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Håkan Mattsson, GeoVista AB

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

Data in SKB's database can be changed for different reasons. Minor changes in SKB's database will not necessarily result in a revised report. Data revisions may also be presented as supplements, available at www.skb.se.

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Abstract

This report presents the compilation and interpretations of geophysical logging data from the cored boreholes KAS02, KAS04, KAS06, KAS07 and KAS08, and petrophysical measurements on rock samples from the boreholes KAS02, KAS06 and KAS08.

The boreholes were drilled and investigated in the 1980's during the construction of the Äspö Hard Rock Laboratory (HLR). The number of logging methods is therefore fewer for these boreholes compared with the data collected during the site investigations at Oskarshamn and Forsmark. The quality control led to that many of the logs had to be length adjusted with reference to the updated rock type mapping. Noise levels are generally low or moderate and the density and magnetic susceptibility logs fit well with data from core samples.

The main objective of the investigation was to use the results as supportive information during the geological core mapping and as supportive information during the geological single-hole interpretation.

The interpretation shows a general dominance of silicate density in the range 2,720–2,820 kg/m^3, and along these sections of the boreholes the natural gamma radiation is c. 10–20 μR/h and the magnetic susceptibility is c. 0.010–0.050 SI. This combination of physical properties most likely corresponds to occurrences of Äspö diorite.

In all five boreholes there are one (or a couple) of fairly long sections, 20–100 m, of significantly increased natural gamma radiation, decreased density and magnetic susceptibility; a combination of physical properties that is typical for fine-grained granite. Along these sections there are generally indications of possible deformation zones and also significant anomalies in the vertical fluid temperature gradient, which indicates that the fine-grained dykes are related to water bearing deformation zones.

Significantly increased density in combination with decreased natural gamma radiation commonly occurs along short (< 1 m long) sections in all boreholes, and this combination of properties indicates dioritoid-gabbroid rocks. In KAS07 the occurrences of indicated dioritoid-gabbroid are more frequent than in the other boreholes. The magnetization of these rocks varies greatly. In some cases there is a spatial relation between indicated fine-grained dykes and dioritoid-gabbroid dykes, indicating so called composite dykes.

The fracture frequency estimations indicate that the general level of fracturing is low or moderate in all boreholes except in KAS04, in which the fracture frequency is moderate to high. Possible, major deformation zones are indicated in KAS02 at 310–320 m and 805–905 m, in KAS04 at 330–445 m, in KAS06 at 205–235 m, in KAS07 at 413–425 m and 540–590 m and in KAS08 at 268–294 m and 537–595 m.

Sammanfattning

Föreliggande rapport presenterar resultat och tolkningar av geofysiska borrhålsmätningar i kärnborrhålen KAS02, KAS04, KAS06, KAS07 och KAS08 samt petrofysiska mätningar på borrkärnebitar från borrhålen KAS02, KAS06 och KAS08.

Borrhålen och mätningarna i dem härstammar från de undersökningar som gjordes i slutet av 1980-talet inför byggandet av Äspölaboratoriet. Antalet metoder i loggdata är därför färre än för de data som samlades in under platsundersökningarna i Oskarshamn och Forsmark. En kvalitetskontroll av loggdata visade att flera loggar behövde längdjusteras innan bearbetning och tolkning; justeringen utfördes i relation till karterad geologi. Vidare visar kontrollen på generellt låga, eller endast något förhöjda, brusnivåer samt att densitets- och susceptibilitetsdata är nöjsamt kalibrerade.

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 främst som underlag vid den geologiska enhålstolkningen.

Tolkningen av data visar på en generell dominans i samtliga borrhål av silikatdensitet inom intervallet 2 720–2 820 kg/m^3, och längs dessa sektioner är den naturliga gammastrålningen ca 10-20 μR/h och den magnetiska susceptibiliteten är ca 0,010–0,050 SI. Denna kombination av fysikaliska egenskaper är typisk för Äspödiorit.

I samtliga fem borrhål förekommer en (eller några) långa sektioner, 20–100 m, med kraftigt förhöjd naturlig gammastrålning samt avvikande låg densitet och magnetisk susceptibilitet; vilket är typiska egenskaper för finkornig granit. Längs flera av dessa sektioner indikerar de geofysiska loggarna förhöjd sprickfrekvens samt in/utflöde av vatten, vilket tyder på förekomst av större vattenförande spröda deformationszoner.

Kraftigt förhöjd densitet i kombination med låg naturlig gammastrålning är vanligt förekommande längs korta sektioner (ofta < 1 m) i samtliga borrhål, och denna kombination av fysikaliska egenskaper indikerar bergarter typ dioritoid-gabbroid. I KAS07 är förekomsten av indikerad dioritoid-gabbroid vanligare än i de övriga borrhålen. Magnetiseringen hos dessa bergarter varierar kraftigt och ibland förekommer de i direkt anslutning till indikerad finkornig granit, vilket tyder på så kallade ”composite dykes”.

Den beräknade sprickfrekvensen är generellt låg till moderat förutom i KAS04 där den är moderat till hög. Möjliga större deformationszoner indikeras förekomma i KAS02 längs 310–320 m och 805–905 m, i KAS04 längs 330–445 m, i KAS06 längs 205–235 m, i KAS07 längs 413–425 m och 540–590 m samt i KAS08 längs 268–294 m och 537–595 m.

Contents

1 Introduction

This document reports the interpretations of geophysical borehole measurements and petrophysical data gained from the cored boreholes KAS02, KAS04, KAS06, KAS07 and KAS08, which is one of the activities performed within the work of upgrading the geological model of the Äspö HRL (Figure 1-1). The work was carried out in accordance with activity plans AP TD F140-10-005, AP TD F140-10-009 and AP TD F140-10-020. In Table 1-1 controlling documents for performing this activity are listed. Activity plans and method descriptions are SKB's internal controlling documents.

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

Activity plan	Number	Version
Tolkning av loggade geofysiska data samt petrofysiska data från borrhålet KAS02	AP TD F140-10-005	1.0
Tolkning av loggade geofysiska data samt petrofysiska data från borrhålen KAS04, KAS06 och KAS08	AP TD F140-10-009	1.0
Tolkning av loggade geofysiska data från borrhålet KAS07	AP TD F140-10-020	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för tolkning av geofysiska borrhålsdata	SKB MD 221.003	3.0

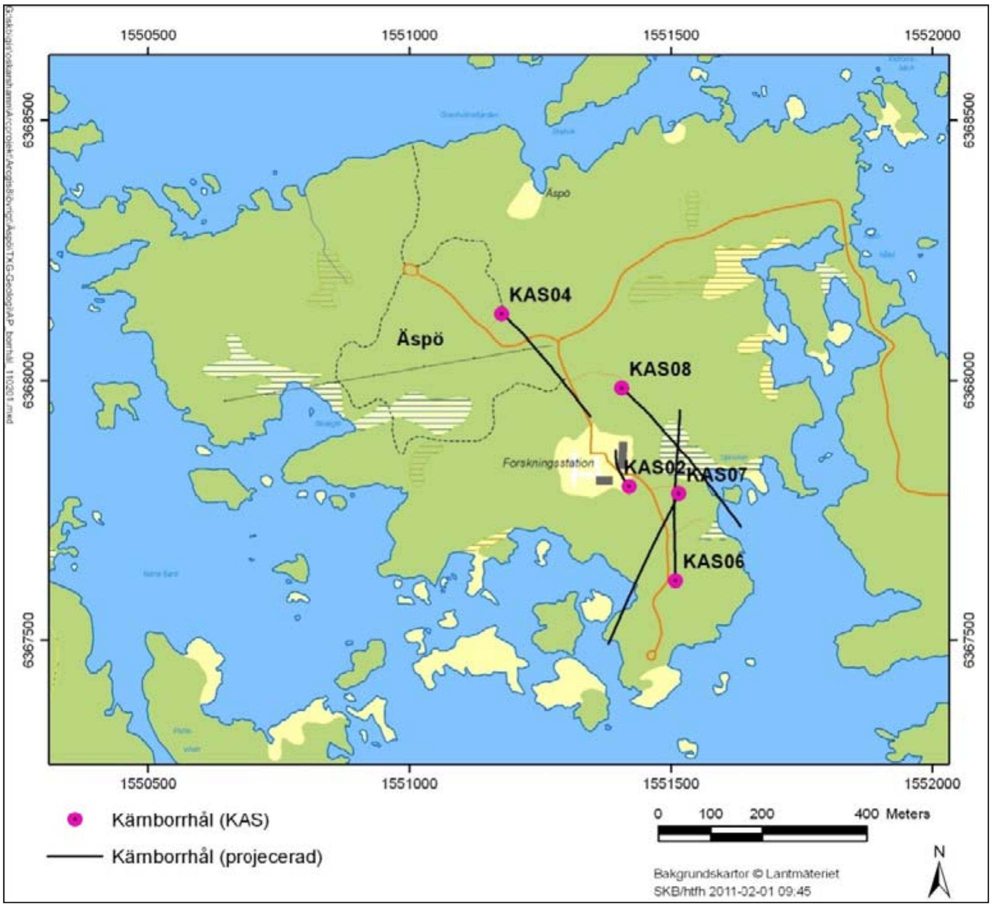


Figure 1-1. General overview over Äspö showing the locations of the investigated boreholes KAS02, KAS04, KAS06, KAS07 and KAS08.

Generalized geophysical loggings related to lithological variations are presented together with indicated fracture loggings, including estimated fracture frequency. The logging measurements were conducted by Malå GeoScience in the late 1980s.

The investigations performed prior to the construction of the Äspö HRL did not follow the same standards used during the site investigations in Forsmark and Oskarshamn. These older geophysical logging data differ from the data collected during the site investigations and the number and type of logging methods varies between the different boreholes, see Table 1-2.

The interpretation presented in this report is performed by GeoVista AB in accordance with the instructions and guidelines from SKB and under supervision of Leif Stenberg, SKB.

The data and interpretation products are stored in the database Sicada and are traceable by the activity plan numbers.

Table 1-2. Existing logging data.

Loggningsparameter	KAS02	KAS04	KAS06	KAS07	KAS08
Fluid temp. / resistivity	X	X	X	X	X
Fluid temp. gradient		X	X	X	X
Fluid salinity				X	
Nat. Gamma	X	X	X	X	X
SP resistance	X	X	X		X
Normal res. 1.6 m	X	X			
Lateral res.	X	X			
Caliper	X			X	
Magn. Susceptibility	X	X	X	X	X
Sonic	X	X	X	X	X
Neutron-Neutron				X	
Density			X	X	X

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, sonic and caliper loggings.

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 interpretation tools for analyses of logging data

The software used for the interpretation are WellCad v4.0 (ALT) and Strater 1.00.24 (Golden Software), that are mainly used for plotting, Grapher v7 (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 logging data in general

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 length adjustment procedure was specifically important since no such processing have previously been performed on the data. The length adjustment was performed in WellCAD with reference to the geological Boremap data.

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 and magnetic susceptibility logging data are generally calibrated with respect to petrophysical data from samples from the drill core. For KAS02 and KAS04 the susceptibility logging data were calibrated with respect to sample data from KAS02. For these two boreholes there are no density logging data. The density and susceptibility data of KAS06 and KAS08 were calibrated with respect to petrophysical data from samples from each borehole, respectively. The calibration equations estimated for KAS06 and KAS08 indicate that these data already were calibrated, and it was therefore decided that no calibration was to be performed on the data from KAS07.

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

The silicate density is calculated with reference to /1/ and the data are then divided into 5 sections *indicating* a mineral composition corresponding to granite, granodiorite, tonalite, diorite and gabbro rocks, according to /2/. 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" (< 10 μR/h), "medium" (10 μR/h < gamma < 20 μR/h), "high" (20 μR/h < gamma < 30 μR/h) and "very high" (> 30 μR/h).

3. 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 "fracture loggings" SPR, sonic, resistivity and fluid temperature data. 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 used in the previous site investigation at Oskarshamn were estimated by correlating the weighted sum to the mapped fracture frequency in the cored boreholes KLX03 and KLX04. The parameters were based on logging data from sonic, caliper, normal resistivity, SPR and focused resistivity measurements. However, in these old Äspö data the main fracture indicative loggings used are SPR and sonic. The parameters of the power functions have therefore been adjusted to fit a "back ground" fracture frequency of ca 2–3 fractures/m. The powers and linear coefficients (weights) used are presented in Table 4-1.

4. Report evaluating the results.

Table 4-1. Threshold values, powers and weights used for estimating position of fractures and calculate estimated fracture frequency.

	Borehole	SPR	Normal res. 64	Sonic	Lateral res.	Caliper
Threshold	KAS02	5.0	10.0	2.0	3.0	–
Power	KAS02	0.5	0.5	1.0	1.0	–
Weight	KAS02	5.0	2.9	1.0	7.1	–
Threshold	KAS04	2.0	5.0	1.2	2.0	–
Power	KAS04	0.5	0.5	1.0	1.0	–
Weight	KAS04	5.0	2.9	1.0	7.1	–
Threshold	KAS06	2.0	–	1.0	–	–
Power	KAS06	0.5	–	1.0	–	–
Weight	KAS06	5.0	–	1.0	–	–
Threshold	KAS07	2.0	–	0.8	–	0.5
Power	KAS07	0.5	–	1.0	–	1.0
Weight	KAS07	5.0	–	1.0	–	1.0
Threshold	KAS08	2.0	–	0.7	–	–
Power	KAS08	0.5	–	1.0	–	–
Weight	KAS08	5.0	–	1.0	–	–

4.2 Preparations and data handling

The logging data were delivered as Microsoft Excel files via email from SKB. 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
- Normal resistivity (160 cm)
- Lateral resistivity
- Single point resistance (SPR)
- Fluid resistivity
- Fluid temperature
- Sonic (P-wave velocity)
- Caliper 1 arm (bore hole diameter)

The density and susceptibility logging data were calibrated with reference to petrophysical measurements made on core samples. The logging data at the same section coordinate as the sample core location were extracted from the data files and a cross-plot was created with logging data on one axis and the petrophysical data on the other. Linear regression technique was applied to establish a calibration equation, which then was applied to the logging data.

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 SPR, sonic, resistivity, caliper and fluid temperature (including the vertical fluid temperature gradient) loggings are mainly used for identifying sections with increased fracturing.

4.4 Nonconformities

No nonconformities are reported.

5 Results

5.1 Results of the petrophysical measurements and calibrations of logging data

Density is considered one of the most important physical parameters since it is directly related to the mineral content and hence also to rock type. Density logging data exist for the boreholes KAS06, KAS07 and KAS08. For KAS02 there were no density data collected during the logging survey but 121 rock samples were collected with a fairly even spacing of c. 5–10 m along the borehole. Petrophysical measurements were performed in the 1980s on these samples and the analyses included the parameters density, magnetic susceptibility, Q-value, porosity, IP (induced polarization) and resistivity. The petrophysical data were retrieved from Sicada together with the logging data from the five investigated boreholes.

New petrophysical measurements were performed on 11 samples from KAS06 and 10 samples from KAS08. The measurements were performed at the petrophysical laboratory at Luleå University of Technology and include the parameters density and magnetic susceptibility.

Density-susceptibility classification diagrams are presented in Figure 5-1 for KAS02 and Figure 5-2 for KAS06 and KAS08. In the data from KAS02 it is clear that the Ävrö granite-granodiorite can be divided into two distinct groups, one with indicated granitic composition and the other with indicated granodioritic to tonalitic composition. The latter group overlaps with the Äspö diorite. Note that also the Äspö diorite shows a fairly wide distribution in both density and magnetic susceptibility. All samples of fine-grained granite show decreased density, but the magnetic susceptibility varies in the range 0.0003–0.02 SI, clearly indicating that this rock type may carry fair amounts of magnetite and cannot, as a rule, always be related with low magnetic anomalies.

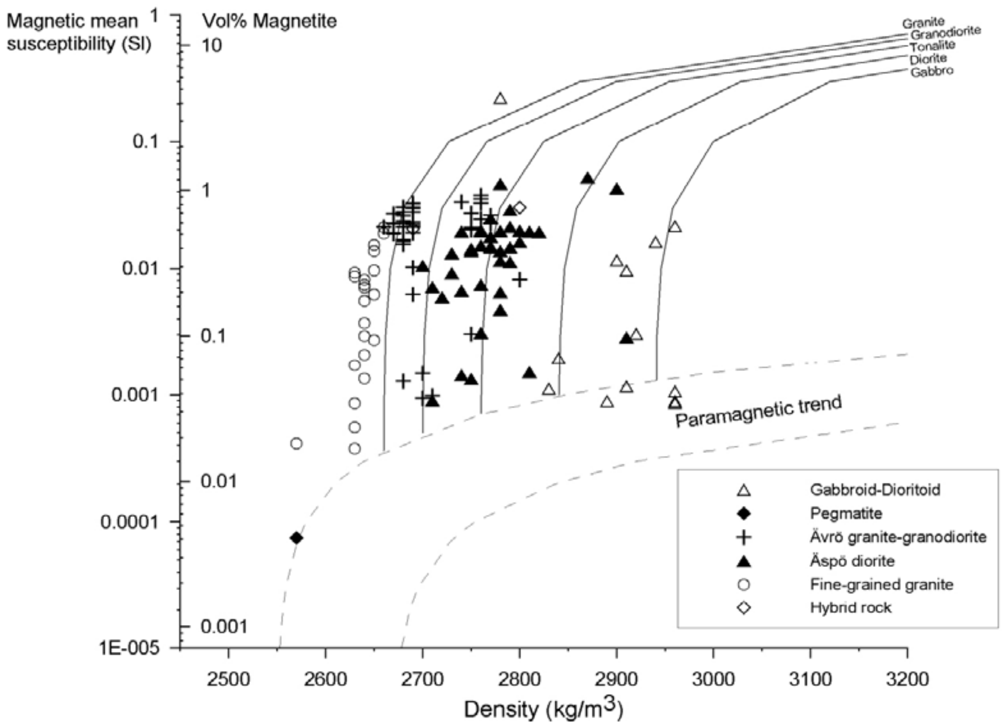


Figure 5-1. *Density-susceptibility classification diagram of 121 rock samples from KAS02.*

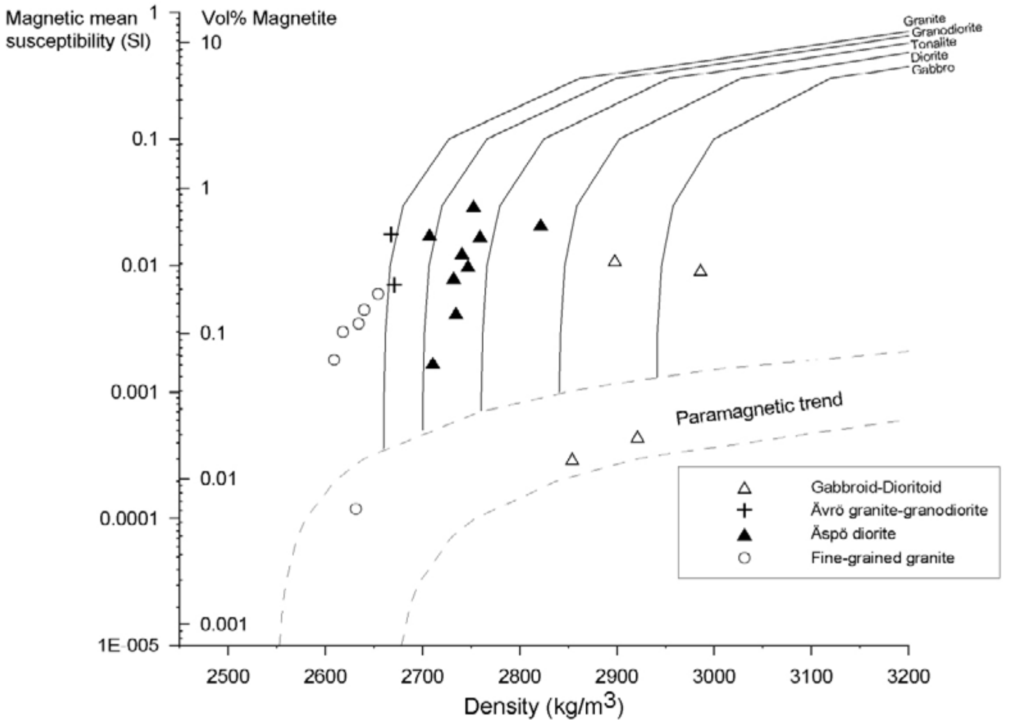


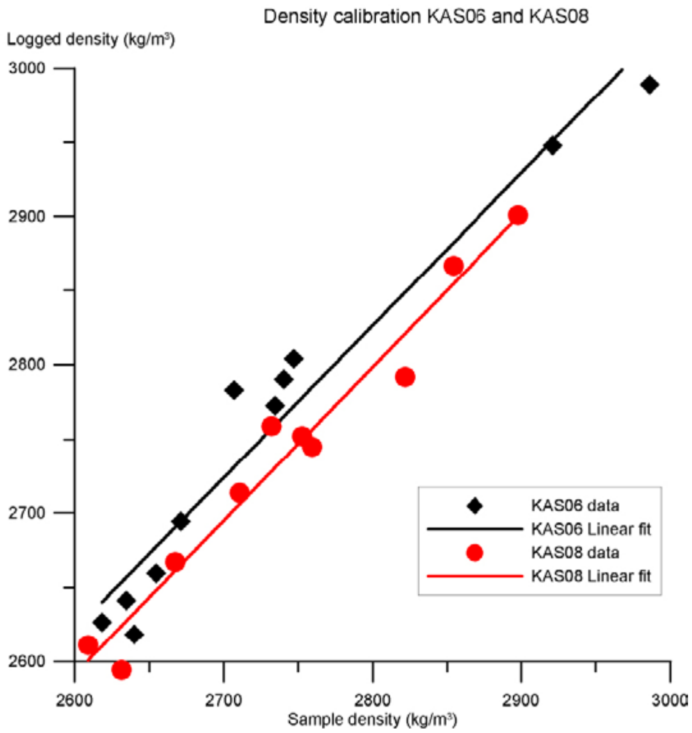
Figure 5-2. Density-susceptibility classification diagram of 11 rock samples from KAS06 and 10 samples from KAS08.

The susceptibility logging data of KAS02 were calibrated with reference to the sample susceptibility data shown in Figure 5-1 and the density and susceptibility logging data of KAS06 and KAS08 were calibrated with reference to the data from the sample measurements presented in Figure 5-2. The calibration procedure is performed by plotting the sample data versus the logging data at the corresponding section length coordinate (after length adjustment an average filtering) in a cross-plot, and then performing linear regression analysis, see Figure 5-3. The calibration is then performed by applying the linear equation achieved from the analysis to the logging data.

The density cross-plot for KAS06 and KAS08 that is shown in Figure 5-3a displays a nice linear distribution for the data from both boreholes. Both linear equations fit well to their data, and the slopes of the lines are close to 1.0. The results are similar for the magnetic susceptibility data (Figure 5-3b).

The calibration results show that there are only minor differences between the logged parameters and the sample measurements, which most likely indicates that these old logging data already were calibrated before they were stored in the Sicada database. No calibration was therefore performed on the data from KAS04 and KAS07.

a)



b)

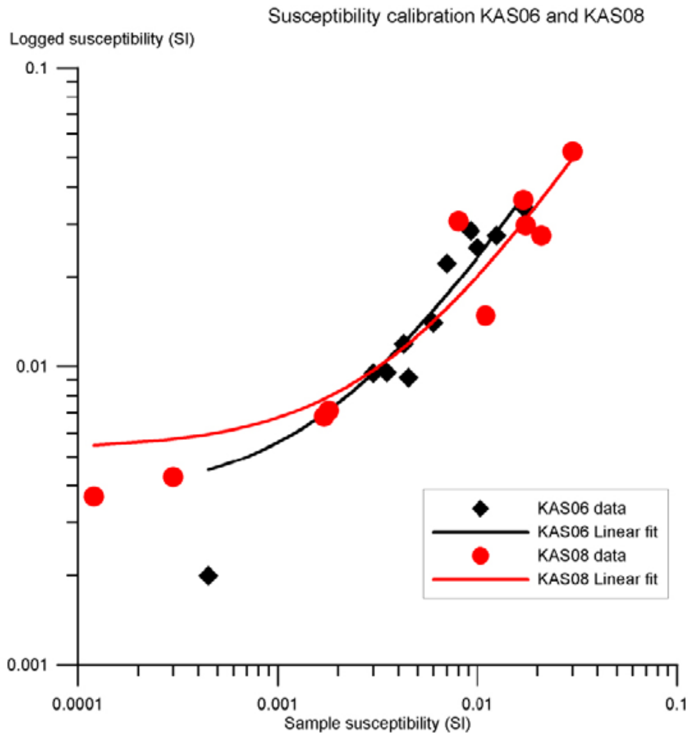


Figure 5-3. *Cross-plots of logging versus sample data from KAS06 and KAS08 for a) density and b) magnetic susceptibility.*

5.2 Quality control of the logging data

Noise levels of the raw data for each logging method are presented in Table 5-1. For all boreholes the natural gamma radiation data have noise levels above the recommended value 0.3 µR/h. These increased noise levels may have affected the interpretation of the data, especially the response from small rock bodies such as dykes. The susceptibility and density data generally have noise levels close to, or slightly above, the recommended level, and most other parameters have noise levels below the recommended levels. 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), and all null values were disregarded in the interpretation.

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

5.3.1 Interpretation of KAS02

The results of the generalized logging data and fracture estimations of KAS02 are presented in Figure 5-5. There were no density data collected during the logging of this borehole. However, the density of 121 core samples is displayed versus borehole length in Figure 5-4. The uppermost 100 m section of KAS02 has a larger borehole diameter than the deeper parts of the borehole. The increased borehole diameter significantly affects the geophysical logging data and this part of the borehole is therefore omitted in the interpretation.

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

Logging method	KAS02	KAS04	KAS06	KAS07	KAS08	Recommended max noise level
Density (kg/m^3)	–	–	12	12	11	3–5
Magnetic susceptibility (SI)	$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$6 \cdot 10^{-4}$	$6 \cdot 10^{-4}$	$7 \cdot 10^{-4}$	$1 \cdot 10^{-4}$
Natural gamma radiation (µR/h)	0.4	0.6	1.1	1.1	1.0	0.3
Fluid resistivity (%)	0.04	–	–	0.24	–	2
Fluid temperature (°C)	$5 \cdot 10^{-4}$	$1 \cdot 10^{-3}$	$3 \cdot 10^{-5}$	$3 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	0.01
SPR (%)	0.03	0.6	0.3	0.2	0.3	No data
Normal resistivity (%)	0.03	0.2	–	–	–	2.0
Lateral resistivity	0.2	0.01	–	–	–	2.0
Sonic (m/s)	10	15	15	–	18	20
Caliper (m)	$1 \cdot 10^{-5}$	–	–	–	–	$5 \cdot 10^{-4}$

The borehole can, with reference to the sampled density data presented in Figure 5-4, be divided into three sub sections of c. 0–40 m, 40–450 m and 450–950 m. The upper and lowermost sections have a general density level in the range 2,730–2,800 kg/m^3, whereas the intermediate section is dominated by density in the range 2,650–2,710 kg/m^3. The decreased density range indicates a composition that corresponds to granite (indicating Ävrö granite) and the increased density range indicates a mineral composition that corresponds to granodiorite to tonalite, which suggests the occurrences of Ävrö granodiorite and/or Äspö diorite. In Figure 5-4 it is evident that some samples with increased density have been classified as Ävrö granite-granodiorite and samples with decreased density have been classified as Äspö diorite.

The sub-division of KAS02 as indicated by the sample density data is not indicated in the natural gamma radiation or the magnetic susceptibility logs. The natural gamma radiation level is generally in the range 10–20 µR/h and the magnetic susceptibility is generally in the range 0.015–0.035 SI (Figure 5-5). The most significant deviations from the general radiation and magnetization levels occur at borehole section lengths c. 260–320 m, 350–380 m, 520–555 m, 655–715 m and 865–910 m. Along these five sections the natural gamma radiation is significantly increased and the magnetic susceptibility is decreased. From the geologically classified samples we know that the rock type along these sections is dominated by fine-grained granite, which is known to have increased natural gamma radiation and decreased magnetic susceptibility. Sections with decreased magnetic susceptibility without increased natural gamma radiation (e.g. 310–320 m, 800–815 m and 835–840 m) may indicate occurrences of alteration and/or increased fracturing. Some few, generally short, section with significantly increased magnetic susceptibility (e.g. 618–622 m) suggest occurrences of gabbroid rocks.

Significant anomalies in the resistivity, SPR and sonic data occur in the sections c. 210–215 m, 310–320 m, 450–460 m and 805–905 m. The anomalies indicate increased fracture frequency. In the two sections at 310–320 m and 805–905 m there are also distinct anomalies in the vertical fluid temperature gradient, which indicates in or out flow of water and suggests that the possible deformation zones are water bearing. At c. 203 m borehole length there is a short but distinct low resistivity and low velocity anomaly that coincides with an anomaly in the vertical fluid temperature gradient, which most likely indicates a single water bearing fracture.

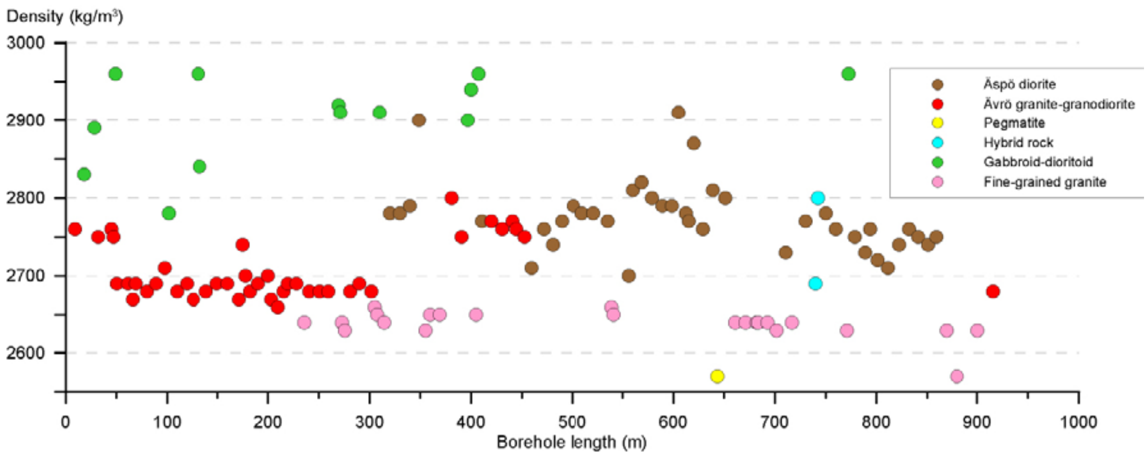


Figure 5-4. *Density of core samples from KAS02 plotted versus borehole length.*

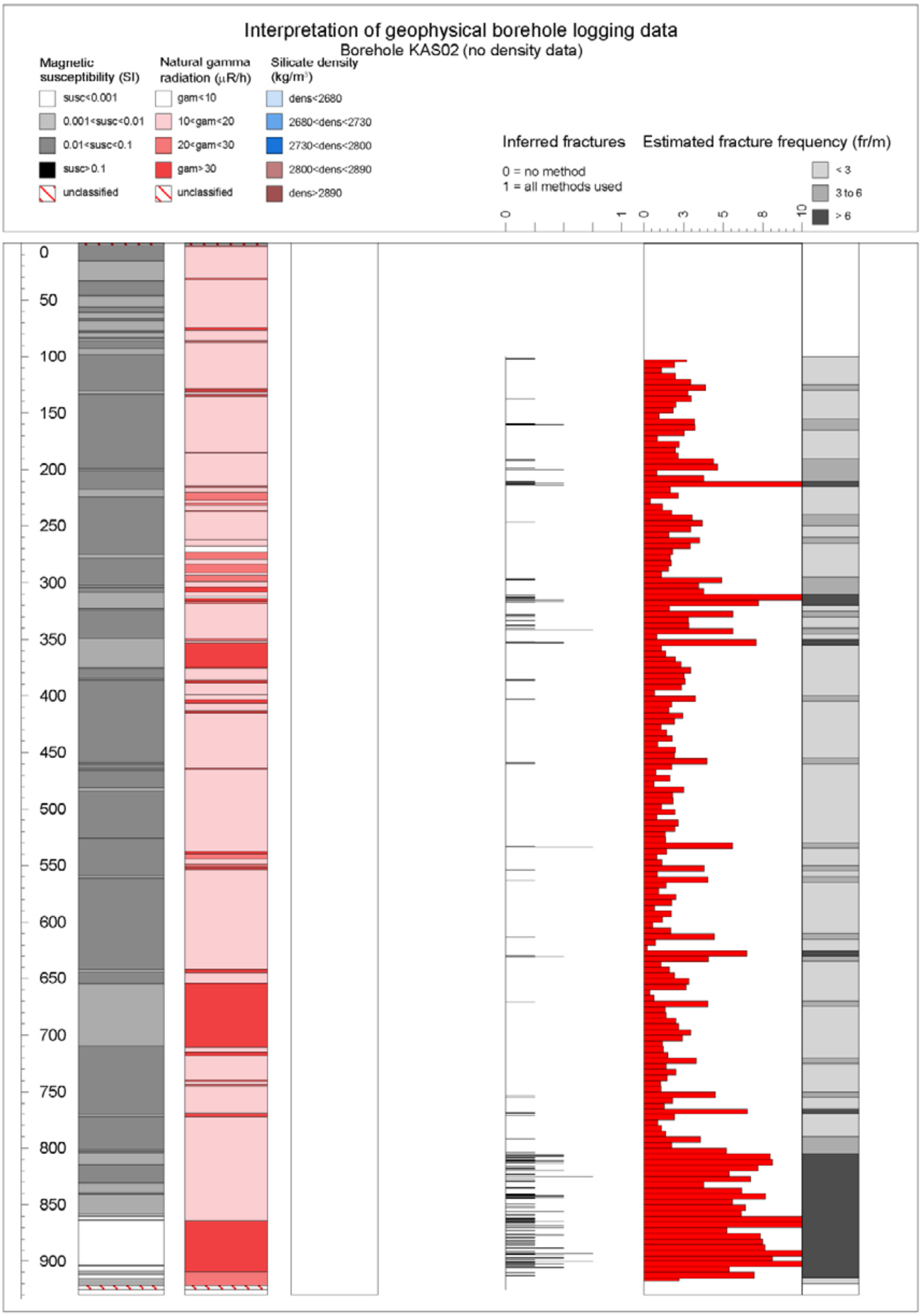


Figure 5-5. *Generalized geophysical logs of KAS02.*

5.3.2 Interpretation of KAS04

The results of the generalized logging data and fracture estimations of KAS04 are presented in Figure 5-6 below. There were no density data collected in this borehole. The uppermost 100 m section of KAS04 has a larger borehole diameter than the deeper parts of the borehole. The increased borehole diameter significantly affects the geophysical logging data and this part of the borehole is therefore omitted in the interpretation.

The sections c. 100–330 m and 460–480 m are dominated by natural gamma radiation in the range 10–20 μR/h and magnetic susceptibility of 0.005–0.020 SI. The combination of physical properties indicates occurrences of Äspö diorite and/or Ävrö granite-granodiorite. However, along these two sections there are also several 1–2 m long sections with significantly increased gamma radiation, that most likely correspond to fine-grained granite (or possibly, but less likely, pegmatite). There are large variations in magnetic susceptibility of the indicated fine-grained granite rocks, showing that they in some cases carry fair amounts of magnetite. A few short sections with significantly increased magnetic susceptibility indicate minor occurrences of gabbroid rocks, e.g. at c. 205 m and 276 m. The anomaly at 276 m is located right beside an indicated dyke of fine-grained granite, which suggests an occurrence of a so called composite dyke.

The section c. 330–460 m is dominated by increased natural gamma radiation, in the range 30–40 μR/h, which most likely indicates the occurrence of fine-grained granite, even though the amplitude of the radiation is slightly lower than what is the "normal" for this rock type. In the sub-section 330–360 m the magnetic susceptibility is clearly decreased, whereas in other part of the section the magnetic susceptibility equals that of Ävrö granodiorite or Äspö diorite. It is possible that the upper sub-section has suffered from alteration and/or deformation.

The estimated fracture frequency is generally moderate or high, which is explained by a fairly large number of low resistivity and low velocity anomalies along the borehole. The most prominent anomalies occur in the sections c. 115–119 m, 174–180 m, 217–219 m, 229–233 m, 290–292 m, 335–345 m and 400–418 m. In the resistivity data there is a clear indication of a generally decreased bulk resistivity along the entire section c. 330–445 m, which may suggest that the entire rock volume along this part of the borehole is more porous or has suffered from increased fracturing. There are also several anomalies in the vertical temperature gradient data along the entire borehole, which indicates increased occurrences of water bearing fractures. The most significant anomalies occur at c. 110–145 m, 170–180 m, 190–205 m, 220–245 m, 330–360 m and 400–425 m.

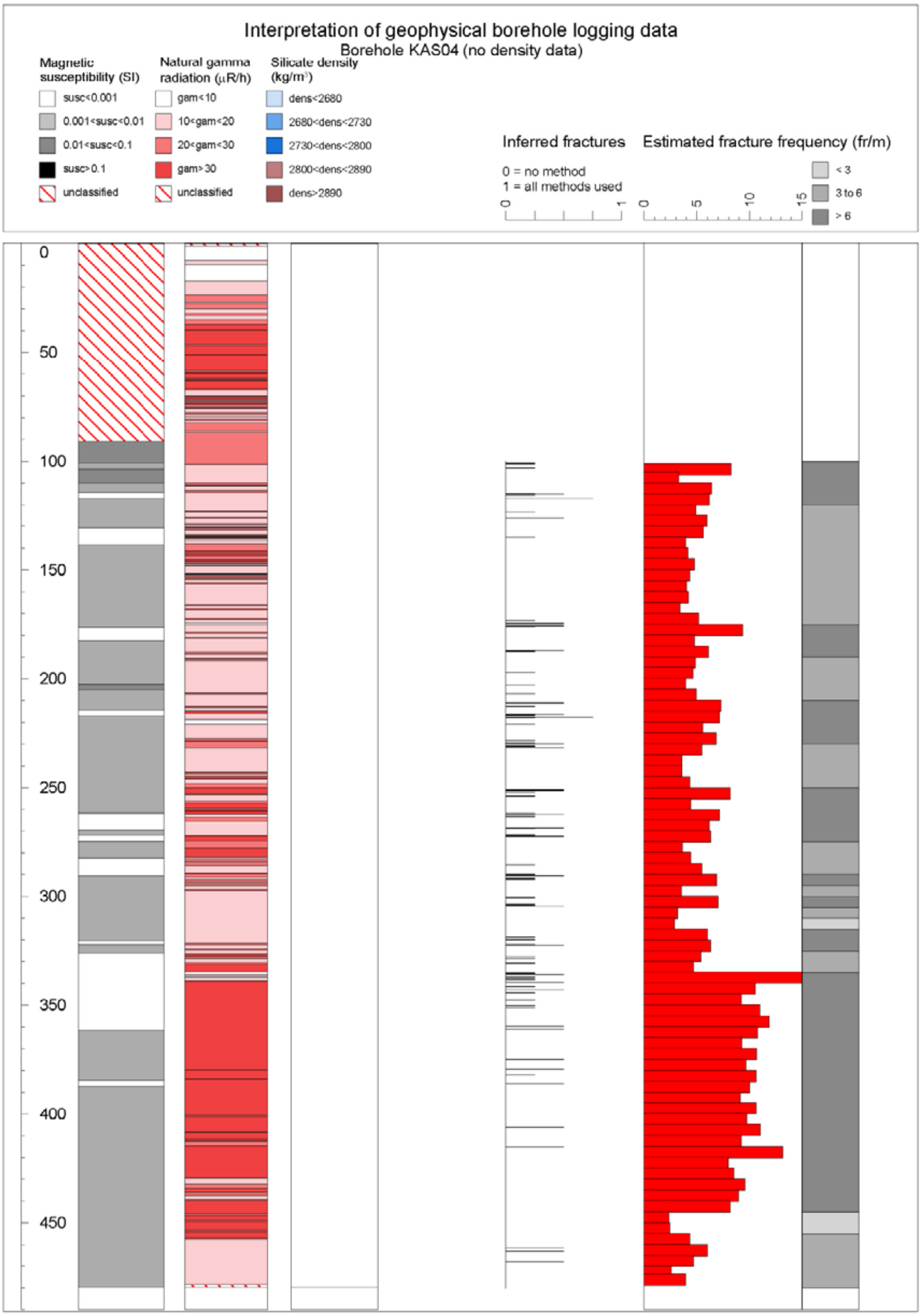


Figure 5-6. Generalized geophysical logs of KAS04.

5.3.3 Interpretation of KAS06

The results of the generalized logging data and fracture estimations of KAS06 are presented in Figure 5-7 below and the distribution of silicate density classes in Table 5-2. The uppermost 100 m section of KAS06 has a larger borehole diameter than the deeper parts of the borehole. However, the density, natural gamma radiation and magnetic susceptibility data do not seem to be significantly affected by the variations in borehole diameter so these data were therefore interpreted along the entire borehole length. The fracture indicative loggings were, however, only interpreted in the section 100–600 m.

The silicate density is dominated by values in the range 2,730–2,780 kg/m^3, and along these sections of the borehole the natural gamma radiation is c. 10–20 µR/h and the magnetic susceptibility is c. 0.020–0.060 SI. This combination of physical properties most likely corresponds to occurrences of Äspö diorite.

The section c. 225–277 m is dominated by increased density (2,870–2,950 kg/m^3), the natural gamma radiation is clearly decreased and the magnetic susceptibility is partly decreased. This indicates the occurrence of dioritoid-gabbroid rock with decreased magnetite content. At the lower end of the section there are indicated occurrences of fine-grained granite suggesting that this is a fairly large composite dyke.

Significantly increased natural gamma radiation in combination with decreased density and magnetic susceptibility occurs along the section c. 460–535 m, which indicates the occurrence of fine-grained granite.

In the section c. 435–460 m the average silicate density is c. 2,670 kg/m^3, the average natural gamma radiation is c. 15 µR/h and the average magnetic susceptibility is c. 0.023 SI, and this combination of properties most likely indicates the occurrence of Ävrö granite-granodiorite.

The estimated fracture frequency is generally moderate or low. Increased estimated fracture frequency, suggesting occurrences of possible deformation zones, is indicated by distinct amplitude decrease in the SPR and sonic logging data along the intervals c. 205–235 m and 440–450 m. In the section 205–235 m there is a major anomaly in the vertical fluid temperature gradient, which indicates a significant flow of water in the inferred deformation zone.

Table 5-2. Distribution of silicate density classes with borehole length in KAS06.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens<2,680 (granite)	175	30
2,680<dens<2,730 (granodiorite)	105	18
2,730<dens<2,800 (tonalite)	258	43
2,800<dens<2,890 (diorite)	32	5
dens>2,890 (gabbro)	25	4

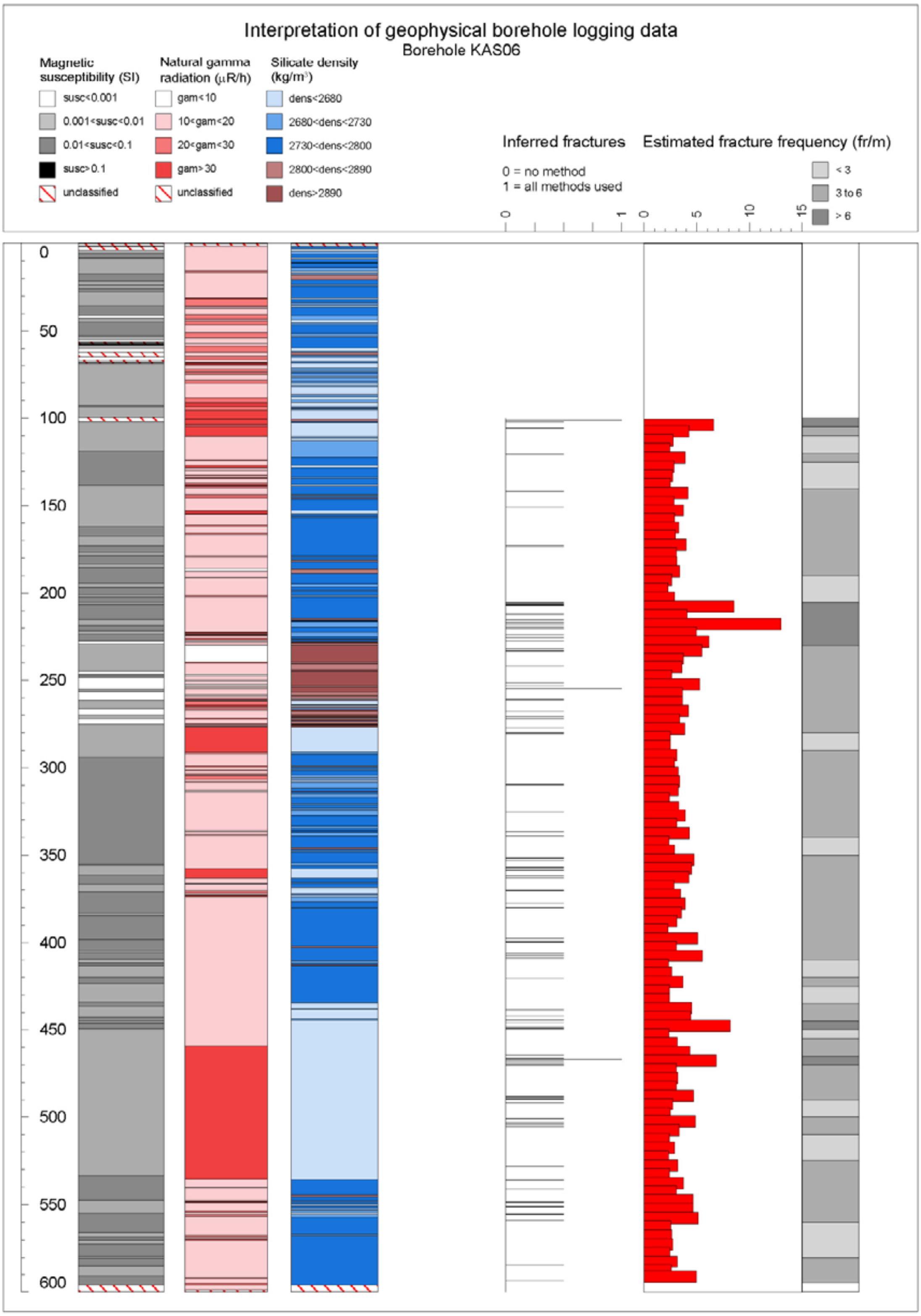


Figure 5-7. Generalized geophysical logs of KAS06.

5.3.4 Interpretation of KAS07

The results of the generalized logging data and fracture estimations of KAS07 are presented in Figure 5-8 below. The distribution of silicate density classes with borehole length is presented in Table 5-3. The uppermost 100 m section of KAS07 has a larger borehole diameter than the deeper parts of the borehole. However, the density, natural gamma radiation and magnetic susceptibility data do not seem to be significantly affected by the variations in borehole diameter so these data were therefore interpreted along the entire borehole length. The fracture indicative loggings were, however, only interpreted in the section c. 100–600 m.

Almost 50% of the borehole length is characterized by silicate density in the range 2,760–2,820 kg/m^3, natural gamma radiation of c. 10–15 µR/h and the magnetic susceptibility is c. 0.025–0.050 SI. This combination of physical properties most likely corresponds to occurrences of Äspö diorite.

In the section c. 244–264 m significantly increased natural gamma radiation in combination with decreased density and magnetic susceptibility indicates the occurrence of fine-grained granite. Along the entire borehole there are numerous short sections, generally < 1 m long, of indicated fine-grained granite.

There are four sections, at c. 14–24 m, 192–215 m, 377–384 m and 530–566 m, with silicate density in the range 2,890–3,000 kg/m^3, decreased natural gamma radiation and significantly decreased magnetic susceptibility. The physical properties correspond to dioritoid-gabbroid rock with very low content of magnetite.

In the lowermost part of the borehole, section c. 565–595 m, partly increased natural gamma radiation and an average density of 2,670 kg/m^3 indicates the occurrence of Ävrö granite. In the upper parts of the borehole, sections c. 25–70 m and 150–173 m, the average density of 2,700 kg/m^3 and natural gamma radiation of 10–15 µR/h indicate the occurrences of Ävrö granodiorite.

The estimated fracture frequency in KAS07 is generally low. There are two sections, c. 413–425 m and 540–590 m, where there are significant SPR, caliper and sonic anomalies that indicate possible deformation zones. In the section c. 215–280 m there are four distinct anomalies in the vertical fluid temperature gradient, and also short but distinct SPR and sonic anomalies, that most likely indicate single water bearing fractures.

Table 5-3. Distribution of silicate density classes with borehole length in KAS07.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens<2,680 (granite)	101	17
2,680<dens<2,730 (granodiorite)	113	19
2,730<dens<2,800 (tonalite)	282	47
2,800<dens<2,890 (diorite)	45	8
dens>2,890 (gabbro)	53	9

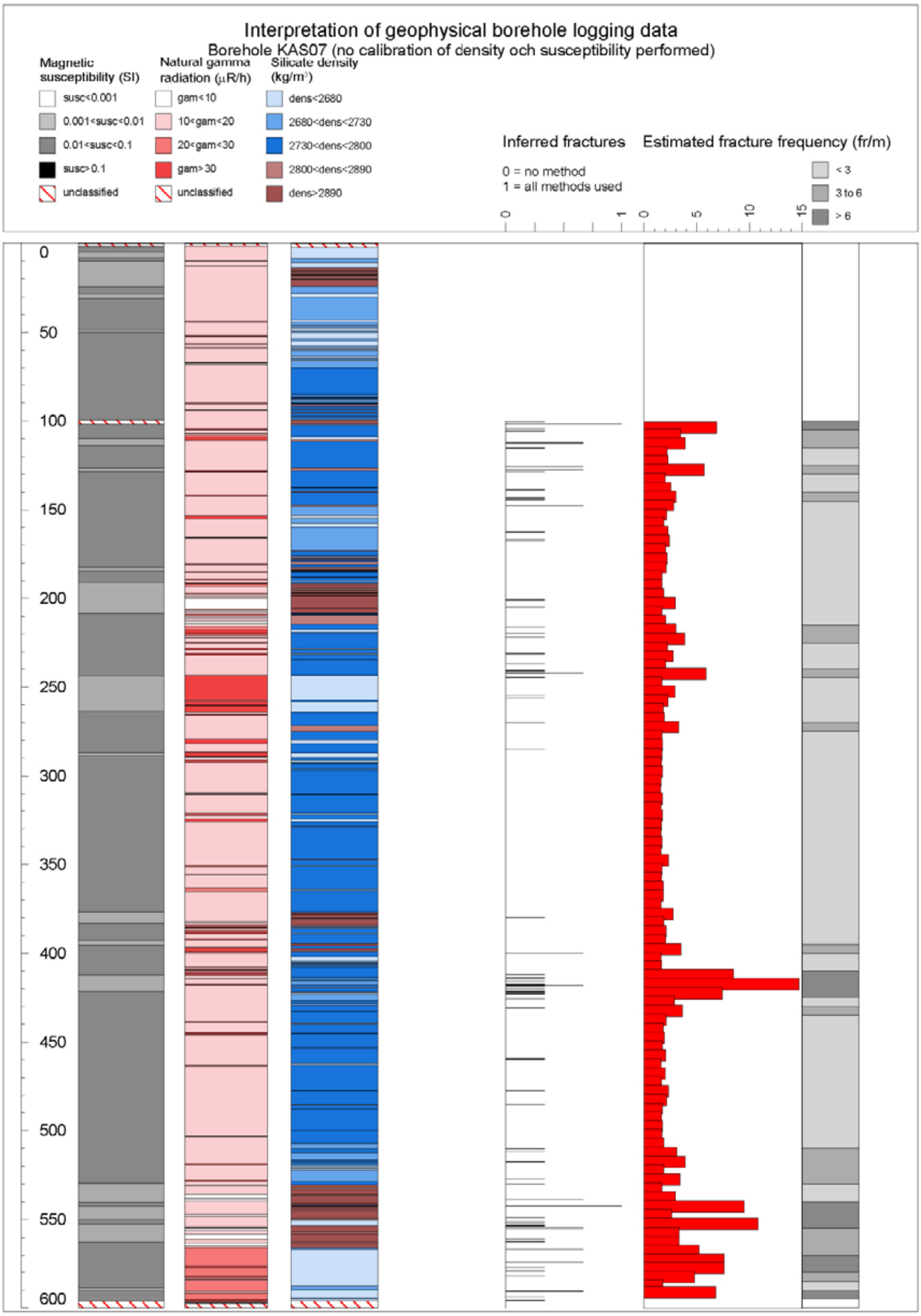


Figure 5-8. Generalized geophysical logs of KAS07.

5.3.5 Interpretation of KAS08

The results of the generalized logging data and fracture estimations of KAS08 are presented in Figure 5-9 below. The distribution of silicate density classes with borehole length is presented in Table 5-4. The uppermost 100 m section of KAS08 has a larger borehole diameter than the deeper parts of the borehole. The increased borehole diameter significantly affects the geophysical logging data and this part of the borehole is therefore omitted in the interpretation.

The silicate density distribution in KAS08 indicates that c. 46% of the rocks have a mineral composition that corresponds to tonalite rocks (Table 5-3), and along these sections of the borehole the natural gamma radiation is c. 10–15 μR/h and the magnetic susceptibility is c. 0.010–0.025 SI. This combination of physical properties most likely corresponds to occurrences of Äspö diorite.

In the section c. 543–579 m significantly increased natural gamma radiation in combination with decreased density and magnetic susceptibility indicates the occurrence of fine-grained granite. Along the entire borehole, but with a clear concentration in the lower half, there are numerous short sections, generally < 1 m long, of indicated fine-grained granite.

In the section 245–314 m partly increased natural gamma radiation and an average density of 2,670 kg/m^3 indicates the occurrence of Ävrö granite. There is one section at c. 465–500 m, with silicate density in the range 2,890–3,000 kg/m^3, decreased natural gamma radiation and significantly decreased magnetic susceptibility. The physical properties correspond to dioritoid-gabbroid rock with very low content of magnetite. However there are also a number of very short sections with increased density and magnetic susceptibility that indicate occurrences of mafic dykes (dolerite or gabbroid rock) with an increased content of magnetite.

The estimated fracture frequency in KAS08 is generally low. In the section c. 268–294 m and 537–595 m there are distinct anomalies in the SPR and sonic data that most likely indicate highly increased fracturing. There are also anomalies in the vertical fluid temperature gradient along these two sections, which indicates in or out flow of water most likely related to water bearing fractures. At the borehole length co-ordinates 141 m, 154 m, 184 m and 462 there are short but distinct anomalies in the SPR, sonic and vertical fluid temperature gradient data that most likely correspond to single water bearing fractures.

Table 5-4. Distribution of silicate density classes with borehole length in KAS08.

Silicate density interval (kg/m^3)	Borehole length (m)	Relative borehole length (%)
dens<2,680 (granite)	152	31
2,680<dens<2,730 (granodiorite)	65	13
2,730<dens<2,800 (tonalite)	226	46
2,800<dens<2,890 (diorite)	39	8
dens>2,890 (gabbro)	11	2

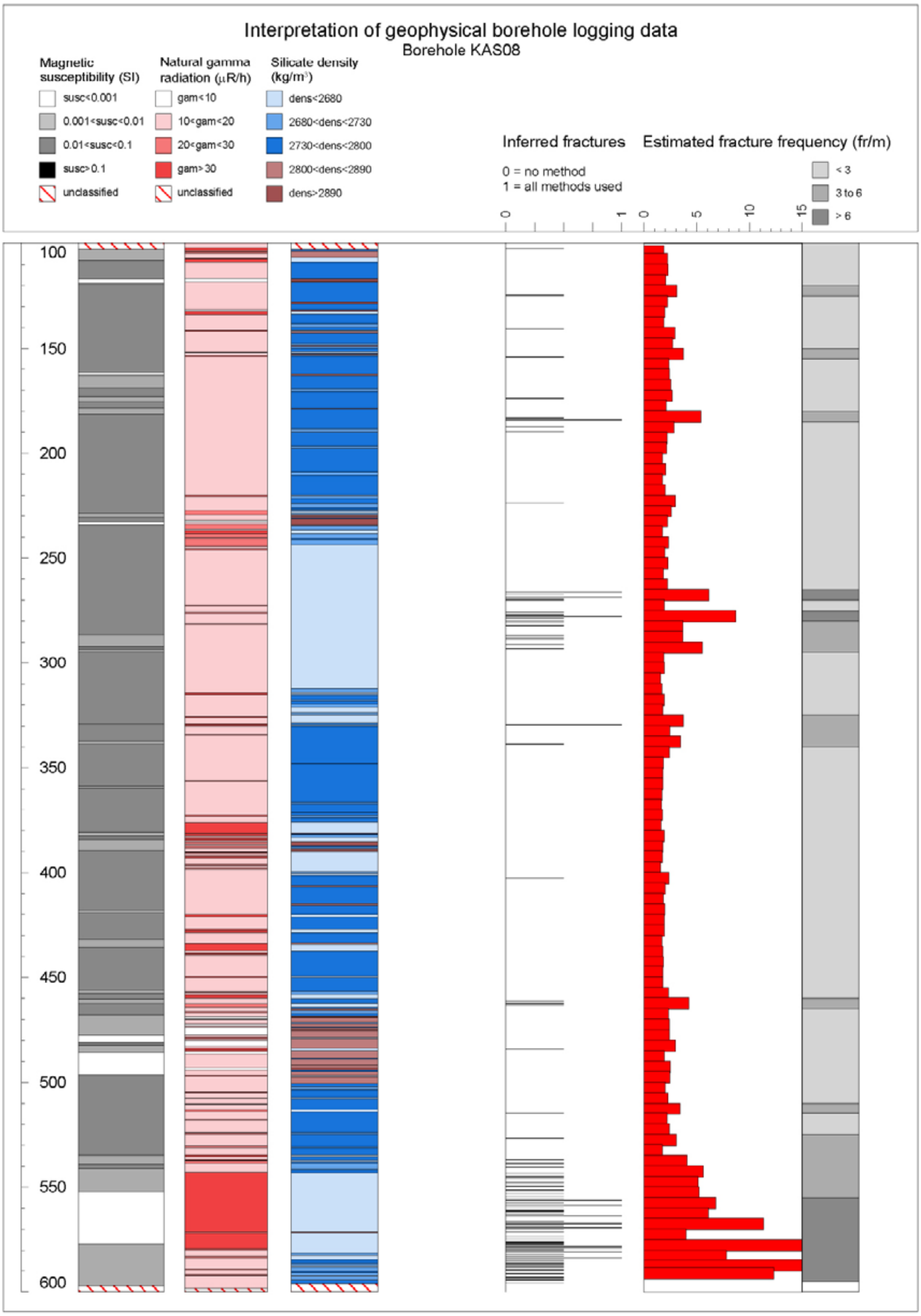


Figure 5-9. Generalized geophysical logs of KAS08.

References

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

/2/ **Puranen R, 1989.** Susceptibilities, iron and magnetite content of precambrian rocks in Finland. Geological survey of Finland, Report of investigations 90, 45 pp.