocks along this section contain water bearing fractures. However, the most prominent temperature gradient anomaly occurs at c 562 m section length. Also note that there is a clear increase in the occurrence of temperature gradient anomalies along the section c 910–980 m. The upper part of this section of possible water bearing fractures coincides with a rapid increase in the fluid water salinity at c 929 m. Apart from this stepwise increase, the estimated fluid water salinity is fairly constant at c 200–300 ppm NaCl.

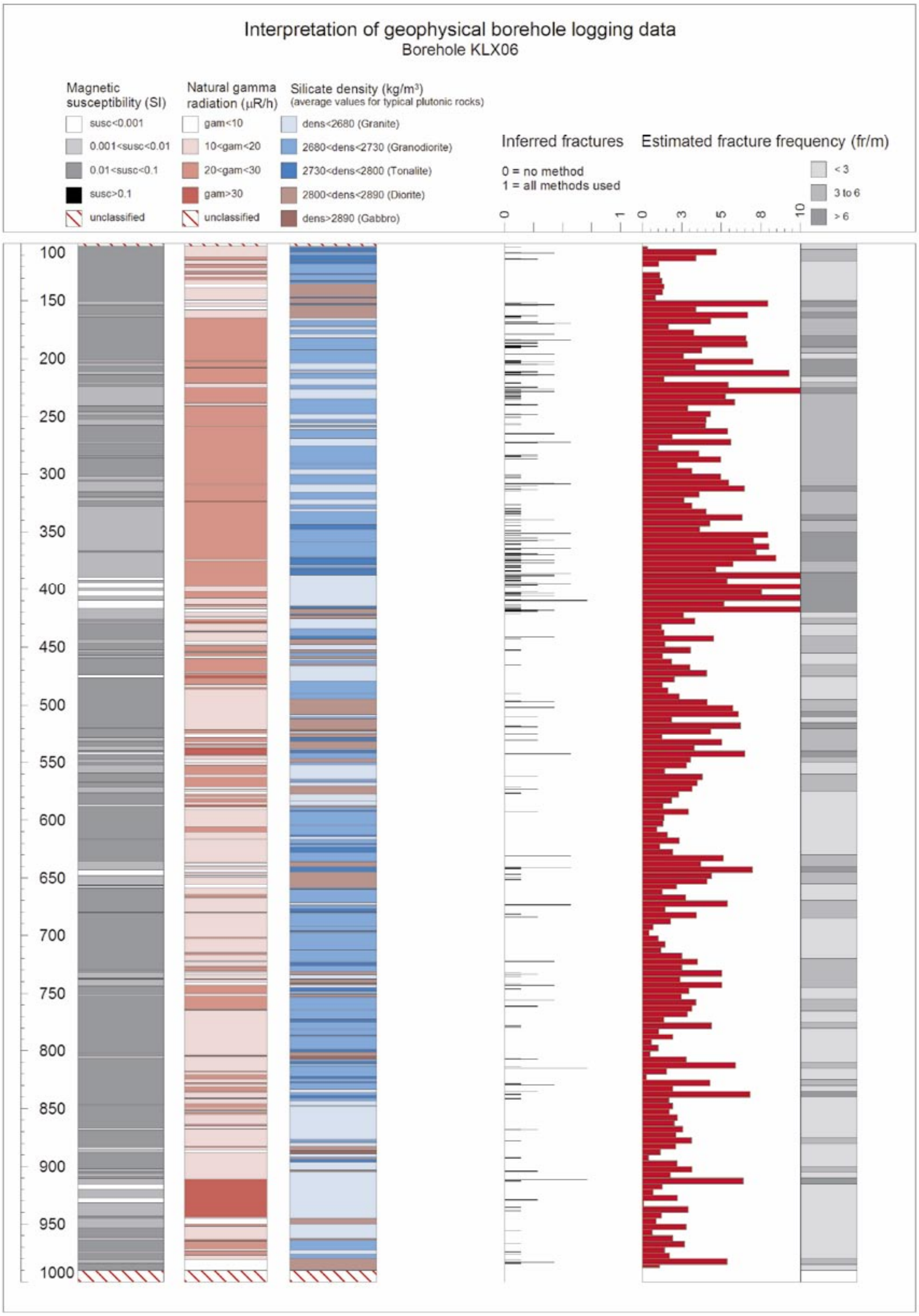

Figure 5-1. Generalized geophysical logs of KLX06.

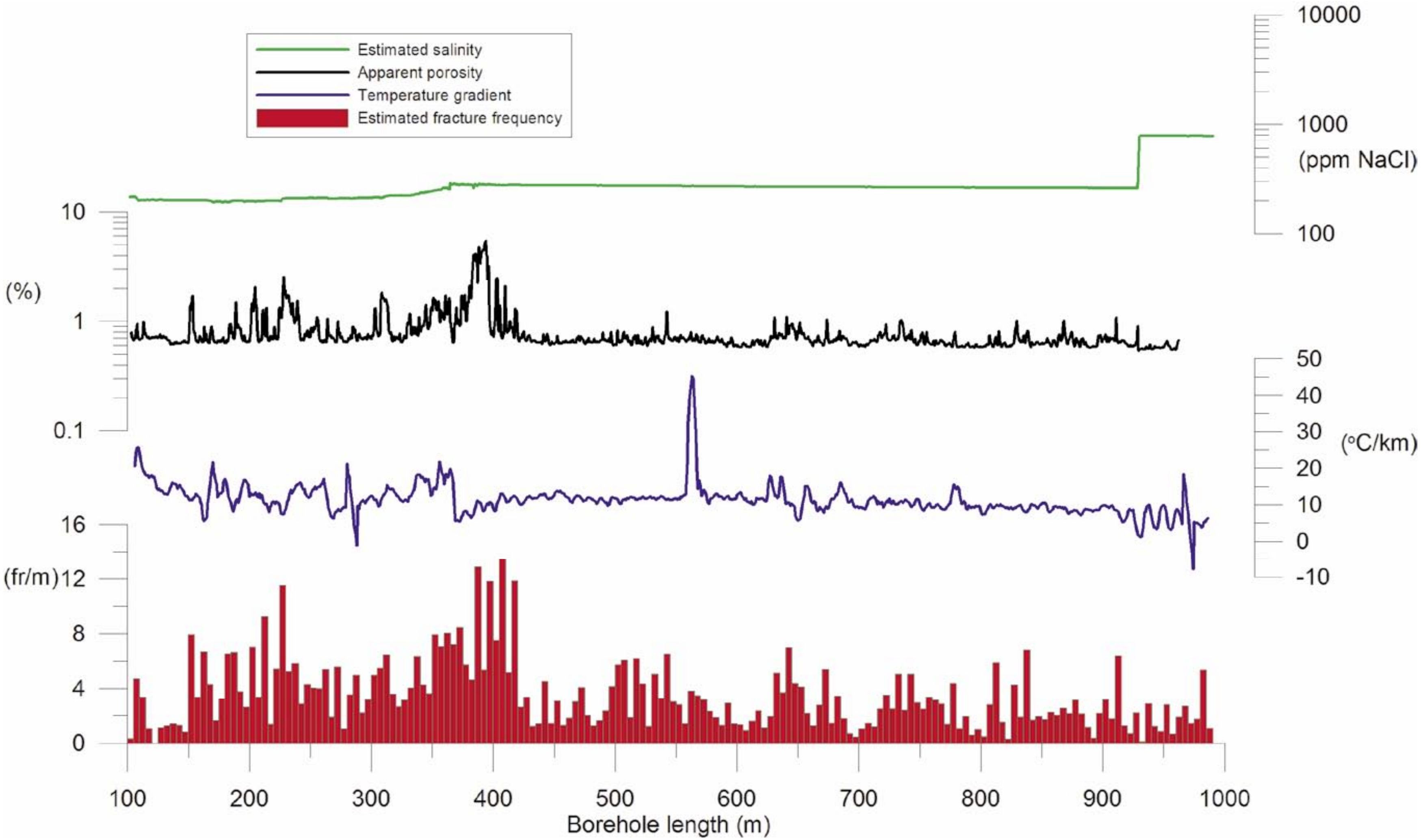

Figure 5-2. *Estimated salinity, apparent porosity, vertical temperature gradient and estimated fracture frequency of KLX06.*

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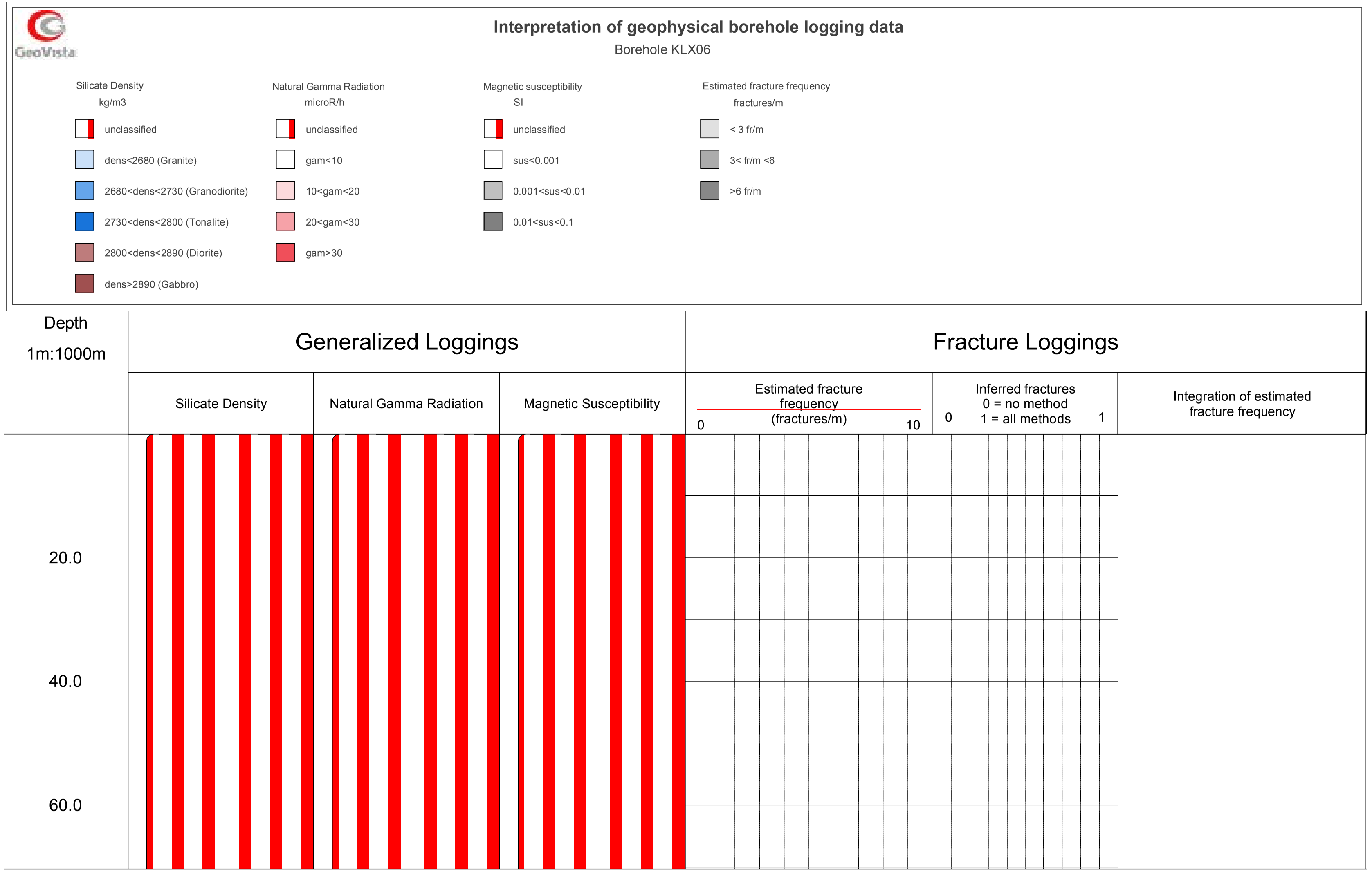
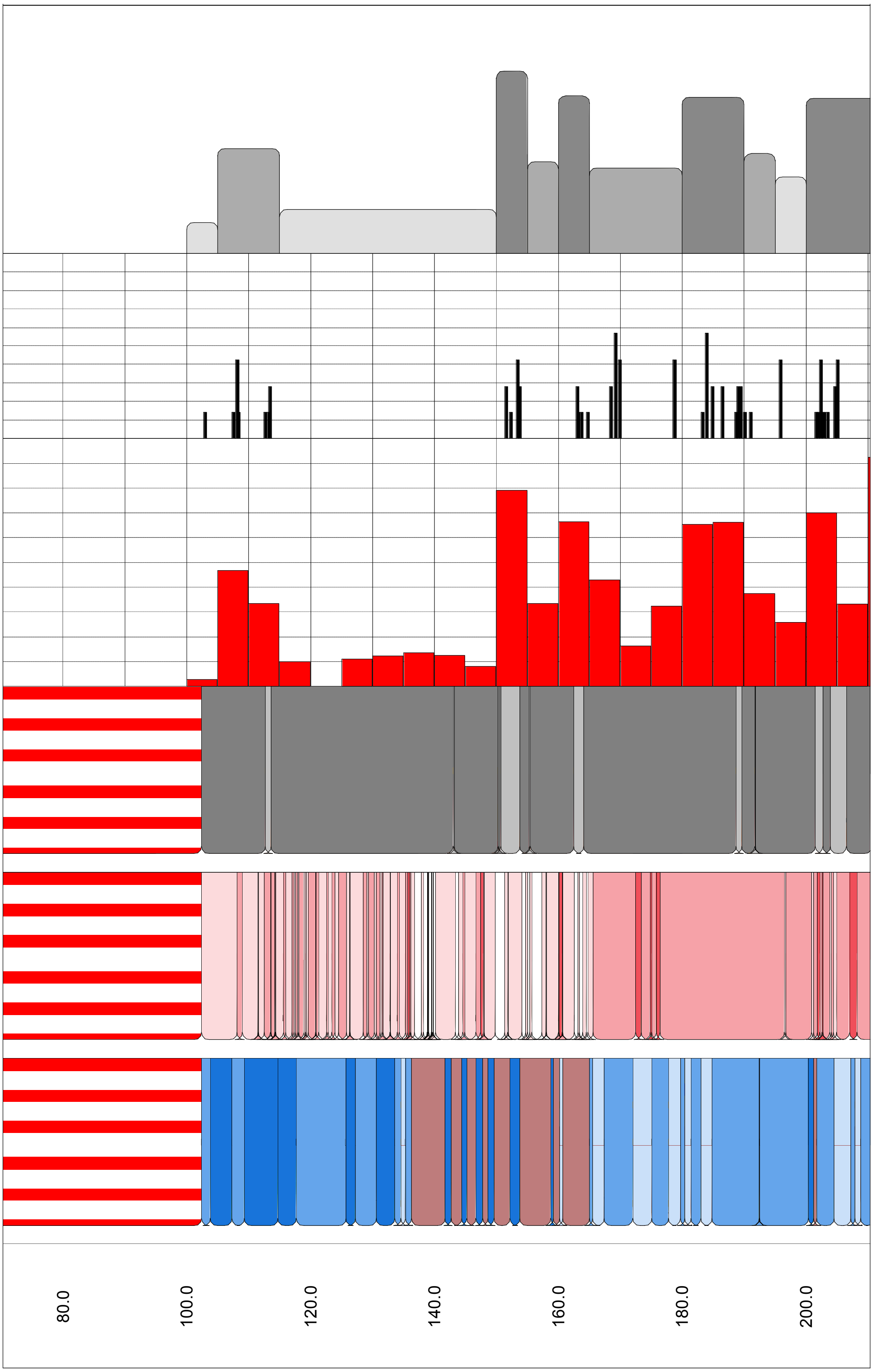
Appendix 1

Generalized geophysical loggings of KLX06

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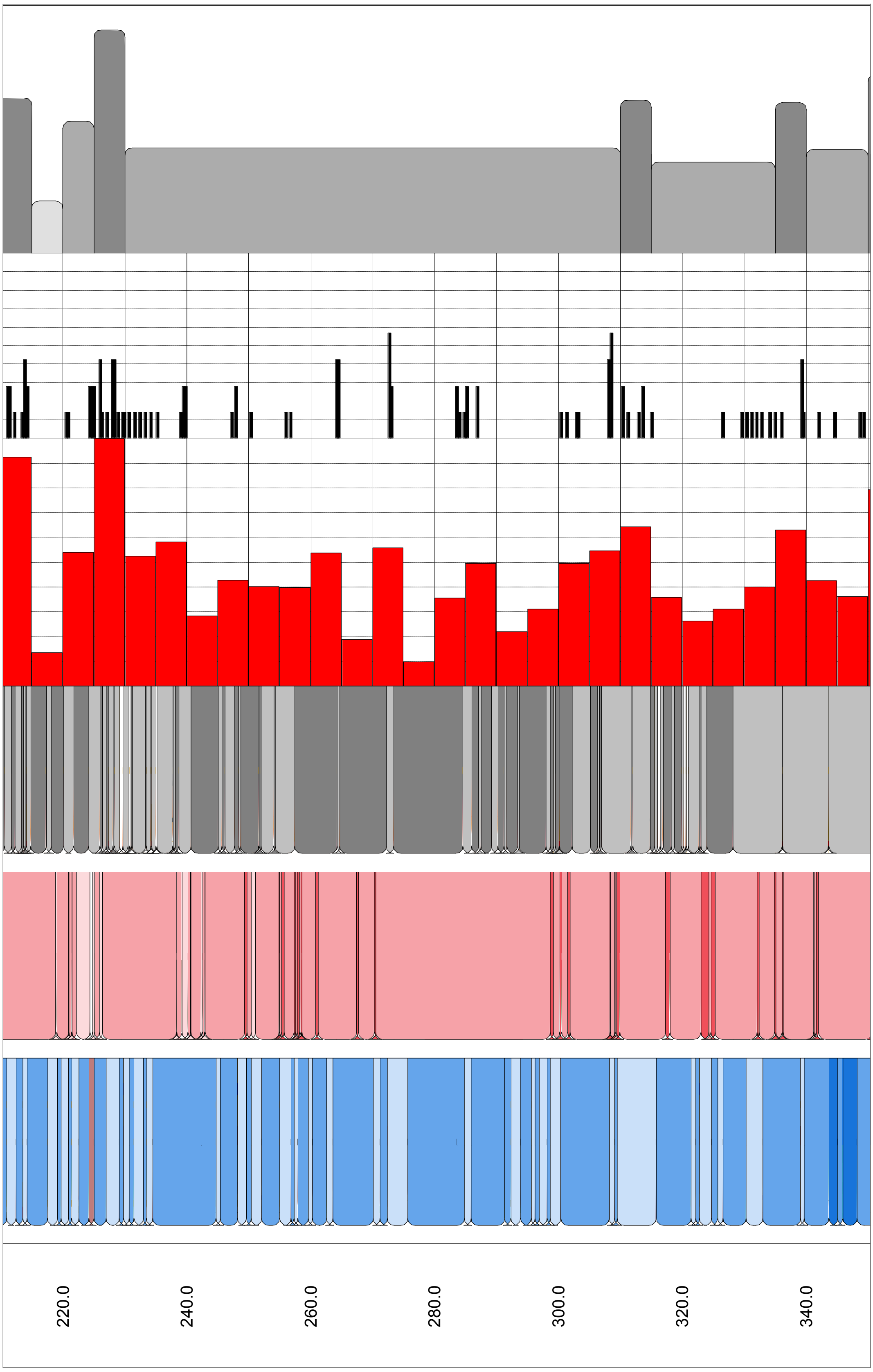
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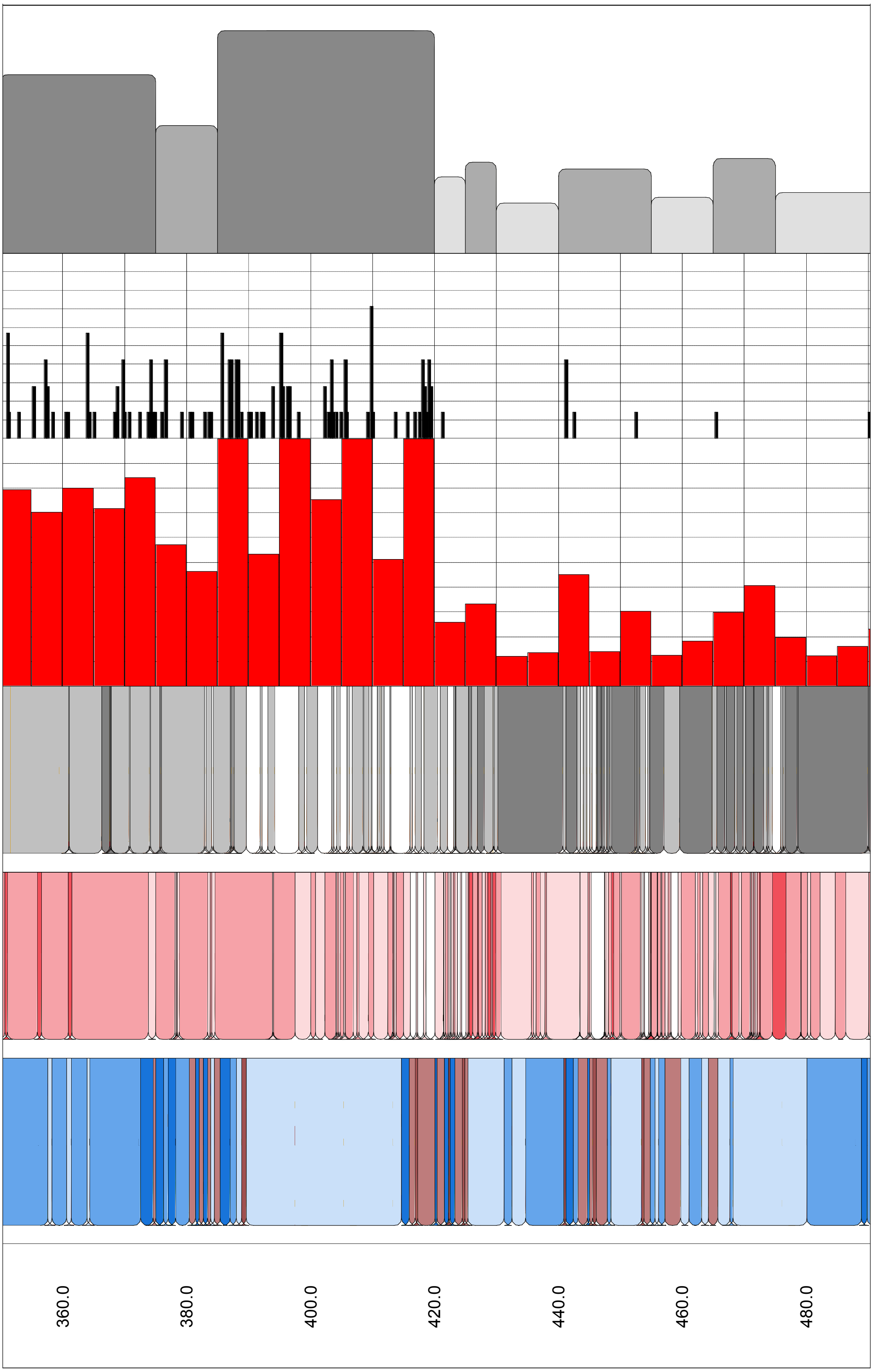
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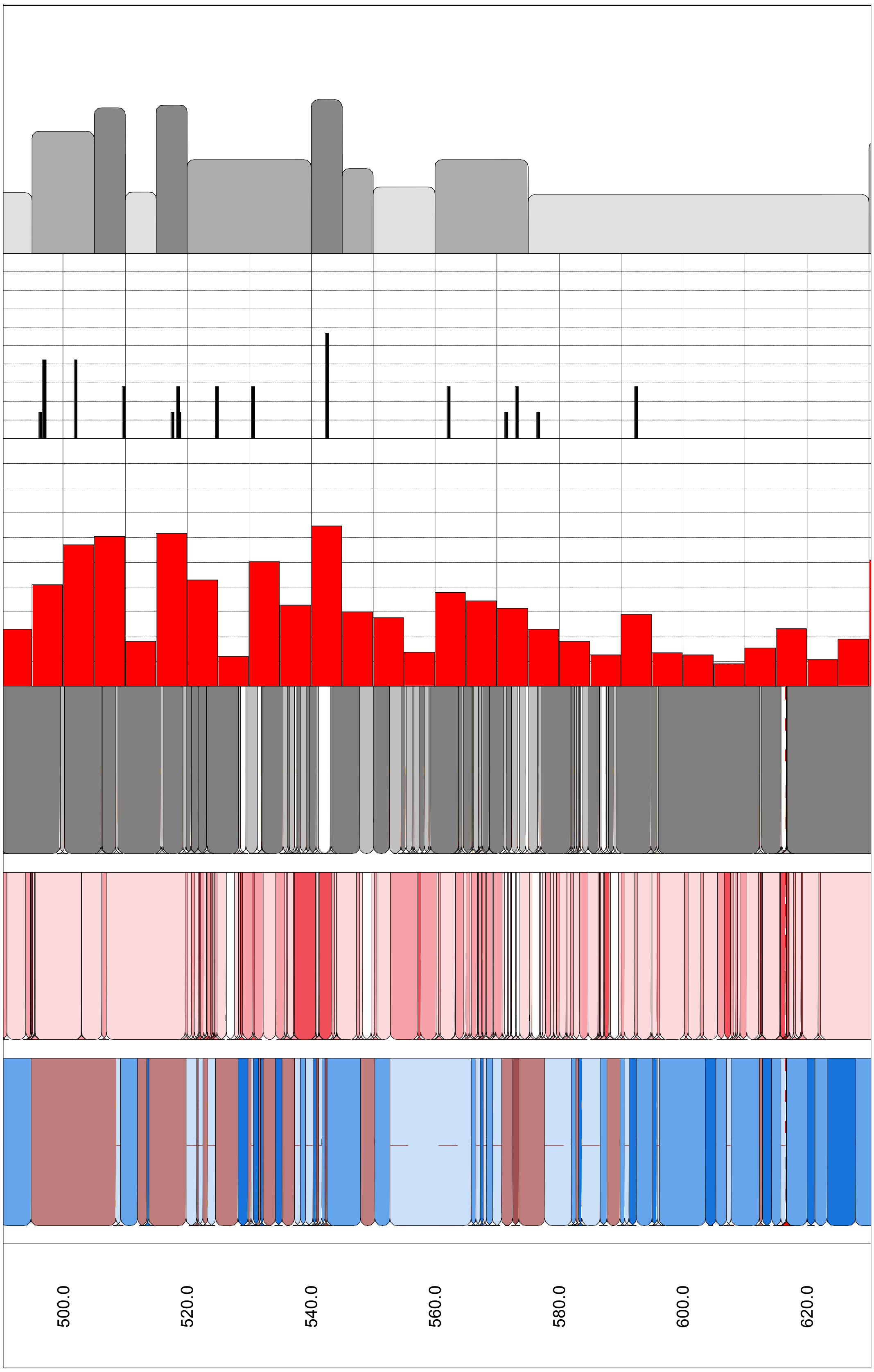
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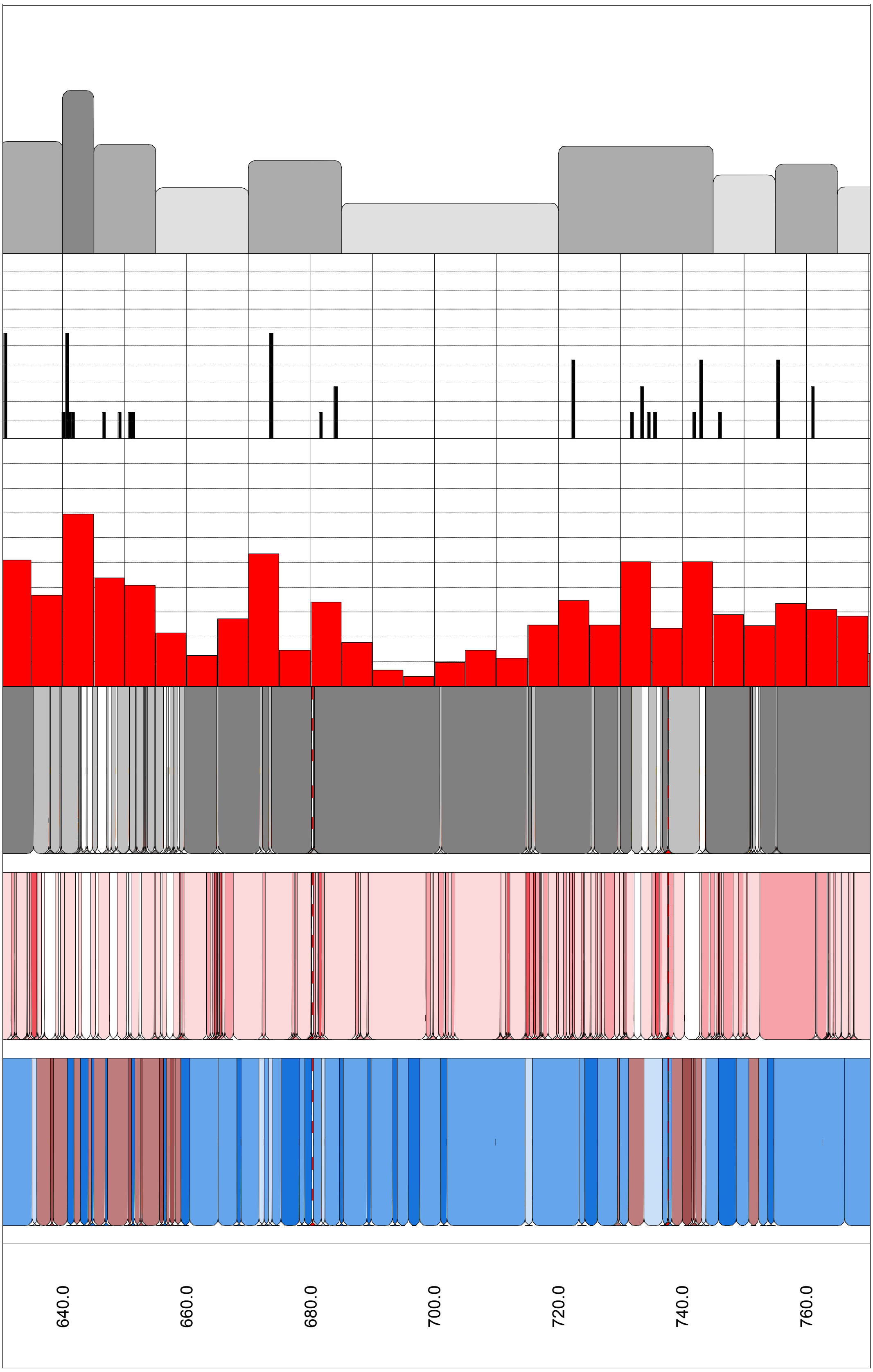
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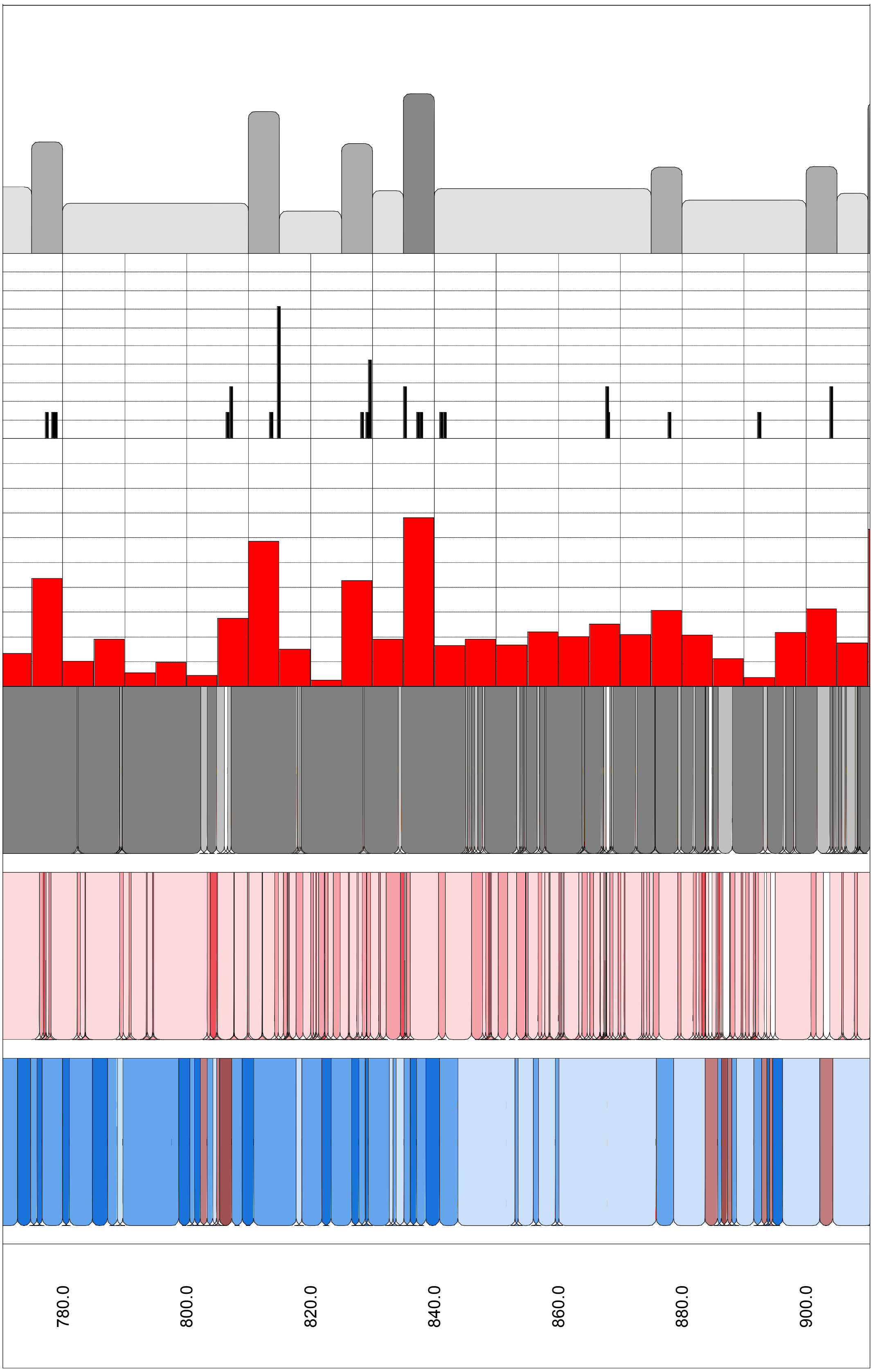
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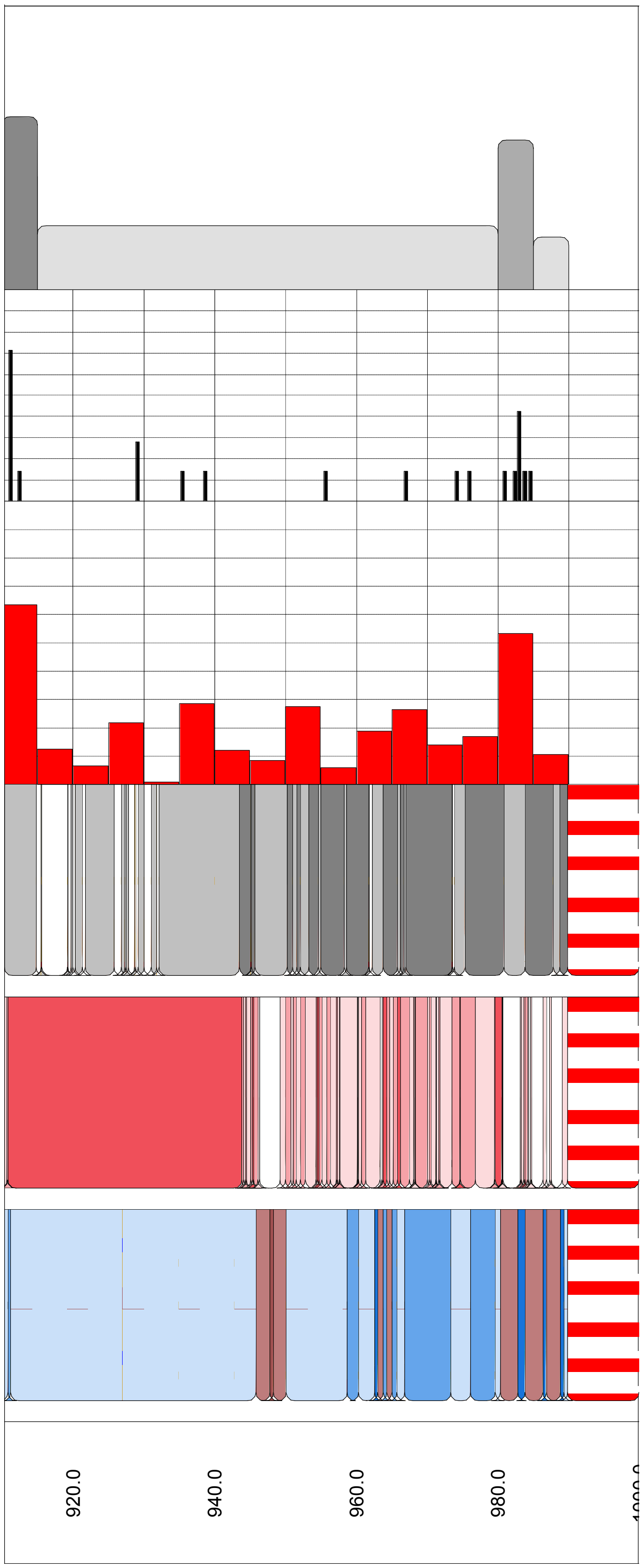
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