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October 2007

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Abstract

This report presents geological single-hole interpretations of the cored borehole KFM11A and the percussion boreholes HFM33, HFM34 and HFM35 at Forsmark. The interpretation combines the geological core mapping, generalized geophysical logs and borehole radar measurements to identify where rock units and possible deformation zones occur in the boreholes. A brief description of the character of each rock unit and possible deformation zone is provided.

The geological single-hole interpretation shows that nine rock units (RU1–RU9) occur in KFM11A. However, the borehole can be divided into thirteen separate sections due to the repetition of RU3 (RU3a and RU3b), RU6 (RU6a and RU6b) and RU7 (RU7a, RU7b and RU7c).

Felsic to intermediate metavolcanic rock (103076), with a variable composition and structure, dominates borehole KFM11A in rock units RU1, RU2, RU3, RU5 and RU7. The upper part of the borehole, down to 196 m borehole length (RU1) is heterogeneous and predominantly composed of felsic to intermediate metavolcanic rock (103076) and amphibolite (102017). There is also an increased frequency of fractures, particularly gently dipping fractures, in RU1 relative to RU2. Down to c. 410 m borehole length, in rock units RU1, RU2 and RU3, the metavolcanic rock shows a fine banding and a medium to strong foliation. Beneath c. 410 m, in rock units RU5 and RU7, the metavolcanic rock lacks banding but remains medium to strongly foliated. Metavolcanic rock with a more felsic composition dominates beneath c. 660 m (RU7). Rock units dominated by amphibolite (102017) in RU4, aplitic metagranite (101058) in rock unit RU6, fine- to medium-grained granite (111058) in rock unit RU8, and fine- to medium-grained metagranitoid (101051) with a granodioritic composition in RU9 occur along subordinate borehole sections. One possible deformation zone of brittle character has been identified in KFM11A (DZ1). This zone occupies the long borehole interval 245 to 824 m, along which ductile deformation is also conspicuous.

The percussion borehole HFM33 is dominated by felsic to intermediate metavolcanic rock (103076) and pegmatitic granite (101061). Pegmatitic granite dominates in the lower part of the borehole. These constitute two rock units in HFM33 (RU1 and RU2). A subordinate rock type is amphibolite (102017). No possible deformation zones have been identified in the borehole. However, the drilling was interrupted at 140.20 m drill length after penetrating a permeable fracture at 136 m.

The percussion borehole HFM34 is dominated by felsic to intermediate metavolcanic rock (103076) and pegmatitic granite (101061), which alternate and constitute three rock units (RU1–RU3). However, the borehole can be divided into six separate sections due to the repetition of RU1 (RU1a, RU1b and RU1c) and RU2 (RU2a and RU2b). A subordinate rock type is amphibolite (102017). Three possible deformation zones of brittle character have been identified in HFM34 (DZ1–DZ3).

Felsic to intermediate metavolcanic rock (103076), pegmatitic granite (101061) and aplitic metagranite (101058) dominate in three rock units in percussion borehole HFM35 (RU1–RU3). Subordinate rock types are amphibolite (102017) and fine-to medium-grained granite (111058). Three possible deformation zones of brittle character have been identified in HFM35 (DZ1–DZ3).

Sammanfattning

Denna rapport behandlar geologisk enhålstolkning av kärnborrhål KFM11A och hammarborrhålen HFM33, HFM34 och HFM35 i Forsmark. Den geologiska enhålstolkningen syftar till att utifrån den geologiska karteringen, tolkade geofysiska loggar och borrhålsradarmätningar indikera olika litologiska enheters fördelning i borrhålen samt möjliga deformationszoners läge och utbredning. En kort beskrivning av varje bergenhet och möjlig deformationszon presenteras.

Denna undersökning visar att det i KFM11A finns nio litologiska enheter (RU1–RU9). Baserat på repetition av enheterna RU3 (RU3a och RU3b), RU6 (RU6a och RU6b) och RU7 (RU7a, RU7b och RU7c) kan borrhålet delas in i tretton sektioner.

Felsisk till intermediär metavulkanisk bergart (103076) med varierande sammansättning och struktur dominerar borrhålet KFM11A i de litologiska enheterna RU1, RU2, RU3, RU5 och RU7. Övre delen av borrhålet, ner till 196 m borrhålslängd (RU1), består av en heterogen blandning dominerad av felsisk till intermediär metavulkanisk bergart (103076) och amfibolit (102017). Även en ökad frekvens av sprickor, i synnerhet flackt stupande, i RU1 relativt till RU2. Ner till c. 410 m borrhålslängd, i enheterna RU1, RU2 och RU3, visar den metavulkaniska bergarten en fin bandning och en medelstark till stark foliation. Nedanför c. 410 m, i enheterna RU5 och RU7, saknar den metavulkaniska bergarten bandning men behåller den medelstarka till starka foliationen. Metavulkanisk bergart med en mer felsisk sammansättning dominerar nedanför c. 660 m (RU7). Litologiska enheter dominerade av amfibolit (102017) i RU4, aplitisk metagranit (101058) i RU6, fin- till medelkornig granit (111058) i RU8, och fin- till medelkornig metagranitoid (101051) med en granodioritisk sammansättning i RU9 förekommer i underordnade borrhålssektioner. En möjlig deformationszon som är spröd har identifierats i KFM11A (DZ1). Denna zon upptar det långa borrhålsintervallet 245 till 824 m, längs med vilket även plastisk deformation är markant.

Hammarborrhål HFM33 domineras av felsisk till intermediär metavulkanisk bergart (103076) samt pegmatitisk granit (101061). Pegmatitisk granit dominerar i botten av borrhålet. De två bergarterna utgör två litologiska enheter i HFM33 (RU1 och RU2). I mindre omfattning förekommer amfibolit (102017). Ingen möjlig deformationszon har identifierats i HFM33. Däremot avbröts hammarborrningen vid 140.20 m efter penetration av en vattenförande spricka vid 136 m.

Hammarborrhål HFM34 domineras av felsisk till intermediär metavulkanisk bergart (103076) och pegmatitisk granit (101061), vilka alternerar i borrhålet och utgör tre litologiska enheter (RU1–RU3). Baserat på repetition av enheterna RU1 (RU1a, RU1b och RU1c) och RU2 (RU2a och RU2b) kan borrhålet delas in i sex sektioner. I mindre omfattning förekommer amfibolit (102017). Tre möjliga deformationszoner som är spröda har identifierats i HFM34 (DZ1–DZ3).

Felsisk till intermediär metavulkanisk bergart (103076), pegmatitisk granit (101061) och aplitisk metagranit (101058) dominerar i tre litologiska enheter i hammarborrhålet HFM35 (RU1–RU3). I mindre omfattning förekommer amfibolit (102017) och fin- till medelkornig granit (111058). Tre möjliga deformationszoner som är spröda har identifierats i HFM35 (DZ1–DZ3).

Contents

1 Introduction

Much of the primary geological and geophysical borehole data stored in the SKB database SICADA need to be integrated and synthesized before they can be used for modelling in the 3D-CAD Rock Visualization System (RVS). The end result of this procedure is a geological single-hole interpretation, which consists of an integrated series of different logs and accompanying descriptive documents.

This document reports the geological single-hole interpretations of boreholes KFM11A, HFM33, HFM34 and HFM35 in the Forsmark area. The horizontal projections of the boreholes are shown in Figure 1-1. The work was carried out in accordance with Activity Plan AP PF 400-07-016. The controlling documents for performing this activity are listed in Table 1-1. Both the Activity Plan and Method Description are SKB's internal controlling documents.

Figure 1-1. Map showing position and horizontal projection of the cored borehole KFM11A and the percussion boreholes HFM33, HFM34 and HFM35.

Original data from the reported activity are stored in the primary database Sicada, where they are traceable by the Activity Plan number (AP PF 400-07-016). Only data in SKB's databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major data revisions entail a revision of the P-report. Minor data revisions are normally presented as supplements, available at www.skb.se.

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

Activity Plan	Number	Version
Geologisk enhålstolkning av KFM11A samt HFM33–35	AP PF 400-07-016	1.0
Method Description	**Number**	**Version**
Metodbeskrivning för geologisk enhålstolkning	SKB MD 810.003	3.0

2 Objective and scope

A geological single-hole interpretation is carried out in order to identify and to describe briefly the characteristics of major rock units and possible deformation zones within a borehole. The work involves an integrated interpretation of data from the geological mapping of the borehole (Boremap), different borehole geophysical logs and borehole radar data.

The geological mapping of the cored borehole involves a documentation of the character of the bedrock in the drill core. This work component is carried out in combination with an inspection of the oriented image of the borehole walls that is obtained with the help of the Borehole Image Processing *S*ystem (BIPS). The geological mapping of the percussion borehole focuses more attention on an integrated interpretation of the information from the geophysical logs and the BIPS images. For this reason, the results from the percussion borehole mapping are more uncertain. The interpretations of the borehole geophysical and radar logs are available when the single-hole interpretation is completed. The result from the geological single-hole interpretation is presented in a WellCad plot. A more detailed description of the technique is provided in the Method Description for geological single-hole interpretation (SKB MD 810.003, internal document). The work reported here concerns stage 1 in the single-hole interpretation, as defined in the Method Description.

3 Data used for the geological single-hole interpretation

The following data and interpretations have been used for the single-hole interpretation of the boreholes KFM11A, HFM33, HFM34 and HFM35:

- Boremap data (including BIPS and geological mapping data) /3, 4/.
- Generalized geophysical logs and their interpretation /5, 6/.
- Radar data and their interpretation /7, 8/.

The material used as a basis for the geological single-hole interpretation was a WellCad plot consisting of parameters from the geological mapping in the Boremap system, geophysical logs and borehole radar. An example of a WellCad plot used during geological single-hole interpretation is shown in Figure 3-1. The plot consists of ten main columns and several subordinate columns. These include:

1: Length along the borehole

2: Rock type
  - 2.1: Rock type
  - 2.2: Rock type structure
  - 2.3: Rock type texture
  - 2.4: Rock type grain size
  - 2.5: Structure orientation
  - 2.6: Rock occurrence (< 1 m)
  - 2.7: Rock alteration
  - 2.8: Rock alteration intensity

3: Unbroken fractures
  - 3.1: Primary mineral
  - 3.2: Secondary mineral
  - 3.3: Third mineral
  - 3.4: Fourth mineral
  - 3.5: Alteration, dip direction

4: Broken fractures
  - 4.1: Primary mineral
  - 4.2: Secondary mineral
  - 4.3: Third mineral
  - 4.4: Fourth mineral
  - 4.5: Aperture (mm)
  - 4.6: Roughness
  - 4.7: Surface
  - 4.8: Alteration, dip direction

5: Crush zones
  - 5.1: Primary mineral
  - 5.2: Secondary mineral
  - 5.3: Third mineral
  - 5.4: Fourth mineral
  - 5.5: Roughness
  - 5.6: Surface
  - 5.7: Crush alteration, dip direction
  - 5.8: Piece (mm)
  - 5.9: Sealed network
  - 5.10: Core loss

6: Fracture frequency
    6.1: Open fractures
    6.2: Sealed fractures

7: Geophysics
    7.1: Magnetic susceptibility
    7.2: Natural gamma radiation
    7.3: Possible alteration
    7.4: Silicate density
    7.5: Estimated fracture frequency

8: Radar
    8.1: Length
    8.2: Angle

9: Reference mark (not used for percussion-drilled boreholes)

10: BIPS

The geophysical logs are described below:

Magnetic susceptibility: The rock has been classified into sections of low, medium, high, and very high magnetic susceptibility. The susceptibility measurement is strongly connected to the magnetite content in the different rock types.

Natural gamma radiation: The rock has been classified into sections of low, medium, and high natural gamma radiation. Low radiation may indicate mafic rock types and high radiation may indicate younger, fine-grained granite or pegmatite. The rocks with high natural gamma radiation have been included in the younger, Group D intrusive suite /1/.

Possible alteration: This parameter has not been used in the geological single-hole interpretation in the Forsmark area.

Silicate density: This parameter indicates the density of the rock after subtraction of the magnetic component in the rock. It provides general information on the mineral composition of the rock types, and serves as a support during classification of rock types.

Estimated fracture frequency: This parameter provides an estimate of the fracture frequency along 5 m sections, calculated from short and long normal resistivity, SPR, P-wave velocity as well as focused resistivity 140 and 300. The estimated fracture frequency is based on a statistical connection after a comparison has been made between the geophysical logs and the mapped fracture frequency. The log provides an indication of sections with low and high fracture frequencies.

Close inspection of the borehole radar data was carried out during the interpretation process, especially during the identification of possible deformation zones. The occurrence and orientation of radar anomalies within the possible deformation zones are commented upon in the text that describes these zones.

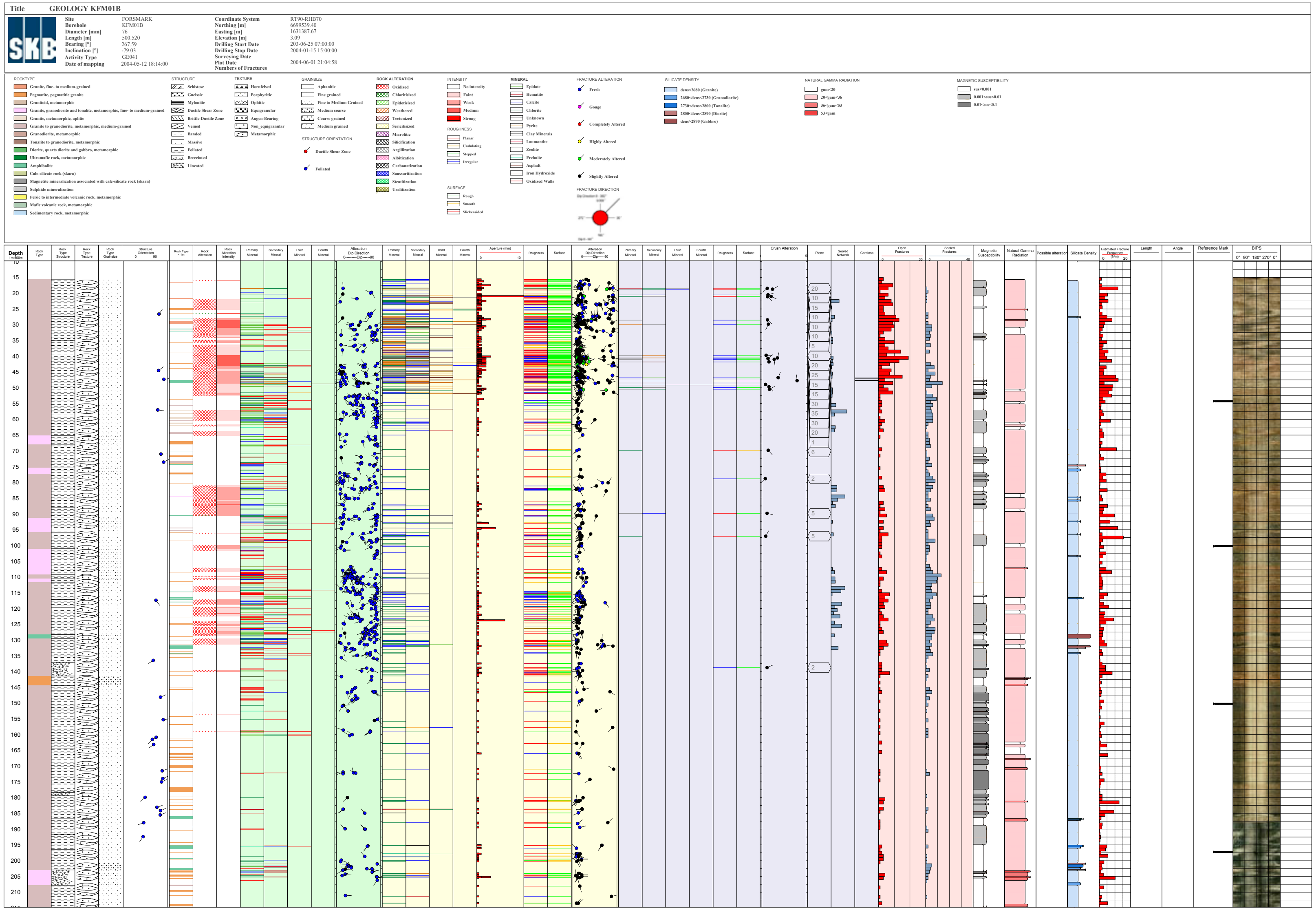

Figure 3-1. *Example of WellCad plot (from borehole KFM01B) used as a basis for the single-hole interpretation.*

4 Execution of the geological single-hole interpretation

4.1 General

The geological single-hole interpretation has been carried out by a group of geoscientists consisting of both geologists and geophysicists. Several of these geoscientists previously participated in the development of the source material for the single-hole interpretation. All data to be used (see Chapter 3) are visualized side by side in a borehole document extracted from the software WellCad. The working procedure is summarized in Figure 4-1 and in the text below.

The first step in the working procedure is to study all types of data (rock type, rock alteration, silicate density, natural gamma radiation, etc.) related to the character of the rock type and to merge sections of similar rock types, or sections where one rock type is very dominant, into rock units (minimum length of c. 5 m). Each rock unit is defined in terms of the borehole length interval and provided with a brief description for inclusion in the WellCad plot. The confidence in the interpretation of a rock unit is made on the following basis: 3 = high, 2 = medium and 1 = low.

The second step in the working procedure is to identify possible deformation zones by visual inspection of the results of the geological mapping (fracture frequency, fracture mineral, aperture, alteration, etc.) in combination with the geophysical logging and radar data. The section of each identified possible deformation zone is defined in terms of the borehole length interval and provided with a brief description for inclusion in the WellCad plot. This includes a brief description of the rock types affected by the possible deformation zone. The confidence in the interpretation of a possible deformation zone is made on the following basis: 3 = high, 2 = medium and 1 = low.

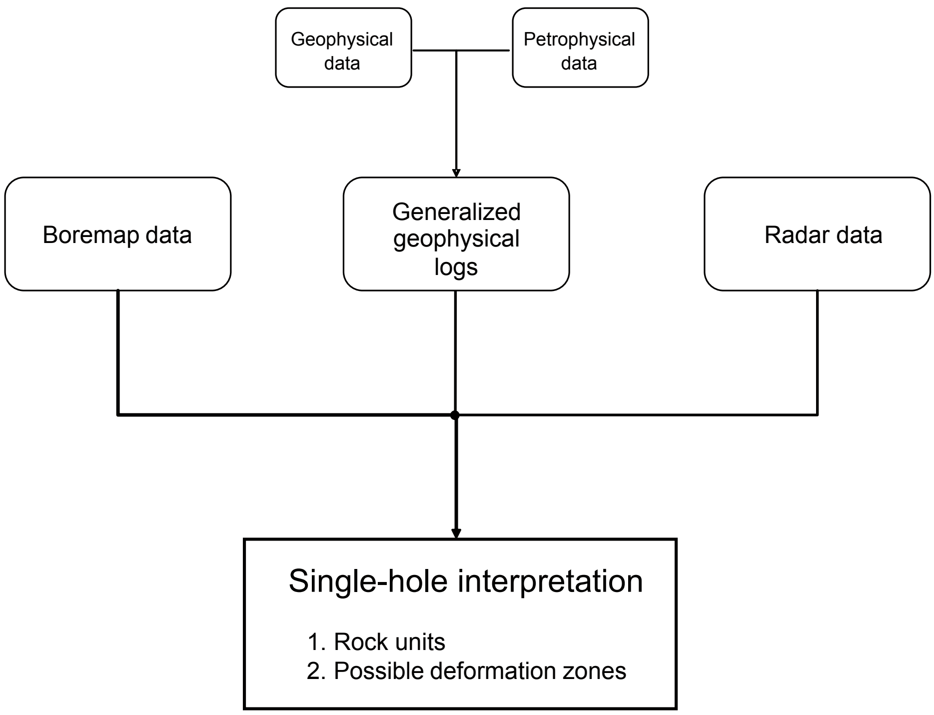

Figure 4-1. *Schematic chart that shows the procedure for the development of a geological single-hole interpretation.*

Inspection of BIPS images is carried out wherever it is judged necessary during the working procedure. Furthermore, following definition of rock units and possible deformation zones, with their respective confidence estimates, the drill cores are inspected in order to check the selection of the boundaries between these geological entities. If judged necessary, the location of these boundaries is adjusted.

Possible deformation zones that are brittle in character have been identified primarily on the basis of the frequency of fractures, according to the concept presented in /2/. Brittle deformation zones defined by an increased fracture frequency of extensional fractures (joints) or shear fractures (faults) are not distinguished. Both the transitional part, with a fracture frequency in the range 4–9 fractures/m, and the core part, with a fracture frequency > 9 fractures/m, have been included in each zone (Figure 4-2). The frequencies of open and sealed fractures have been assessed in the identification procedure, and the character of the zone has been described accordingly. Partly open fractures are included together with open fractures in the brief description of each zone. The presence of bedrock alteration, the occurrence and, locally, inferred orientation of radar reflectors, the resistivity, SPR, P-wave velocity, caliper and magnetic susceptibility logs have all assisted in the identification of the zones. The anomalies in these parameters that assist with the identification are presented in the short description.

Since the frequency of fractures is of key importance for the definition of the possible deformation zones, moving average plots for this parameter are shown for the cored borehole KFM11A and the percussion boreholes HFM33, HFM34 and HFM35 (Figures 4-3 to 4-6). A 5 m window and 1 m steps have been used in the calculation procedure. The moving average for open fractures alone, the total number of open fractures (open, partly open and crush), the sealed fractures alone, and the total number of sealed fractures (sealed and sealed fracture network) are shown in each diagram.

The occurrence and orientation of radar anomalies within the possible deformation zones are used during the identification of these zones. Overviews of the borehole radar measurements in KFM11A and the percussion boreholes HFM33, HFM34 and HFM35 are shown in Figures 4-7 to 4-10. A conductive environment causes attenuation of the radar wave, which in turn decreases the penetration. The effect of attenuation can be observed in the borehole and is conspicuous in the lower part of KFM11A (Figure 4-7) and generally in HFM34 (Figure 4-9). The effect of attenuation varies between the different antenna frequencies (20 MHz, 100 MHz, 250 MHz and 60 MHz directional antenna). In some cases, alternative orientations for oriented radar reflectors are presented. One of the alternatives is considered to be correct, but due to uncertainty in the interpretation of radar data, a decision concerning which of the alternatives that represent the true orientation cannot be made. Orientations from directional radar are presented as strike/dip using the right-hand-rule method.

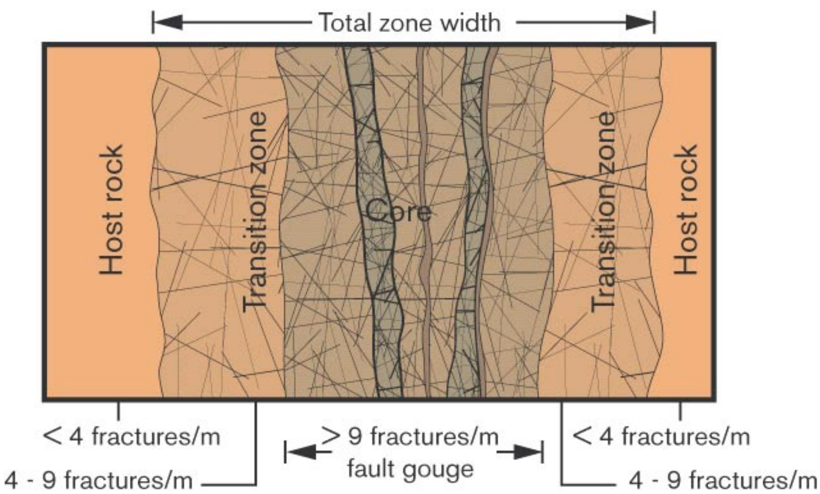

Figure 4-2. *Terminology for brittle deformation zones (after /2/).*

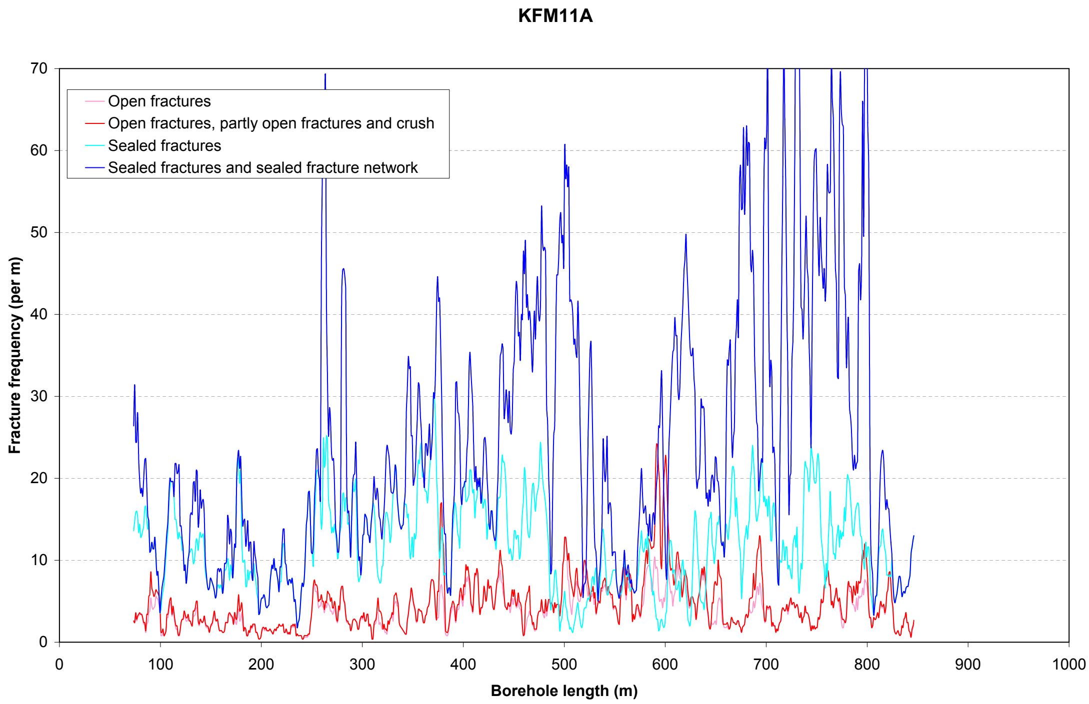

Figure 4-3. *Fracture frequency plot for KFM11A. Moving average with a 5 m window and 1 m steps.*

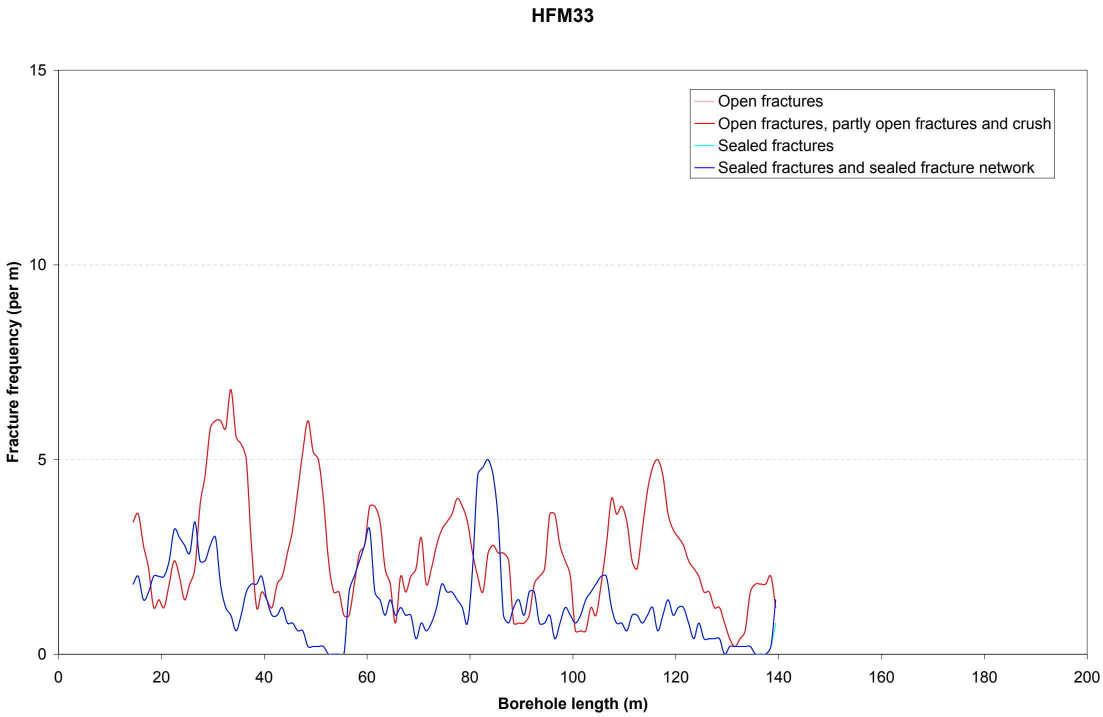

Figure 4-4. *Fracture frequency plot for HFM33. Moving average with a 5 m window and 1 m steps.*

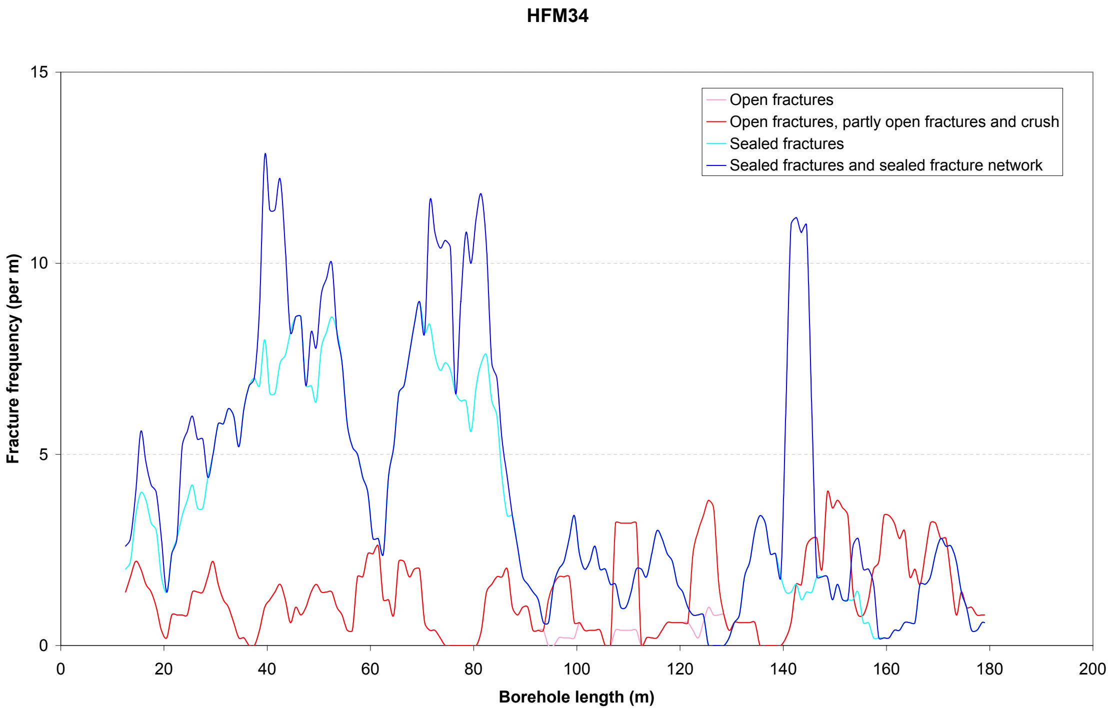

Figure 4-5. *Fracture frequency plot for HFM34. Moving average with a 5 m window and 1 m steps.*

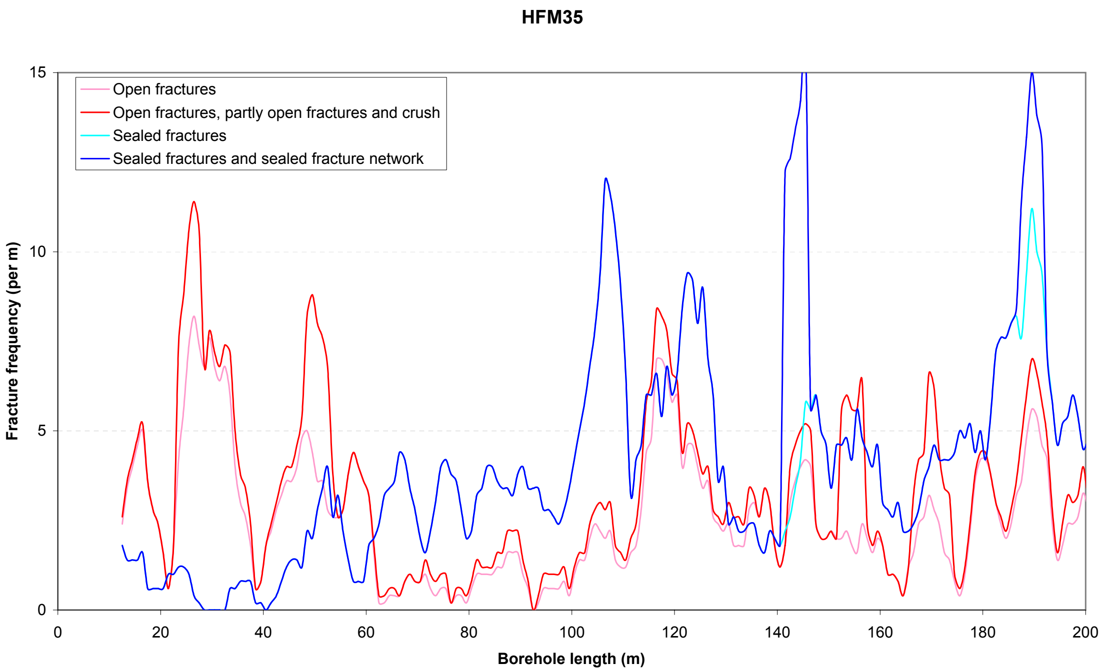

Figure 4-6. *Fracture frequency plot for HFM35. Moving average with a 5 m window and 1 m steps.*

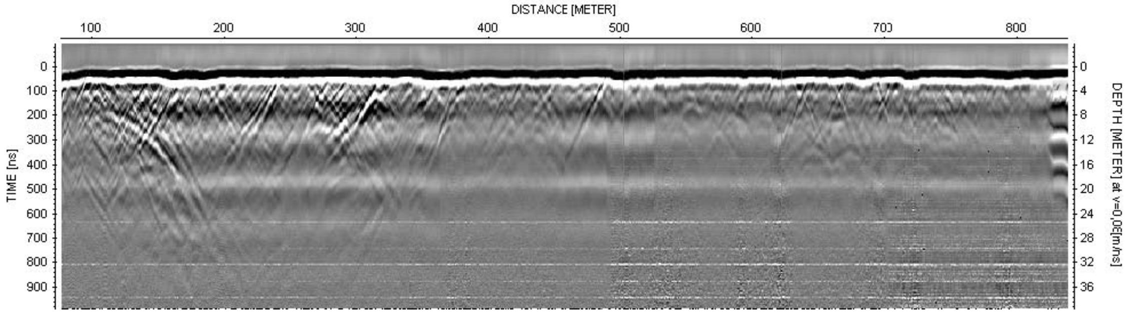

Figure 4-7. *Overview (20 MHz data) of the borehole radar measurements in KFM11A.*

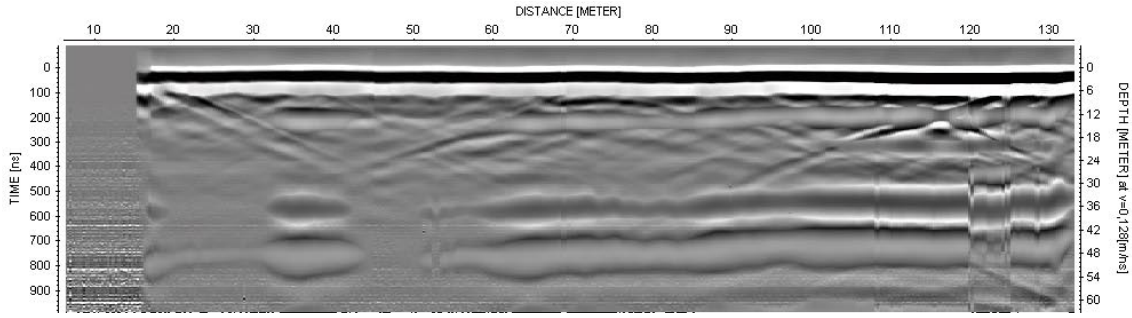

Figure 4-8. *Overview (20 MHz data) of the borehole radar measurements in HFM33.*

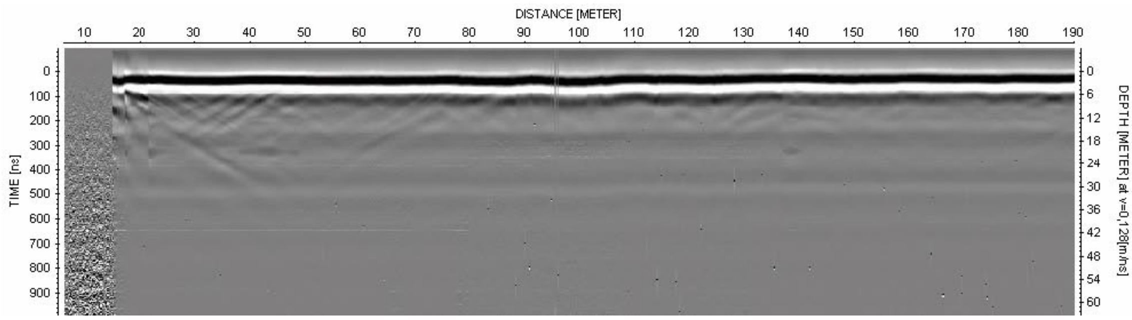

Figure 4-9. *Overview (20 MHz data) of the borehole radar measurements in HFM34.*

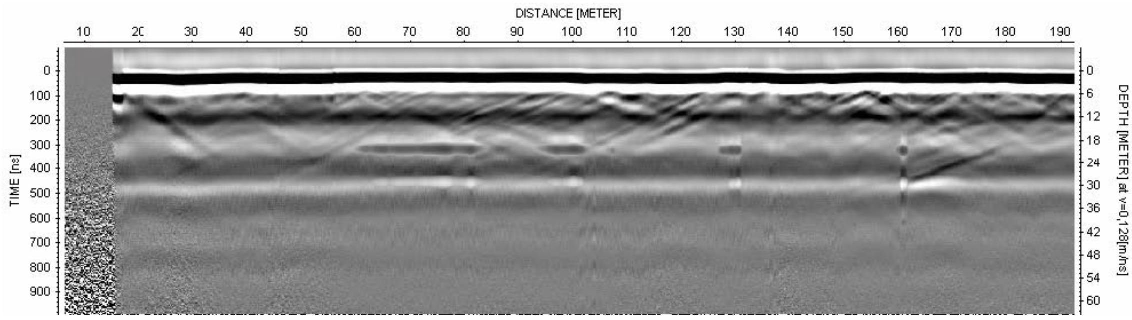

Figure 4-10. *Overview (20 MHz data) of the borehole radar measurements in HFM35.*

4.2 Nonconformities

The section below 179.0 m in HFM34 was not mapped due to very poor quality of the BIPS-image.

5 Results

The results of the geological single-hole interpretations are presented as print-outs from the software WellCad (Appendix 1 for KFM11A, Appendix 2 for HFM33, Appendix 3 for HFM34 and Appendix 4 for HFM35).

5.1 KFM11A

The borehole direction at the start is 040°/–61°.

Rock units

The borehole can be divided into nine different rock units, RU1–RU9. Rock unit 3 occurs in two separate length intervals, rock unit 6 occurs in two separate length intervals and rock unit 7 occurs in three separate length intervals. The rock units have been recognized with a high degree of confidence, except for RU7c at the bottom of the borehole, which has been recognized with a medium degree of confidence.

71.60–196.0 m

RU1: Heterogeneous unit consisting of felsic to intermediate metavolcanic rock (103076) and amphibolite (102017), and subordinate occurrences of calc-silicate rock (108019), pegmatitic granite (101061) and fine- to medium-grained granite (111058). Density of the metavolcanic rock is generally around 2,680–2,730 kg/m^3. The main rock types are finely banded and show medium to strong foliation. Increased frequency of fractures, particularly gently dipping fractures, relative to RU2 (see below). Three crush zones occur at 88.82–88.84 m, 90.28–90.31 m and 179.38–179.42 m. The metavolcanic rock has been affected by generally faint to weak albitization in the interval 120–152m. Locally faint to weak epidotization of the amphibolites. Confidence level = 3.

196.0–246.0 m

RU2: Felsic to intermediate metavolcanic rock (103076), with subordinate fine- to medium-grained granite (111058). Density of the metavolcanic rock ranges from 2,680 to 2,760 kg/m^3. Higher density in the lower part, which also coincides with higher magnetic susceptibility. The metavolcanic rock is finely banded, shows medium to strong foliation and is locally affected by faint to medium chloritization. Confidence level = 3.

246.0–356.75 m

RU3a: Felsic to intermediate metavolcanic rock (103076), with subordinate amphibolite (102017) and fine- to medium-grained granite (111058). The density of the metavolcanic rock ranges from 2,660 to 2,715 kg/m^3 and is generally lower than that in RU2. The metavolcanic rock is finely banded and shows medium to strong foliation. Confidence level = 3.

356.75–374.62 m

RU4: Amphibolite, locally affected by faint to strong epidotization. Confidence level = 3.

374.62–410.32 m

RU3b: Felsic to intermediate metavolcanic rock (103076), with subordinate pegmatitic granite (101061) and amphibolite (102017). The density of the metavolcanic rock ranges from 2,685 to 2,710 kg/m^3 and is generally lower than that in RU2. The metavolcanic rock is finely banded and shows medium to strong foliation. Confidence level = 3.

410.32–585.37 m

RU5: Medium to strongly foliated felsic to intermediate metavolcanic rock (103076), with subordinate pegmatitic granite (101061), medium-grained metagranodiorite (101056), amphibolite (102017) and medium-grained metagranite-granodiorite (101057). The density of the metavolcanic rock ranges from 2,680 to 2,730 kg/m^3 and is generally lower than that in RU2. Confidence level = 3.

585.37–660.21 m

RU6a: Aplitic metagranite (101058) with subordinate felsic to intermediate metavolcanic rock (103076), pegmatitic granite (101061), amphibolite (102017) and fine- to medium-grained granite (111058). The density of the aplitic metagranite ranges from 2,610 to 2,635 kg/m^3. Confidence level = 3.

660.21–698.80 m

RU7a: Medium to strongly foliated metavolcanic rock (103076), which is generally more felsic in composition, with a density of 2,655–2,685 kg/m^3, relative to metavolcanic rocks in RU1–RU5. Subordinate pegmatitic granite (101061), calc-silicate rock (108019) and amphibolites (102017). Confidence level = 3.

698.80–727.27 m

RU8: Fine- to medium-grained granite (111058) with subordinate pegmatitic granite (101061), amphibolite (102017) and felsic to intermediate metavolcanic rock (103076). Confidence level = 3.

727.27–782.93 m

RU7b: Medium to strongly foliated metavolcanic rock (103076), which is generally more felsic in composition, with a density of 2,665–2,700 kg/m^3, relative to metavolcanic rocks in RU1–RU5. Subordinate medium-grained metagranite-granodiorite (101057), fine- to medium-grained granite (111058), pegmatitic granite (101061) and amphibolite (102017). Confidence level = 3.

782.93–822.12 m

RU6b: Aplitic metagranite (101058) with subordinate pegmatitic granite (101061) and felsic to intermediate metavolcanic rock (103076). The density of the aplitic metagranite ranges from 2,605 kg/m^3 to 2,650 kg/m^3. Confidence level = 3.

822.12–846.39 m

RU9: Fine- to medium-grained metagranitoid (101051) with granodioritic composition. Subordinate occurrences of fine- to medium-grained granite (111058) and amphibolite (102017). Confidence level = 3.

846.39–851.21 m

RU7c: Medium to strongly foliated metavolcanic rock (103076), which is generally more felsic in composition relative to metavolcanic rocks in RU1–RU5. Subordinate occurrences of medium-grained metagranite–granodiorite (101057), pegmatitic granite (101061) and fine- to medium-grained granite (111058). Confidence level = 2.

Possible deformation zones

One possible deformation zone has been recognised with a high degree of confidence in KFM11A.

245–824 m

DZ1: Generally increased frequency of sealed fractures, sealed fracture networks and open fractures, and several intervals with one or more crush zones (317 m, 376–384 m, 437–464 m, 505–522 m, 580–615 m, 649–661 m, 686–696 m and 774–801 m). In the interval 245–498 m, gently dipping fractures and fractures that strike ESE and dip steeply to the SSW dominate. In the interval 498–824 m fractures that strike ESE and dip moderately to steeply to the SSW dominate. Gently dipping fractures are also present. Fracture apertures are generally less than 1 mm, with a few ranging up to 10 mm. Faint to medium oxidation is present along short intervals throughout the possible zone. Predominant fracture minerals are chlorite, calcite, laumontite, adularia, quartz, clay minerals and epidote. Laumontite is common beneath 410 m. Seven intervals with low radar amplitude, low bulk resistivity with low resistivity anomalies, low magnetic susceptibility and scattered low P-wave velocity anomalies can be recognized at 248–279 m, 345–382 m, 405–468 m, 498–630 m, 653–664 m, 676–723 m and 787–824 m.

The interval 498–630 m is characterised by very low bulk resistivity, several caliper anomalies and generally low P-wave velocity. Twenty-nine radar reflectors of which five are oriented (011/16, 086/72, 168/77, 188/49 and 204/21) and a more distinct low radar amplitude also characterise this interval. Furthermore, muscovite alteration of faint to medium intensity more or less affects the whole interval, while steatitisation (talc alteration) occurs in the interval 510–525 m. Between 515 and 575 m, the frequency of particularly sealed fractures decreases relative to the remaining part of the possible zone. Furthermore, calcite, adularia and epidote are generally absent in this interval, while laumontite is prominent. From c. 700 m and downwards, the bulk resistivity diminishes significantly without a relationship to other geophysical anomalies.

The possible zone occurs in felsic to intermediate metavolcanic rock, with subordinate aplitic metagranite, fine- to medium-grained granite, amphibolite, pegmatitic granite, medium-grained metagranite-granodiorite and medium-grained metagranodiorite. The top of the possible zone corresponds to the contact between felsic to intermediate metavolcanic rocks with different densities. The base of the possible zone corresponds to the contact between aplitic metagranite (RU6b) and fine- to medium-grained metagranitoid (RU9). Confidence level = 3.

5.2 HFM33

The borehole direction at the start is 220/–59°.

Rock units

The borehole consists of two rock units, RU1–RU2, one of which has been recognized with a high degree of confidence and one with a medium degree of confidence.

12.35–127.72 m

RU1: Felsic to intermediate metavolcanic rock (103076) with subordinate occurrences of amphibolite (102017) and pegmatitic granite (101061). Density in the metavolcanic rock is generally around 2,650–2,690 kg/m^3. Confidence level = 2.

127.72–139.84 m

RU2: Pegmatitic granite (101061) with high natural gamma radiation. At 136 m, there is a strong radar reflector with an angle of 53º to the borehole axis, which may correspond to a single fracture with an aperture of 8 mm. Confidence level = 3.

Possible deformation zones

No possible deformation zone has been identified in the borehole, but the drilling was interrupted at 140.20 m drilling length after penetrating a permeable fracture at 136 m. The drilling speed decreased dramatically, as most of the compressed air was used for uplift of water instead of supporting the drill hammer.

5.3 HFM34

The borehole direction at the start is 030/–59˚.

Rock units

The borehole consists of three rock units, RU1–RU3. Rock unit 1 occurs in three separate length intervals and rock unit 2 occurs in two separate length intervals. One of the rock units has been recognized with a high degree of confidence, three with a medium degree of confidence and two with a low degree of confidence.

12.08–103.29 m

RU1a: Felsic to intermediate metavolcanic rock (103076) with subordinate occurrences of amphibolite (102017) and pegmatitic granite (101061). Density in the metavolcanic rock is generally around 2,670–2,780 kg/m^3. Confidence level = 2.

103.29–124.83 m

RU2a: Pegmatitic granite (101061) with subordinate occurrences of felsic- to intermediate metavolcanic rock (103076). Minor increase in natural gamma radiation in the inferred pegmatitic granite. Confidence level = 1.

124.83–135.20 m

RU1b: Felsic to intermediate metavolcanic rock (103076) with subordinate occurrences of pegmatitic granite (101061). Density in the metavolcanic rock is generally around 2,645–2,690 kg/m^3. Confidence level = 2.

135.20–143.78 m

RU3: Pegmatitic granite (101061) with high natural gamma radiation. Confidence level = 3.

143.78–182.49 m

RU1c: Felsic to intermediate metavolcanic rock (103076) with subordinate occurrences of pegmatitic granite (101061) and amphibolite (102017). Density in the metavolcanic rock is generally around 2,650–2,705 kg/m^3. Due to poor BIPS-image, mapping has only been carried out down to 179 m. Judgement of rock type has been based only on geophysical data beneath this borehole length. Confidence level = 2.

182.49–200.75 m

RU2b: Pegmatitic granite (101061) with subordinate occurrences of felsic to intermediate metavolcanic rock (103076). Minor increase in natural gamma radiation in the inferred pegmatitic granite. Due to poor BIPS-image, mapping has only been carried out down to 179 m. Judgement of rock type has been based only on geophysical data beneath this borehole length. Confidence level = 1.

Possible deformation zones

Three possible deformation zones of brittle character, of which one has been recognised with a medium degree of confidence and two with a low degree of confidence, are present in HFM34.

37–133 m

DZ1: Increased frequency of sealed fractures in the upper half of the possible deformation zone, and low resistivity, low P-wave velocity, low magnetic susceptibility and several caliper anomalies in the lower half of the possible zone (82–133 m). Fractures that strike ESE and dip steeply to the SSW and fractures that are gently dipping dominate. The lower half of the possible zone contains three crush zones and several low radar amplitude anomalies. In the possible deformation zone, there are 23 identified radar reflectors with an intersection angle of 34–90º. Fracture apertures are generally less than 1 mm. Zone situated in metavolcanic rock and pegmatitic granite with subordinate amounts of amphibolite. Confidence level = 2.

180–184 m

DZ2: Low resistivity, low P-wave velocity, low magnetic susceptibility and several caliper anomalies. One identified radar reflector with an intersection angle of 53º. Due to poor BIPS-image, mapping of fractures and rock types has not been carried out. Judgement of possible deformation zone has been based only on geophysical data. Confidence level = 1.

188–192 m

DZ3: Low resistivity, low P-wave velocity, low magnetic susceptibility and several caliper anomalies. One identified radar reflector with an intersection angle of 57º. Due to poor BIPS-image, mapping of fractures and rock types has not been carried out. Judgement of possible deformation zone has been based only on geophysical data. Confidence level = 1.

5.4 HFM35

The borehole direction at the start is 033/–59˚.

Rock units

The borehole consists of three rock units, RU1–RU3, one of which has been recognized with a high degree of confidence, one with a medium degree, and one with a low degree of confidence.

12.04–60.30 m

RU1: Felsic to intermediate metavolcanic rock (103076) with subordinate occurrences of pegmatitic granite (101061) and amphibolite (102017). Density in the metavolcanic rock is generally around 2,655–2,695 kg/m^3. Confidence level = 2.

60.30–126.89 m

RU2: Pegmatitic granite (101061) with subordinate occurrences of felsic to intermediate metavolcanic rock (103076) and in the lower half fine- to medium-grained granite (111058) and amphibolite (102017). Increased natural gamma radiation in the pegmatitic rock and the granite. Confidence level = 3.

126.89–200.52 m

RU3: Aplitic metagranite (101058) with subordinate occurrences of pegmatitic granite (101061), felsic to intermediate metavolcanic rock (103076). Minor occurrences of amphibolite (102017) and fine- to medium-grained granite (111058). With the exception of amphibolites, the density in the rock unit is 2,550–2,610 kg/m^3. Confidence level = 1.

Possible deformation zones

Three possible deformation zones of brittle character, of which all have been recognised with a high degree of confidence, are present in HFM35.

24–33 m

DZ1: Increased frequency of open fractures and one crush zone in the upper part of the possible zone. Fractures that strike SE and dip steeply to the SW and fractures that are gently dipping dominate. Fracture apertures are generally less than 1 mm, with a few ranging up to 3 mm. Low resistivity, low P-wave velocity, low magnetic susceptibility and several caliper anomalies. Four identified radar reflectors with an intersection angle of 45–74º. Zone situated in metavolcanic rock and subordinate pegmatitic granite. Confidence level = 3.

47.2–52.5 m

DZ2: Open fractures strike SSE and dip variably to the WSW. Two crush zones. Apertures are generally less than 1 mm. Low resistivity, low P-wave velocity, low magnetic susceptibility and several caliper anomalies. Two identified radar reflector with an intersection angle of 50º and 72º. Zone situated in metavolcanic rock and subordinate pegmatitic granite. Confidence level = 3.

104–200 m

DZ3: Increased frequency of open and sealed fractures. Fractures that strike SE and dip steeply to the SW and fractures that are gently dipping dominate. Five crush zones in the lower half. Fracture apertures are generally less than 1 mm, with a few ranging up to 6 mm. Below 114 m, low resistivity, low P-wave velocity, low magnetic susceptibility and several caliper anomalies. 39 identified radar reflectors with intersection angles ranging from 31º to 90º. Several low radar amplitude intervals. Zone situated in aplitic metagranite with subordinate pegmatitic granite, metavolcanic rock, amphibolite and fine- to medium-grained granite. Confidence level = 3.

6 Comments

The results of the geological single-hole interpretation of KFM11A, HFM33, HFM34 and HFM35 are presented in WellCad plots (Appendices 1–4). Each WellCad plot consists of the following columns:

1: Depth (length along the borehole).

2: Rock type.

3: Rock alteration.

4: Sealed fractures.

5: Open and partly open fractures.

6: Crush zones.

7: Silicate density.

8: Magnetic susceptibility.

9: Natural gamma radiation.

10: Estimated fracture frequency.

11: Description: Rock unit.

12: Stereogram for sealed fractures in rock unit (blue symbols).

13: Stereogram for open and partly open fractures in rock unit (red symbols).

14: Description: Possible deformation zone.

15: Stereogram for sealed fractures in possible deformation zone (blue symbols).

16: Stereogram for open and partly open fractures in possible deformation zone (red symbols).

References

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/3/ **Jesper Petersson, Johan Berglund, Ulf B Andersson, Anders Wängnerud, Peter Danielsson, Jan Ehrenborg, 2007.** Forsmark site investigation. Boremap mapping of telescopic drilled borehole KFM11A. SKB P-07-104, Svensk Kärnbränslehantering AB.

/4/ **Döse C, Samuelsson E, 2007.** Forsmark Site Investigation. Boremap mapping of percussion drilled borehole HFM33-37. SKB P-07-106, Svensk Kärnbränslehantering AB.

/5/ **Mattsson H, Keisu M, 2007.** Forsmark site investigation. Interpretation of geophysical borehole measurements from KFM02B, KFM08D and KFM11A. SKB P-07-125, Svensk Kärnbränslehantering AB.

/6/ **Mattsson H, Keisu M, 2007.** Forsmark site investigation. Interpretation of geophysical borehole measurements from KFM10A, KFM08C, HFM30; HFM31, HFM33, HFM34, HFM35 and HFM38. SKB P-06-258, Svensk Kärnbränslehantering AB.

/7/ **Gustafsson J, Gustafsson C, 2007.** Forsmark site investigation. RAMAC and BIPS logging in borehole KFM11A. SKB P-07-10, Svensk Kärnbränslehantering AB.

/8/ **Gustafsson J, Gustafsson C, 2006.** Forsmark site investigation. RAMAC and BIPS logging in boreholes KFM08C, HFM30, HFM31, HFM33 and HFM34. SKB P-06-178, Svensk Kärnbränslehantering AB.

Geological single-hole interpretation of KFM11A

Title SINGLE HOLE INTERPRETATION KFM11A

Site	FORSMARK	**Inclination [°]**	-60.93	**Elevation [m.a.s.l.]**	2.95	**Signed data**	
Borehole	KFM11A	**Date of mapping**	2006-10-10 08:23:00	**Drilling Start Date**	2006-04-12 08:00:00		
Diameter [mm]	77	**Coordinate System**	RT90-RHB70	**Drilling Stop Date**	2006-11-20 00:00:00		
Length [m]	851.210	**Northing [m]**	6701103.82	**Surveying Date**			
Bearing [°]	40.25	**Easting [m]**	1632366.75	**Plot Date**	2007-06-25 23:44:05		

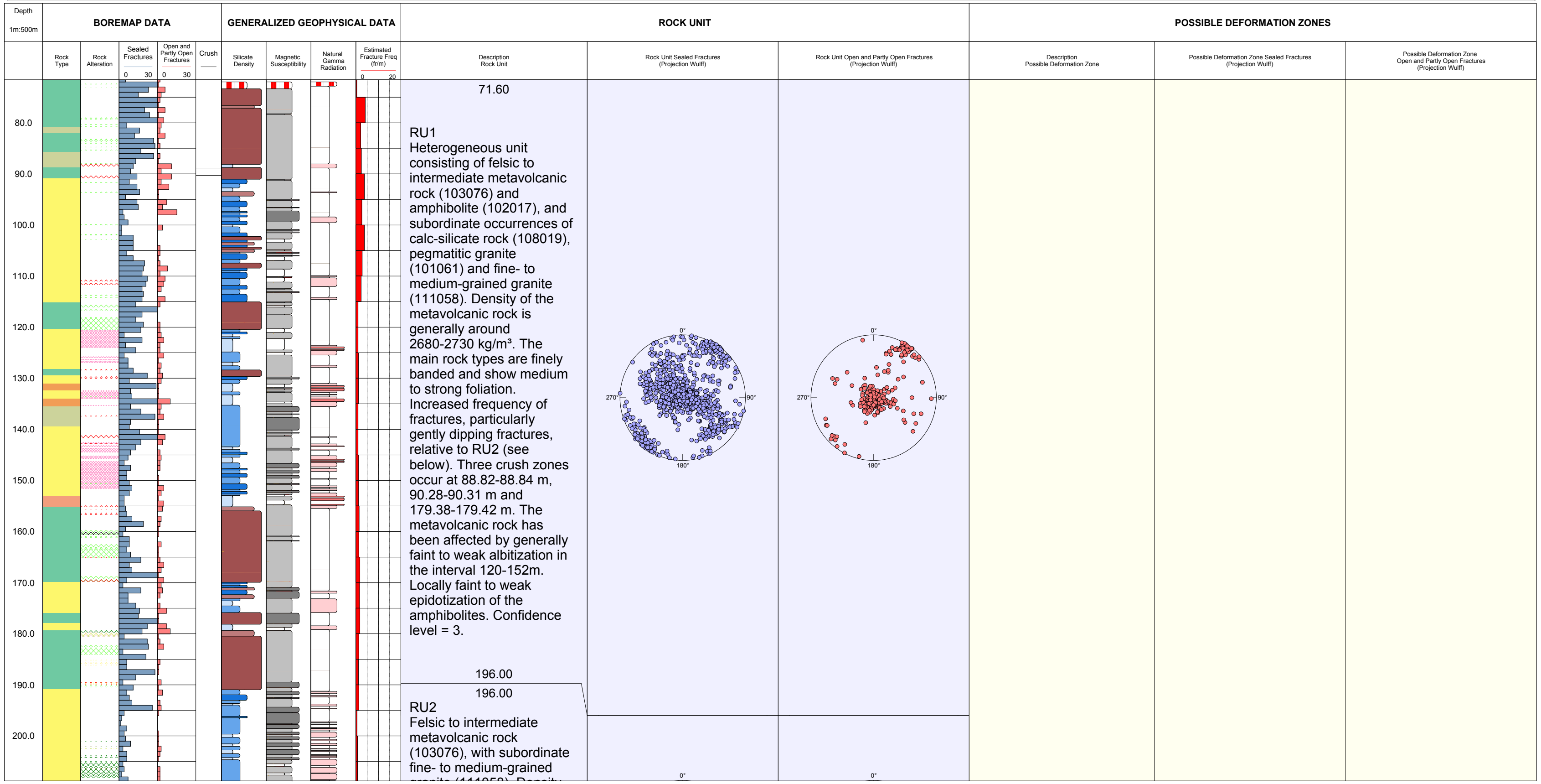
ROCKTYPE FORSMARK
- Granite, fine- to medium-grained
- Pegmatite, pegmatitic granite
- Granitoid, metamorphic
- Granite, granodiorite and tonalite, metamorphic, fine- to medium-grained
- Granite, metamorphic, aplitic
- Granite to granodiorite, metamorphic, medium-grained
- Granodiorite, metamorphic
- Amphibolite
- Calc-silicate rock (skarn)
- Felsic to intermediate volcanic rock, metamorphic

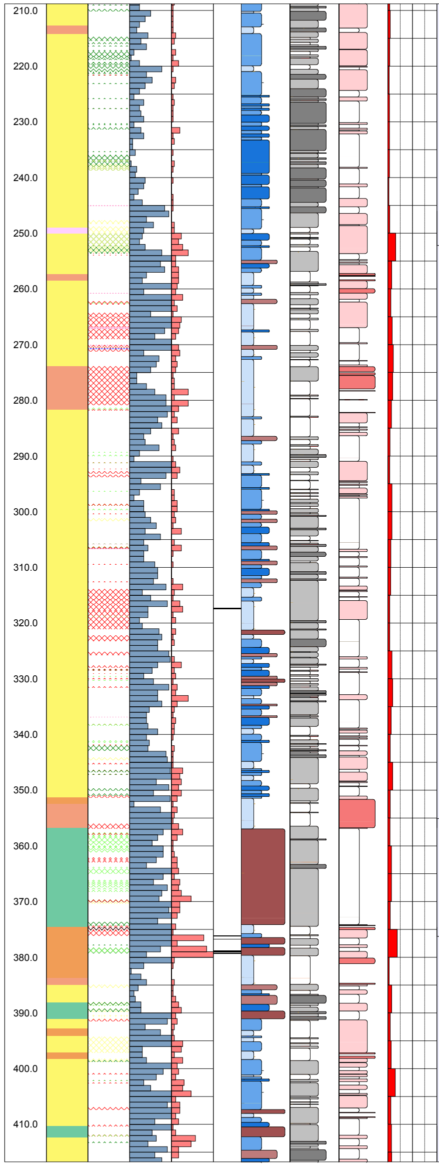
ROCK ALTERATION
- Oxidized
- Chloritisized
- Epidotisized
- Sericitisized
- Argillization
- Albitization
- Carbonatization
- Saussuritization
- Steatitization
- Laumontitization

SILICATE DENSITY
- unclassified
- dens<2680 (Granite)
- 2680<dens<2730 (Granodiorite)
- 2730<dens<2800 (Tonalite)
- 2800<dens<2890 (Diorite)
- dens>2890 (Gabbro)

SUSCEPTIBILITET
- unclassified
- sus<0.001
- 0.001<sus<0.01
- 0.01<sus<0.1

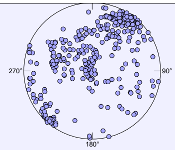
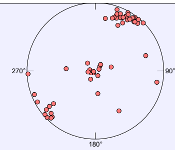
NATURAL GAMMA
- unclassified
- gam<20
- 20<gam<36
- 36<gam<53





granite (111058). Density of the metavolcanic rock ranges from 2680 to 2760 kg/m³. Higher density in the lower part, which also coincides with higher magnetic susceptibility. The metavolcanic rock is finely banded, shows medium to strong foliation and is locally affected by faint to medium chloritization. Confidence level = 3.

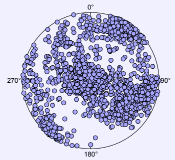
246.00

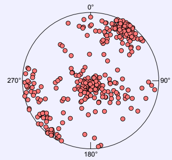



245.00

246.00

RU3a
Felsic to intermediate metavolcanic rock (103076), with subordinate amphibolite (102017) and fine- to medium-grained granite (111058). The density of the metavolcanic rock ranges from 2660 to 2715 kg/m³ and is generally lower than that in RU2. The metavolcanic rock is finely banded and shows medium to strong foliation. Confidence level = 3.



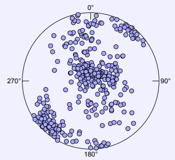


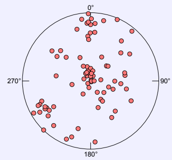
356.75

356.75

RU4
Amphibolite, locally affected by faint to strong epidotization. Confidence level = 3.

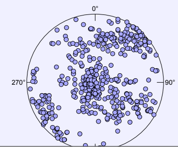
374.62

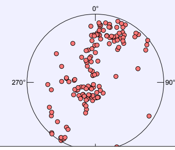


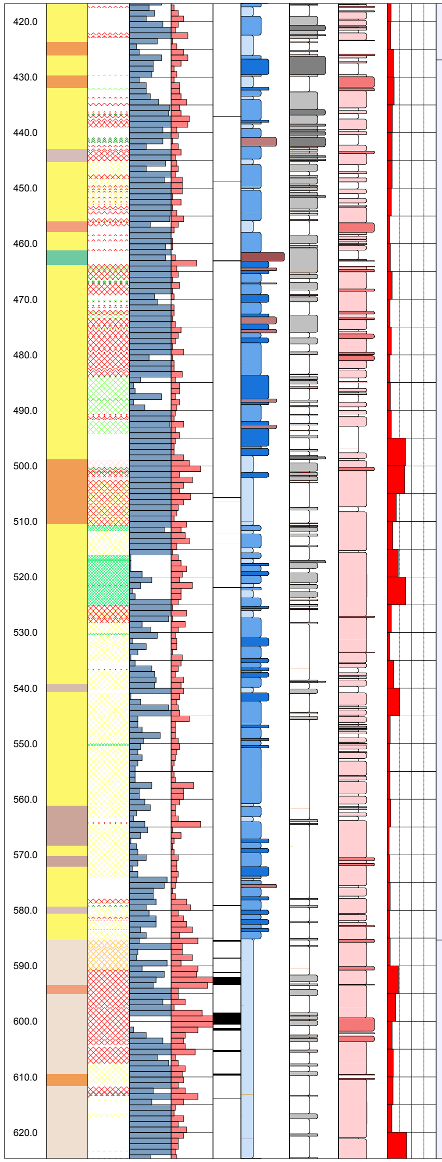


374.62

RU3b
Felsic to intermediate metavolcanic rock (103076), with subordinate pegmatitic granite (101061) and amphibolite (102017). The density of the metavolcanic rock ranges from 2685 to 2710 kg/m³ and is generally lower than that in RU2. The metavolcanic rock is finely banded and shows





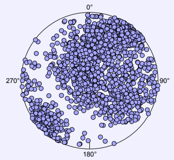


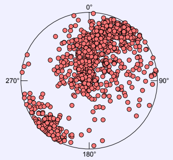
finely banded and shows medium to strong foliation. Confidence level = 3.

410.32

410.32

RU5
Medium to strongly foliated felsic to intermediate metavolcanic rock (103076), with subordinate pegmatitic granite (101061), medium-grained metagranodiorite (101056), amphibolite (102017) and medium-grained metagranite-granodiorite (101057). The density of the metavolcanic rock ranges from 2680 to 2730 kg/m³ and is generally lower than that in RU2. Confidence level = 3.

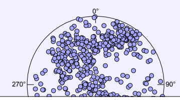


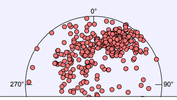


585.37

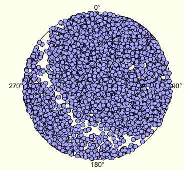
585.37

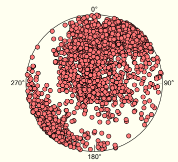
RU6a
Aplitic metagranite (101058) with subordinate felsic to intermediate metavolcanic rock (103076), pegmatitic granite (101061), amphibolite (102017) and fine- to medium-grained

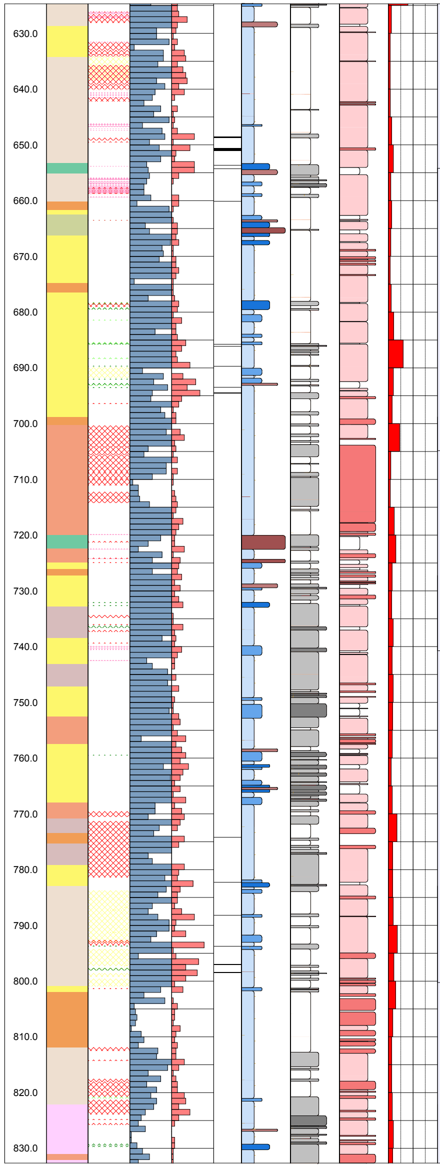




DZ1 For description, see Activity Data in excelfile or text in report







granite (111058). The density of the aplitic metagranite ranges from 2610 to 2635 kg/m³. Confidence level = 3.

660.21

660.21

RU7a

Medium to strongly foliated metavolcanic rock (103076), which is generally more felsic in composition, with a density of 2655-2685 kg/m3, relative to metavolcanic rocks in RU1-RU5. Subordinate pegmatitic granite (101061), calc-silicate rock (108019) and amphibolites (102017). Confidence level = 3.

698.80

698.80

RU8

Fine- to medium-grained granite (111058) with subordinate pegmatitic granite (101061), amphibolite (102017) and felsic to intermediate metavolcanic rock (103076). Confidence level = 3.

727.27

727.27

RU7b

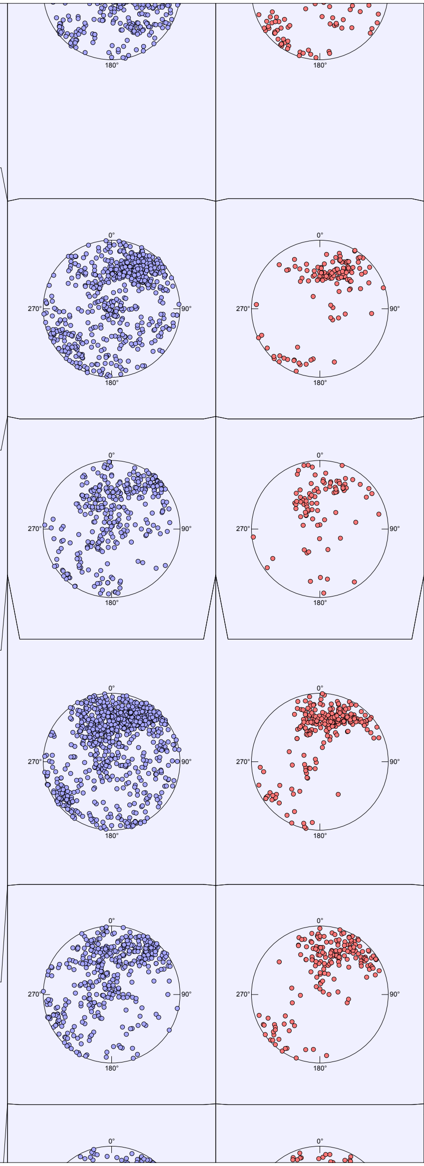
Medium to strongly foliated metavolcanic rock (103076), which is generally more felsic in composition, with a density of 2665-2700 kg/m³, relative to metavolcanic rocks in RU1-RU5. Subordinate medium-grained metagranite-granodiorite (101057), fine- to medium-grained granite (111058), pegmatitic granite (101061) and amphibolite (102017). Confidence level = 3.

782.93

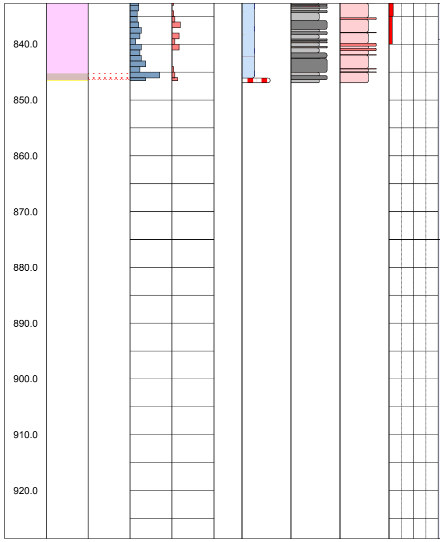
782.93

RU6b

Aplitic metagranite (101058) with subordinate pegmatitic granite (101061) and felsic to intermediate metavolcanic rock (103076). The density of the aplitic metagranite ranges from 2605 kg/m3 to 2650 kg/m³. Confidence



824.00



level = 3.

822.12

822.12

RU9

Fine- to medium-grained metagranitoid (101051) with granodioritic composition. Subordinate occurrences of fine- to medium-grained granite (111058) and amphibolite (102017). Confidence level = 3.

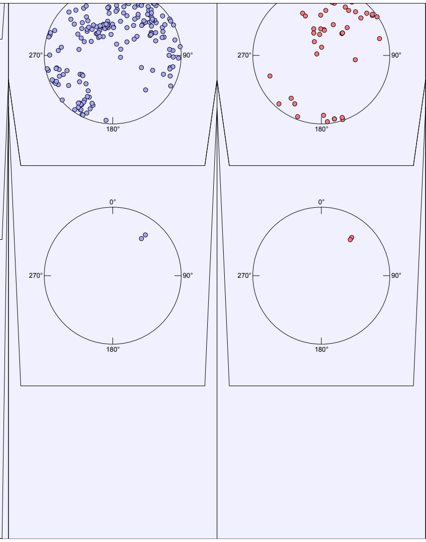
846.39

846.39

RU7c

Medium to strongly foliated metavolcanic rock (103076), which is generally more felsic in composition relative to metavolcanic rocks in RU1-RU5. Subordinate occurrences of medium-grained metagranite–granodiorite (101057), pegmatitic granite (101061) and fine- to medium-grained granite (111058). Confidence level = 2.

851.21



Geological single-hole interpretation of HFM33

Title SINGLE HOLE INTERPRETATION HFM33

Site	FORSMARK	Inclination [°]	-59.18	Elevation [m.a.s.l.]	2.62	Signed data
Borehole	HFM33	Date of mapping	2006-06-12 11:37:00	Drilling Start Date	2006-04-26 10:00:00	
Diameter [mm]	139	Coordinate System	RT90-RHB70	Drilling Stop Date	2006-05-03 12:25:00	
Length [m]	140.200	Northing [m]	6701042.57	Surveying Date		
Bearing [°]	220.03	Easting [m]	1632222.99	Plot Date	2007-06-25 23:44:05	

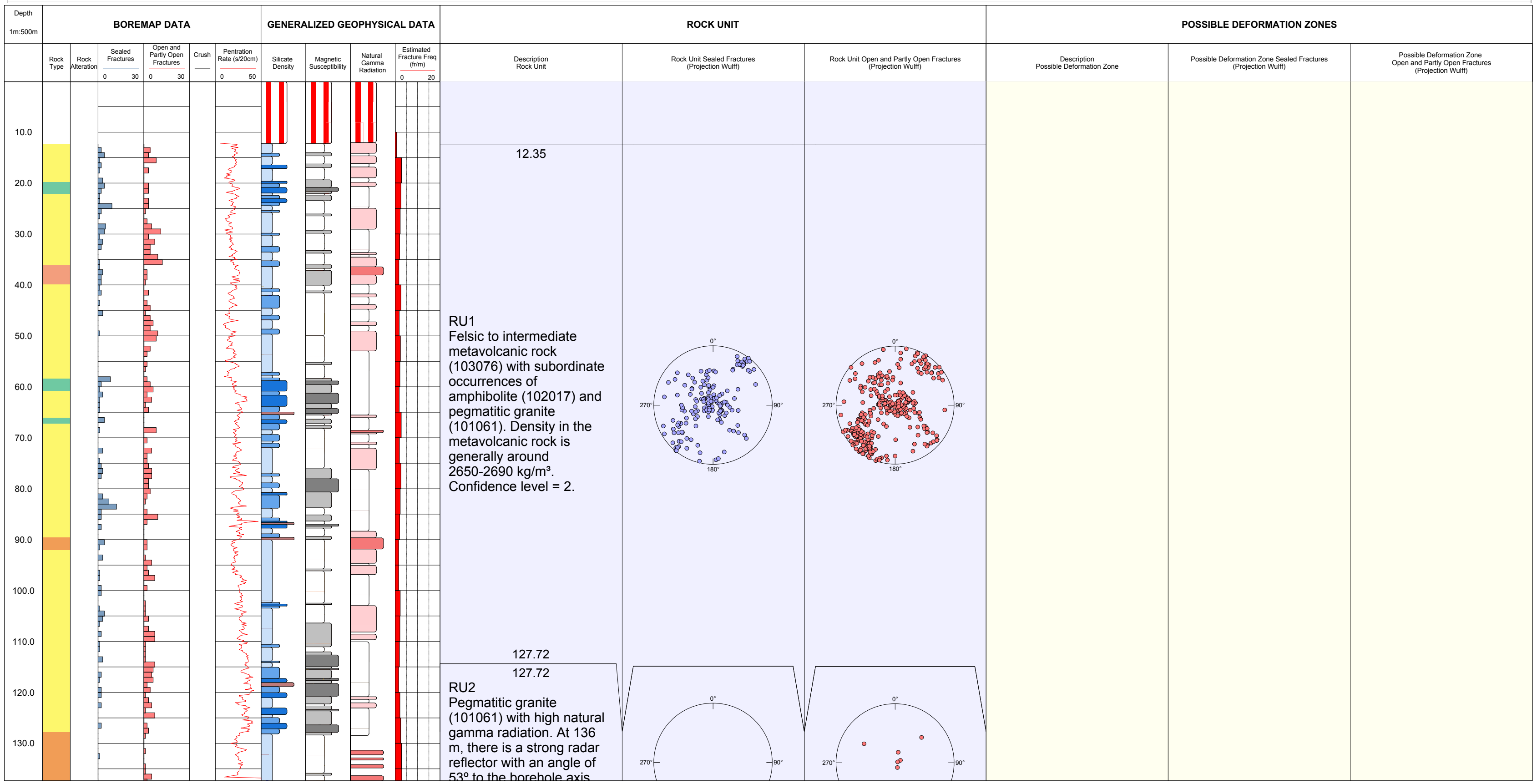
ROCKTYPE FORSMARK
- Granite, fine- to medium-grained
- Pegmatite, pegmatitic granite
- Amphibolite
- Felsic to intermediate volcanic rock, metamorphic

ROCK ALTERATION

SILICATE DENSITY
- unclassified
- dens<2680 (Granite)
- 2680<dens<2730 (Granodiorite)
- 2730<dens<2800 (Tonalite)
- 2800<dens<2890 (Diorite)

SUSCEPTIBILITET
- unclassified
- sus<0.001
- 0.001<sus<0.01
- 0.01<sus<0.1

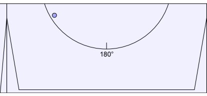
NATURAL GAMMA
- unclassified
- gam<20
- 20<gam<36
- 36<gam<53

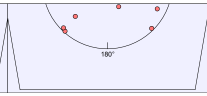


140.0

150.0

which may correspond to
a single fracture with an
aperture of 8 mm.
Confidence level = 3.
139.84





Geological single-hole interpretation of HFM34

Title	SINGLE HOLE INTERPRETATION HFM34					
Site	FORSMARK	Inclination [°]	-58.58	Elevation [m.a.s.l.]	2.45	Signed data
Borehole	HFM34	Date of mapping	2007-02-05 10:41:00	Drilling Start Date	2006-05-24 12:30:00	
Diameter [mm]	137	Coordinate System	RT90-RHB70	Drilling Stop Date	2006-06-02 12:00:00	
Length [m]	200.750	Northing [m]	6701325.06	Surveying Date		
Bearing [°]	30.50	Easting [m]	1632470.21	Plot Date	2007-10-09 22:03:00	

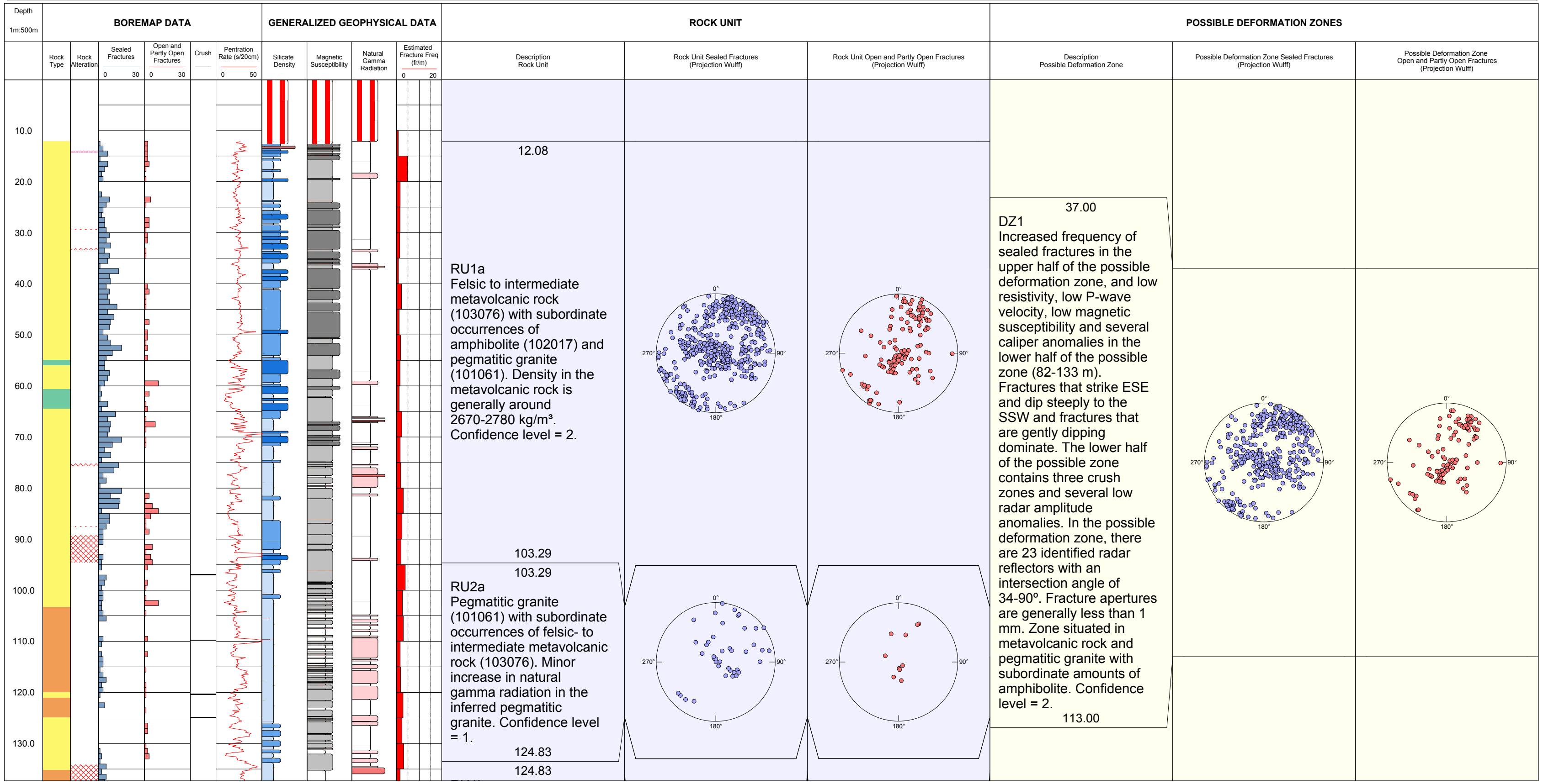
ROCKTYPE FORSMARK
- Pegmatite, pegmatitic granite
- Amphibolite
- Felsic to intermediate volcanic rock, metamorphic

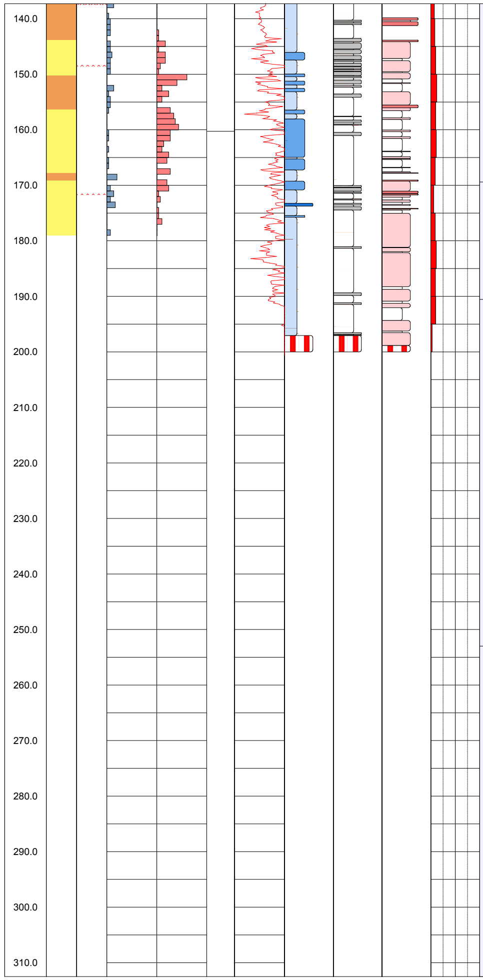
ROCK ALTERATION
- Oxidized
- Albitization

SILICATE DENSITY
- unclassified
- dens<2680 (Granite)
- 2680<dens<2730 (Granodiorite)
- 2730<dens<2800 (Tonalite)
- 2800<dens<2890 (Diorite)

SUSCEPTIBILITET
- unclassified
- sus<0.001
- 0.001<sus<0.01
- 0.01<sus<0.1

NATURAL GAMMA
- unclassified
- gam<20
- 20<gam<36
- 36<gam<53



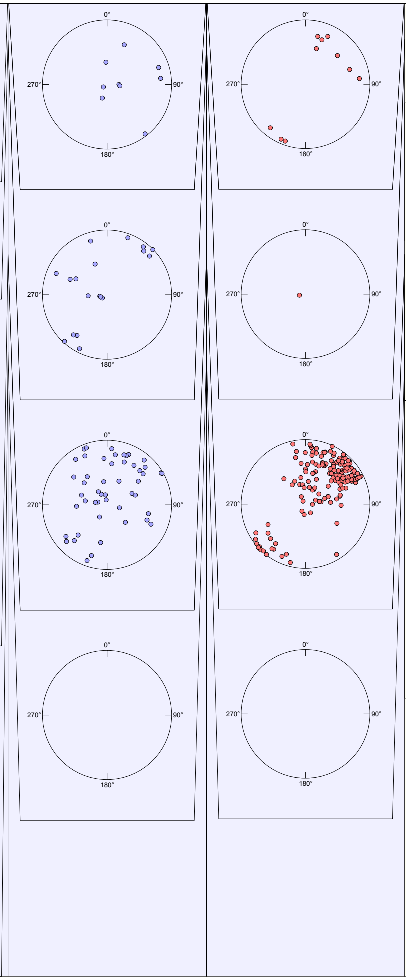


RU1b
Felsic to intermediate metavolcanic rock (103076) with subordinate occurrences of pegmatitic granite (101061). Density in the metavolcanic rock is generally around 2645-2690 kg/m³.
Confidence level = 2.
135.20

135.20
RU3
Pegmatitic granite (101061) with high natural gamma radiation.
Confidence level = 3.
143.78

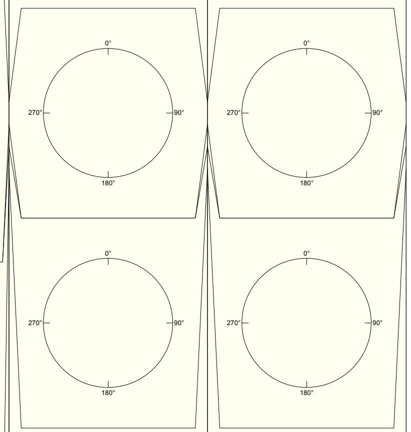
143.78
RU1c
Felsic to intermediate metavolcanic rock (103076) with subordinate occurrences of pegmatitic granite (101061) and amphibolite (102017). Density in the metavolcanic rock is generally around 2650-2705 kg/m³. Due to poor BIPS-image, mapping has only been carried out down to 179 m. Judgement of rock type has been based only on geophysical data beneath this borehole length.
Confidence level = 2.
182.50

182.50
RU2b
Pegmatitic granite (101061) with subordinate occurrences of felsic to intermediate metavolcanic rock (103076). Minor increase in natural gamma radiation in the inferred pegmatitic granite. Due to poor BIPS-image, mapping has only been carried out down to 179 m. Judgement of rock type has been based only on geophysical data beneath this borehole length.
Confidence level = 1.
200.00



180.00
DZ2
Low resistivity, low P-wave velocity, low magnetic susceptibility and several caliper anomalies. One identified radar reflector with an intersection angle of 53º. Due to poor BIPS-image, mapping of fractures and rock types has not been carried out. Judgement of possible deformation zone has been based only on geophysical data.
Confidence level = 1.
184.00

188.00
DZ3
Low resistivity, low P-wave velocity, low magnetic susceptibility and several caliper anomalies. One identified radar reflector with an intersection angle of 57º. Due to poor BIPS-image, mapping of fractures and rock types has not been carried out. Judgement of possible deformation zone has been based only on geophysical data.
Confidence level = 1.
192.00



Appendix 4

Geological single-hole interpretation of HFM35

Title	SINGLE HOLE INTERPRETATION HFM35					
Site	FORSMARK	Inclination [°]	-59.26	Elevation [m.a.s.l.]	1.90	Signed data
Borehole	HFM35	Date of mapping	2007-02-13 14:10:00	Drilling Start Date	2006-06-06 08:00:00	
Diameter [mm]	136	Coordinate System	RT90-RHB70	Drilling Stop Date	2006-06-14 11:00:00	
Length [m]	200.750	Northing [m]	6701555.86	Surveying Date		
Bearing [°]	32.96	Easting [m]	1632320.51	Plot Date	2007-06-25 23:44:05	

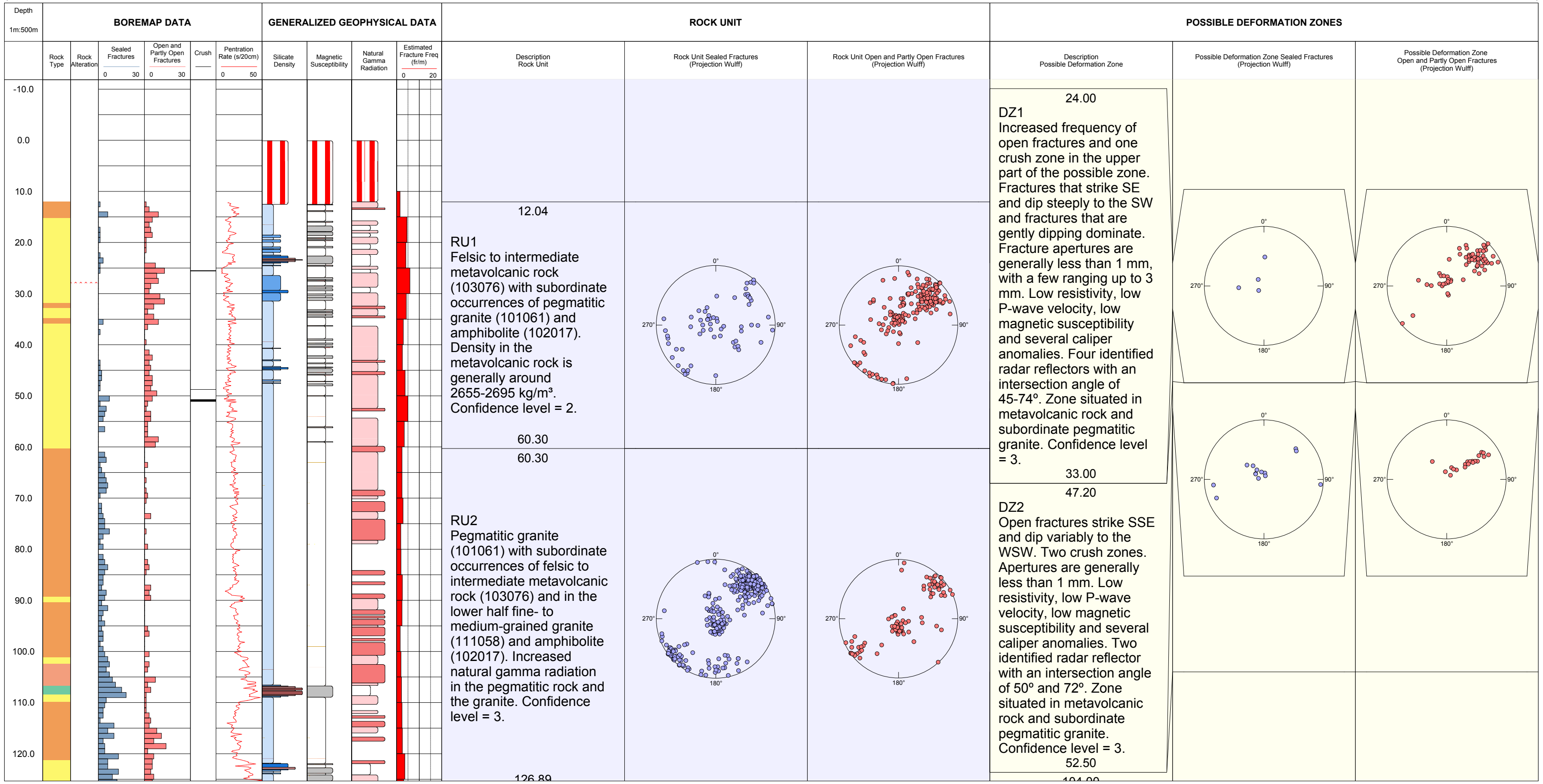
ROCKTYPE FORSMARK
- Granite, fine- to medium-grained
- Pegmatite, pegmatitic granite
- Granite, metamorphic, aplitic
- Amphibolite
- Felsic to intermediate volcanic rock, metamorphic

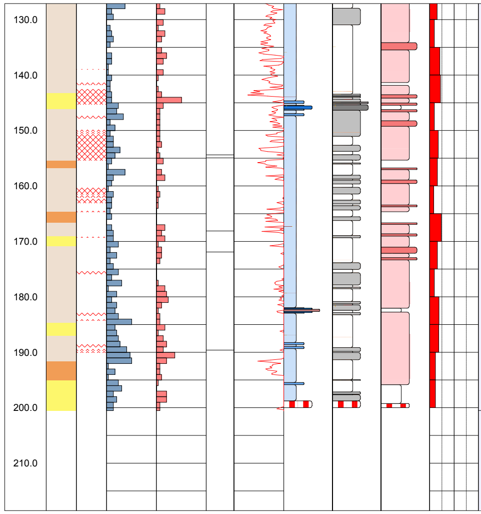
ROCK ALTERATION
- Oxidized
- Epidotized

SILICATE DENSITY
- unclassified
- dens<2680 (Granite)
- 2680<dens<2730 (Granodiorite)
- 2730<dens<2800 (Tonalite)
- 2800<dens<2890 (Diorite)
- dens>2890 (Gabbro)

SUSCEPTIBILITET
- unclassified
- sus<0.001
- 0.001<sus<0.01
- 0.01<sus<0.1

NATURAL GAMMA
- unclassified
- gam<20
- 20<gam<36
- 36<gam<53

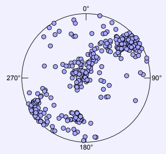


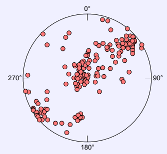


126.89

RU3
Aplitic metagranite (101058) with subordinate occurrences of pegmatitic granite (101061), felsic to intermediate metavolcanic rock (103076). Minor occurrences of amphibolite (102017) and fine- to medium-grained granite (111058). With the exception of amphibolites, the density in the rock unit is 2550-2610 kg/m³. Confidence level = 1.

200.52





DZ3
Increased frequency of open and sealed fractures. Fractures that strike SE and dip steeply to the SW and fractures that are gently dipping dominate. Five crush zones in the lower half. Fracture apertures are generally less than 1 mm, with a few ranging up to 6 mm. Below 114 m, low resistivity, low P-wave velocity, low magnetic susceptibility and several caliper anomalies. 39 identified radar reflectors with intersection angles ranging from 31º to 90º. Several low radar amplitude intervals. Zone situated in aplitic metagranite with subordinate pegmatitic granite, metavolcanic rock, amphibolite and fine- to medium-grained granite. Confidence level = 3.

200.00