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Keywords: Äspö, Geology, Geophysics, Radar, Rock unit, Deformation zone, Borehole, Interpretation, SHI.

Abstract

This report presents the outcome from geological single-hole interpretation of the core drilled borehole KAS07 located on Äspö, and the cored boreholes KA1755A and KC0045F which has been drilled underground in the Äspö HRL tunnel. The geological single-hole interpretation (SHI) is part of the work for the Äspö Site descriptive mode, Äspö SDM. The aim of the work is from data from geological core mapping, interpreted geophysical logs, and borehole radar measurements to identify different rock unit distribution in the boreholes and to identify the location and distribution of possible deformation zones in the boreholes.

The geological mapping was initially performed with the Petrocore system and the Petrocore data was later converted into the Boremap system in order to evaluate and present the geological data for the geological single-hole interpretation in a similar way as was performed during the Laxemar site investigation (SKB 2009). Due to the lack of borehole TV (BIPS)-images, inconclusiveness in the geological documentation and lack of certain parameters such as fracture frequency, along with the fact that geophysical logging data only exist for some or in some parts of the boreholes KAS07, KA1755A and KC0045F a complete geological single-hole interpretation as was made in the Laxemar site investigations (SKB 2009) could not be performed.

The borehole radar measurements in KAS07 were performed with the first generation of radar equipment. The borehole radar measurements in KA1755A and KC0045F were performed with directional antenna and the evaluation of radar data was at that time performed more or less manually by using different programs for the different steps of evaluation. The correlation between radar reflectors and geological structures has been studied elsewhere (see for example Carlsten et al. 1995).

The geological single-hole interpretation shows that the borehole KAS07 is dominated by Äspö diorite (501037). Larger sections with Ävrö granodiorite (501056) occur in the upper and lower part of the borehole. Gabbroid-dioritoid (508107) and fine-grained granite (511058) also occur in larger sections in the borehole. Subordinate rock type comprises occurrences of pegmatite (501061). Nineteen possible deformation zones are identified in KAS07 (DZ1–DZ19).

The geological single-hole interpretation shows that the borehole KA1755A is dominated by Äspö diorite (501037). Larger sections with Ävrö granodiorite (501056), fine-grained granite (511058) and gabbroid-dioritoid (508107) also occur. Subordinate rock types comprise occurrences of pegmatite (501061), mylonite (508004), breccia (508002) and quartz-dominated hydrothermal vein/segregation (508021). Three possible deformation zones are identified in KA1755A (DZ1–DZ3).

The geological single-hole interpretation shows that the upper half of the borehole KC0045F is dominated by fine-grained granite (511058) and the lower half is dominated by Äspö diorite (501037). Larger sections with Ävrö granodiorite (501056) also occur in the borehole. Subordinate rock types comprise occurrences of pegmatite (501061) and gabbroid-dioritoid (508107). Six possible deformation zones are identified in KC0045F (DZ1–DZ6).

Sammanfattning

Denna rapport presenterar resultat från geologisk enhålstolkning av kärnborrhålet KAS07 beläget på Äspö, och kärnborrhålen KA1755A and KC0045F vilka är belägna i Äspölaboratoriets tunnel. Den geologiska enhålstolkningen (SHI) utgör en del av arbetet med Äspö platsbeskrivande modell (SDM). Syftet är att utifrån den geologiska karteringen, tolkade geofysiska loggar och borrhålsradarmätningar identifiera olika bergenheters fördelning i borrhålet samt att ange möjliga deformationszoners läge och utbredning i borrhålet.

Den geologiska borrkärnekarteringen genomfördes inledningsvis med Petrocore. Petrocoredata överfördes senare till Boremapsystemet för att kunna utvärdera och presentera geologiska data i form av geologisk enhålstolkning (geological single-hole interpretation (SHI)) på motsvarande sätt som genomfördes under platsundersökningarna i Laxemar (SKB 2009). I avsaknad av borrhåls-TV (BIPS), oklarheter i den geologiska dokumentationen, och avsaknad av parametrar som sprickfrekvens, samt att vissa geofysiska loggar saknades till viss del i borrhålet KAS07, KA1755A och KC0045F, genomfördes inte en komplett geologisk enhålstolkning på det sätt som den genomfördes under platsundersökningarna i Laxemar (SKB 2009).

Borrhålsradar i KAS07 genomfördes med den första generationen av radarantenner. Borrhålsradar genomfördes i borrhålen KA1755A och KC0045F med radar riktantenn och utvärderingen och tolkningen av radardata genomfördes manuellt med fristående program och i olika steg. Korrelationen mellan orienteringen av radarreflektorer och geologsiska strukturer har studerats tidigare (Carlsten et al. 1995).

Den geologiska enhålstolkningen visar att kärnborrhålet KAS07 domineras av Äspödiorit (501037). Större sektioner med Ävrögranodiorit (501056) förekommer i den övre och den nedre delen av borrhålet. Även gabbroid-dioritoid (508107) och finkornig granit (511058) förekommer i större sektioner. Underordnad bergart utgörs av pegmatit (501061). Nitton möjliga deformationszoner har identifierats i KAS07 (DZ1–DZ19).

Den geologiska enhålstolkningen visar att kärnborrhålet KA1755A i Äspötunneln domineras av Äspödiorit (501037). Större sektioner med Ävrögranodiorit (501056), finkornig granit (511058) och gabbroid-dioritoid (508107) förekommer i borrhålet. Underordnade bergarter utgörs av pegmatit (501061), mylonit (508004), breccia (508002) och kvartsdominerad hydrotermal ådra/segregation (508021). Tre möjliga deformationszoner har identifierats i KA1755A (DZ1–DZ3).

Den geologiska enhålstolkningen visar att den övre halvan av kärnborrhålet KC0045F i Äspötunneln domineras av finkornig granit (511058) och den nedre halvan domineras av Äspödiorit (501037). Större sektioner med Ävrögranodiorit (501056) förekommer i borrhålet. Underordnade bergarter utgörs av pegmatit (501061) och gabbroid-dioritoid (508107). Sex möjliga deformationszoner har identifierats i KC0045F (DZ1–DZ6).

Contents

1 Introduction

1.1 Background

To support predictions and planning of experiments performed in the Äspö Hard Rock Laboratory (Äspö HRL), a site descriptive model (SDM) is under development, Äspö SDM. The purpose is to present an integrated understanding of the Äspö area based on available information from the fields of geology, hydrogeology, hydrogeochemistry, rock mechanics and thermal properties. An essential part in the Äspö SDM project is to incorporate existing borehole data from the earlier investigations, as well from construction and operational phases of the Äspö HRL. This necessitates a reassessment of the available data together with a renewed examination of selected drill cores, along with input from the experiences from the preceding site investigations at Forsmark (SKB 2008) and Laxemar (SKB 2009), as well as the SFR (repository for low and medium activity waste in Forsmark) extension project.

A key input to the geological modelling during the site investigations at Forsmark (SKB 2008) and Laxemar (SKB 2009) has been the complete geological single-hole interpretation (SHI) of borehole data based also on a complete suite of geophysical logging data. The current methodology for geological single-hole interpretation provides an integrated synthesis of the geological and geophysical information in a borehole where the methodology is based on the modelling strategy by Munier et al. (2003). Important input data are the results from the borehole TV (BIPS) investigation of the boreholes, which give the best possible location and true orientation (strike and dip) of the fractures intersecting the borehole and where the fractures are also visible in the core the orientation and grade of openness of the fractures can be estimated. However, due to the lack of borehole TV (BIPS)-images, inconclusiveness in the geological documentation and lack of certain parameters such as fracture frequency, along with the fact that geophysical logging data (only KAS07) only exist for some parts of the boreholes KAS07, KA1755A and KC0045F, complete input data for the geological single hole interpretation is not available as for the site investigations in Forsmark (SKB 2008) and Laxemar (SKB 2009).

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 system Rock Visualization System (RVS). The end result of this procedure is a geological single-hole interpretation, which consists of integrated series of different geophysical loggings and borehole radar data together with inspection of the available drill cores and accompanying descriptive documents (SKB MD 810.003 v.3.0, SKB internal controlling document).

This document reports the results gained by the geological single-hole interpretation of boreholes KAS07 at Äspö, and KA1755A and KC0045F located in the Äspö HRL tunnel (Figure 1-1), which is one of the activities performed within the work of upgrading the geological model of the Äspö Site Descriptive Model (SDM). The work was carried out in accordance with activity plan AP TD F140-10-023. The controlling documents for performing this activity are listed in Table 1-1. Rock type nomenclature (Table 1-2) that has been used is in accordance with method instruction SKB MD 132.004. Activity plan, method description and method instruction are SKB's internal controlling documents.

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

Activity plan	Number	Version
Geologisk enhålstolkning av KAS07, KA1755A och KC0045F	AP TD F140-10-023	1.0
Method description	**Number**	**Version**
Metodbeskrivning för geologisk enhålstolkning	SKB MD 810.003	3.0

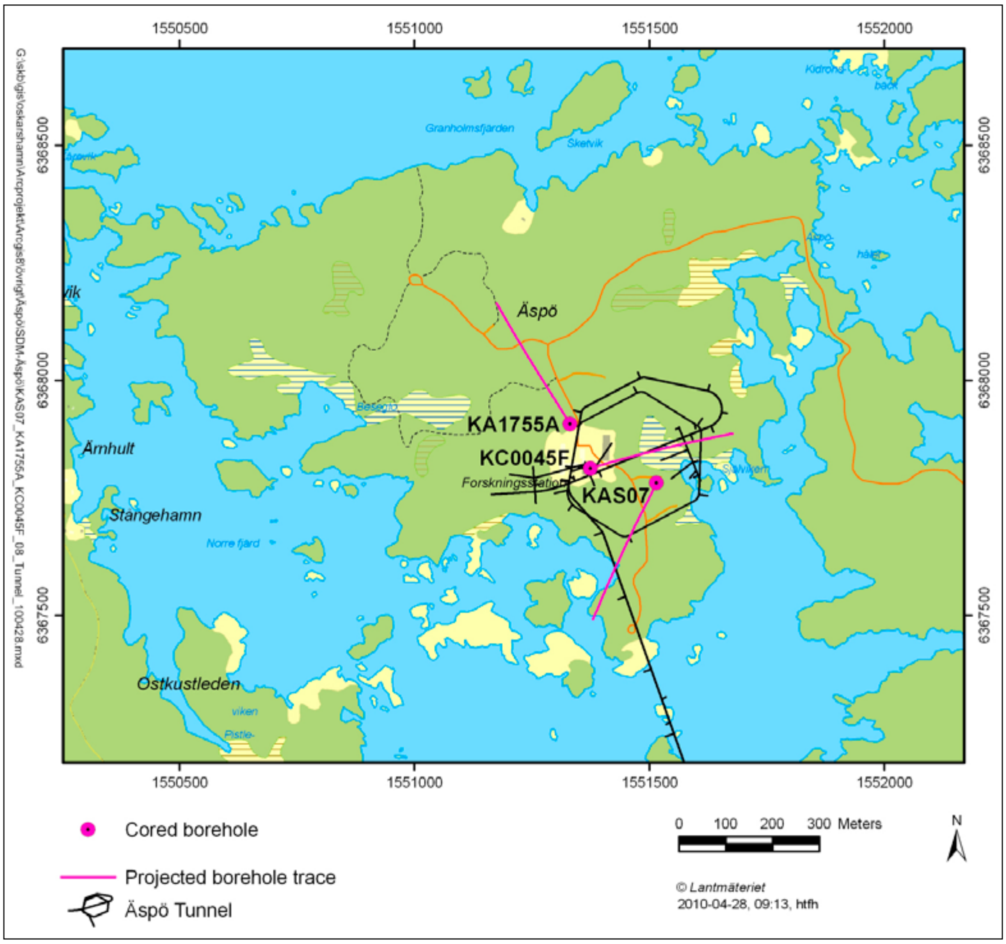

Figure 1-1. *Map showing the position of the cored boreholes KAS07, KA1755A and KC0045F located on Äspö as well as in the Äspö HRL tunnel.*

Table 1-2. Rock type nomenclature for different rock types applied for Äspö SDM.

Rock type	Rock code	Rock Description
Dolerite	501027	Dolerite
Fine-grained Götemar granite	531058	Granite, fine- to medium-grained, ("Götemar granite")
Coarse-grained Götemar granite	521058	Granite, coarse-grained, ("Götemar granite")
Fine-grained granite	511058	Granite, fine- to medium-grained
Pegmatite	501061	Pegmatite
Granite	501058	Granite, medium- to coarse-grained
Ävrö granite	501044	Granite to quartz monzodiorite, generally porphyritic
Ävrö granodiorite	501056	Granite to granodiorite, sparsely porphyritic to porphyritic
Ävrö quartz monzodiorite	501046	Quartz monzonite to quartz monzodiorite, generally porphyritic
Äspö diorite	501037	Quartz monzodiorite to granodiorite, porphyritic
Quartz monzodiorite	501036	Quartz monzonite to monzodiorite, equigranular to weakly porphyritic
Diorite-gabbro	501033	Diorite to gabbro
Fine-grained dioritoid	501030	Intermediate magmatic rock
Fine-grained diorite-gabbro	505102	Mafic rock, fine-grained
Gabbroid-dioritoid	508107	Mafic rock undifferentiated
Mylonite	508004	Mylonite
Sulphide mineralization	509010	Sulphide mineralization
Sandstone	506007	Sandstone
Quartz-dominated hydrothermal vein/segregation	508021	Quartz-dominated hydrothermal vein/segregation
Hybrid rock	505105	Hybrid rock
Breccia	508002	Breccia
Felsic volcanic rock	503076	Felsic volcanic rock

1.2 Objective

This report presents the outcome from geological single-hole interpretation of the core drilled borehole KAS07 located on Äspö and the boreholes KA1755A and KC0045F which are located in the Äspö HRL tunnel. The geological single-hole interpretation (SHI) is part of the work for the Äspö Site descriptive model SDM. The aim of the work is to compile data from geological core mapping, interpreted geophysical logs, and borehole radar measurements in order to identify different rock unit distributions in the boreholes and to identify possible deformation zones location and distribution in the borehole.

The work involved an integrated interpretation of data from the geological mapping of the borehole which initially was performed with the Petrocore system which than was converted into the Boremap system. Different borehole geophysical logs (only KAS07) and borehole radar data were available for the core drilled boreholes KAS07, KA1755A and KC0045F. The methodology for geological single-hole interpretation has been developed during the site investigations in Forsmark (SKB 2008) and Laxemar (SKB 2009). 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 result from the geological single-hole interpretation is presented in WellCAD plots (Appendices 1 to 3) and is described in this report. The work reported here concerns stage 1 in the geological single-hole interpretation, as defined in the method description SKB MD 810.003.

2 Methodology for the geological single-hole interpretation

2.1 Data used for the geological single-hole interpretation

The following data have been used in the single-hole interpretation of boreholes KAS07, KA1755A and KC0045F:

- Boremap data converted to Boremap from geological mapping initially performed in Petrocore (Sehlstedt and Stråhle 1989).
- Generalized geophysical logs and their interpretation, only for KAS07 (Sehlstedt and Stråhle 1989, Mattsson 2011).
- Radar data and their interpretation (Carlsten 1989, Carlsten et al. 1995).

As a basis for the geological single-hole interpretation a combined WellCAD plot consisting of the above mentioned data sets were used. An example of a WellCAd plot used during the geological single-hole interpretation is shown in Figure 2-1. The plot consists of seven main columns and several subordinate columns. Note that Figure 2-1 only serves as an example and that minor differences in the content of the columns between different boreholes might occur. The columns in Figure 2-1 as presented in Table 2-1 include:

Table 2-1. Headings in columns and sub-columns in the WellCAD plot in Figure 2-1.

1: BH Length: Length along the borehole	**4: Fracture alteration orientation**
2: Rock type	4.1: Broken alteration
2.1: Rock type	4.2: Unbroken alteration
2.2: Occurrence, Rock type < 1 m	4.3: Surface
2.3: Rock type structure	**5: Crush zones and core loss**
2.4: Rock type texture	5.1: Crush zone
2.5: Rock type grain size	5.2: Piece length (mm)
2.6: Structure orientation	5.3: Core loss
2.7: Rock alteration	**6: Generalized geophysical data**
2.8: Rock alteration intensity	6.1: Silicate density
3: Fracture frequency	6.2: Magnetic susceptibility
3.1: Natural fractures	6.3: Natural gamma radiation
3.2: Unbroken fractures	6.4: Estimated fracture frequency (fr/m)
3.3: Fracture open orientation	**7: Geophysics**
3.4: Fracture orientation broken/unbroken	7.1: Magnetic susceptibility
3.5: Total fractures	7.2: Sonic
	7.3: Radar directional primary or radar dipole 1
	7.4: Radar directional alternative

The geophysical logs as described in the example from KAS02 are described below:

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

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

Natural gamma radiation: The bedrock 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 fine-grained granite or pegmatite.

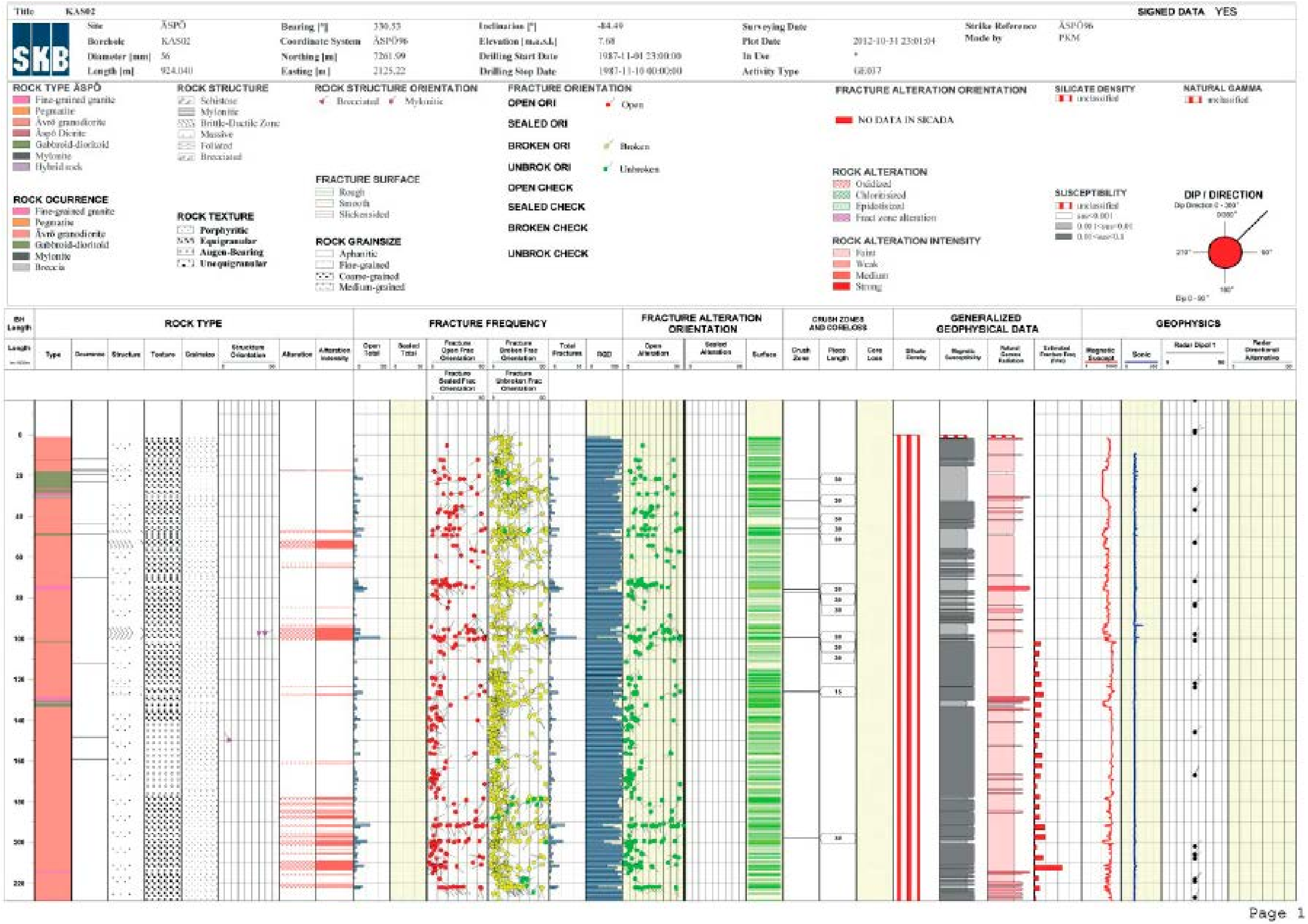

Figure 2-1. Example of WellCAD plot (from borehole KAS02 at Äspö) used as a basis for the geological single-hole interpretation.

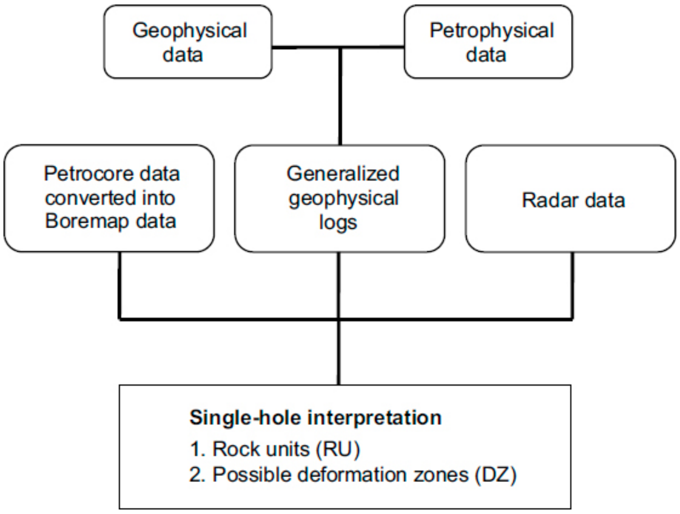

Figure 2-2. *Schematic block-scheme for data used in the geological single-hole interpretation.*

Estimated fracture frequency: This parameter provides an estimate of the fracture frequency along 5 m sections, calculated from short, long and lateral resistivity, SPR, P-wave velocity and caliper data. 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. Separate diagrams with moving averages for open fractures alone, sealed fractures alone, and total number of open and sealed fractures were available during the interpretation process.

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 or alpha angles of radar anomalies within the possible deformation zones are commented upon in the text that describes these zones. Strike is related to Äspö96 North.

The data used for the geological single-hole interpretation is summarized in Figure 2-2.

2.2 Geological single-hole interpretation

The working procedure is to study all available types of data related to the character of the rock types and to merge sections of similar geological character into rock units. All data to be used are presented side by side in a borehole document extracted from the software WellCAD. Geophysical density logs, which represent important input for the work, were available for the boreholes. A minimum length of about 5 m was used for rock units in the geological single-hole interpretations during the site investigations at Forsmark (SKB 2008) and Laxemar (SKB 2009). This minimum length was generally also applied during the current work. The division into rock units was carried out by 2–3 geologists. Each rock unit is defined in terms of the borehole length interval and provided with a brief description. The confidence in the interpretation of a rock unit is assigned according to three classes: 3 = high, 2 = medium and 1 = low.

The procedure to identify possible deformation zones is primarily based on inspection of the drill cores. Each identified possible deformation zone is performed 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. The confidence in the interpretation of a possible deformation zone is made on the following basis: 3 = high, 2 = medium and 1 = low.

Following the definition of rock units and deformation zones, with their respective confidence estimates, the drill cores were inspected in order to check the selection of the boundaries between these geological entities. If judged necessary, the location of these boundaries was adjusted.

Possible deformation zones that are ductile or brittle in character have been identified primarily on the basis of occurrence of protomylonitic to mylonitic foliation and fault rocks and frequency of fractures, respectively, according to the recommendations in Munier et al. (2003). The damaged zone and the deformation zone core have been included in each deformation zone (Figures 2-3 to 2-5). The frequencies of open and sealed fractures have been assessed in the identification procedure, and the character of the deformation zone has been described accordingly. Partly open fractures are included together with open fractures in the brief description of each deformation zone. The presence of bedrock alteration, the occurrence and, locally, inferred orientation of radar reflectors and geophysical data, if available, and geophysical data, if available, have all assisted in the identification of primarily the brittle structures.

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 boreholes KAS07, KA1755A and KC0045F (Figures 2-6 to 2-8). A 5 m window and 1 m steps have been used in the calculation procedure. The moving averages for open fractures alone, the sealed fractures alone, and the total number of open and sealed fractures are shown in diagrams (Figures 2-6 to 2-8).

Observation of the occurrence of radar anomalies was used during the identification of possible deformation zones. Orientations from directional radar are presented as strike/dip using the right-hand-rule method, e.g. 040°/80° corresponds to a strike of N40°E and a dip of 80°to the SE. Strike is related to Äspö96 North.

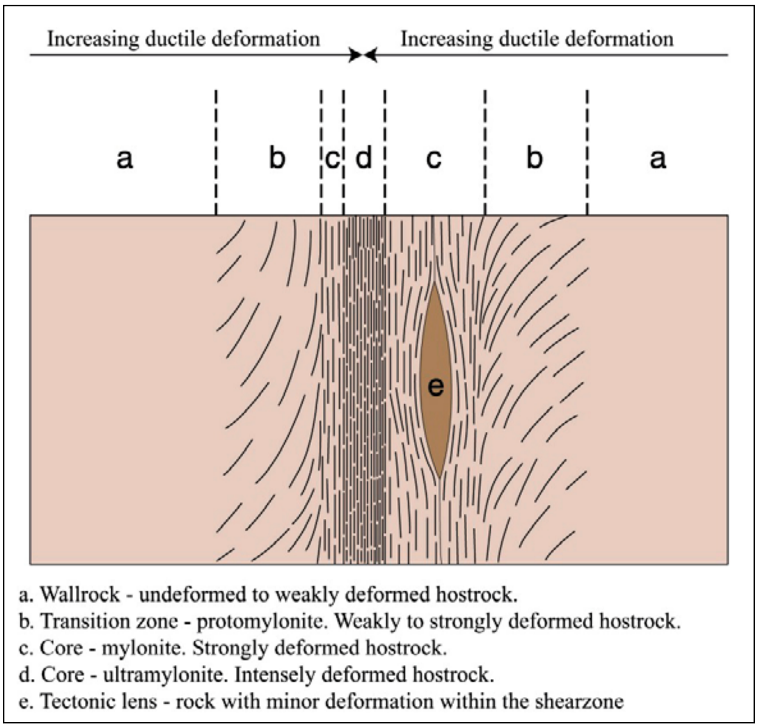

Figure 2-3. *Schematic example of a ductile shear zone. Homogeneous rock which is deformed under low- to medium-grade metamorphic conditions (after Munier et al. 2003).*

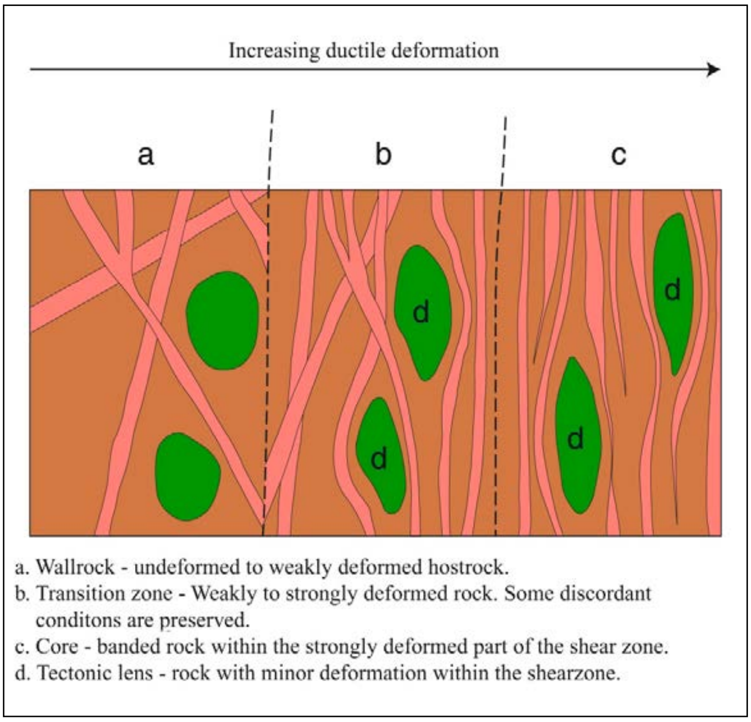

Figure 2-4. *Schematic example of a ductile shear zone. Heterogeneous rock which is deformed under low- to high-grade metamorphic conditions (after Munier et al. 2003).*

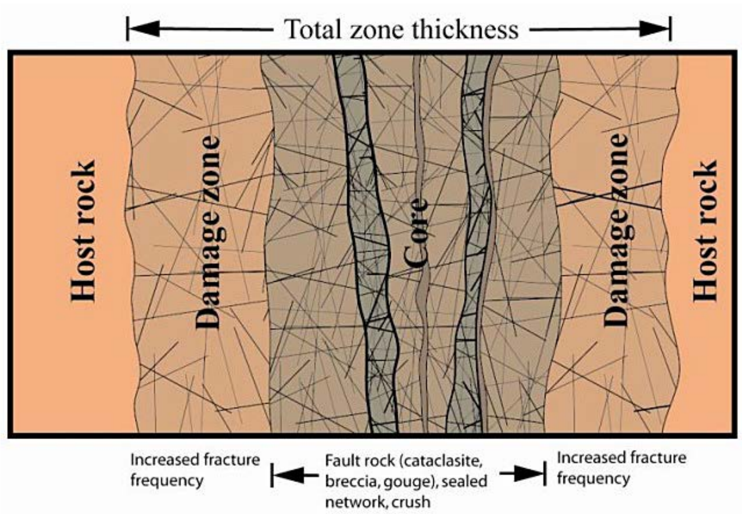

Figure 2-5. *Schematic example of a brittle deformation zone (modified from Munier et al. 2003).*

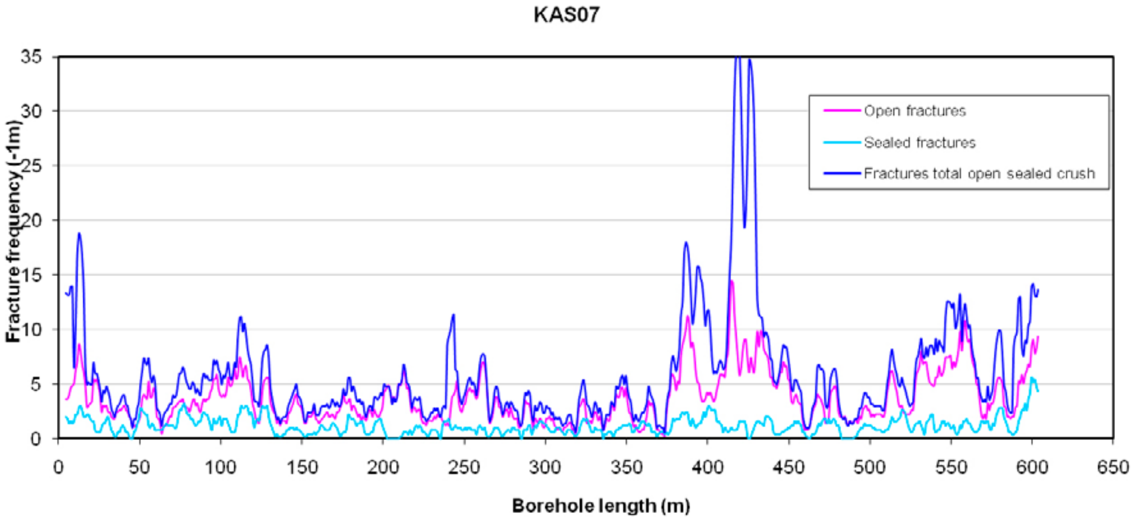

***Figure 2-6.** Fracture frequency plot for KAS07. Moving average with a 5 m window and 1 m steps.*

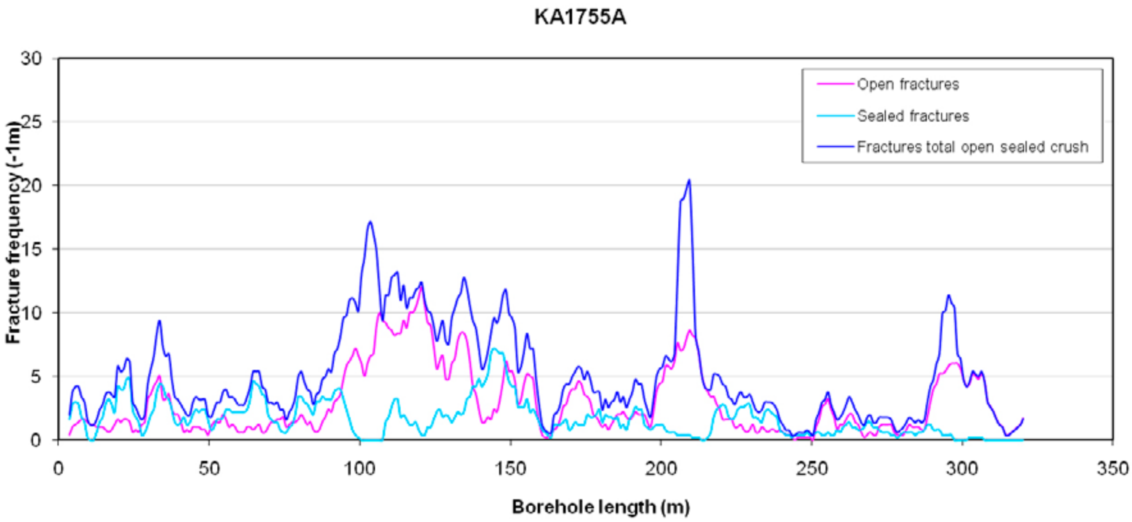

***Figure 2-7.** Fracture frequency plot for KA1755A. Moving average with a 5 m window and 1 m steps.*

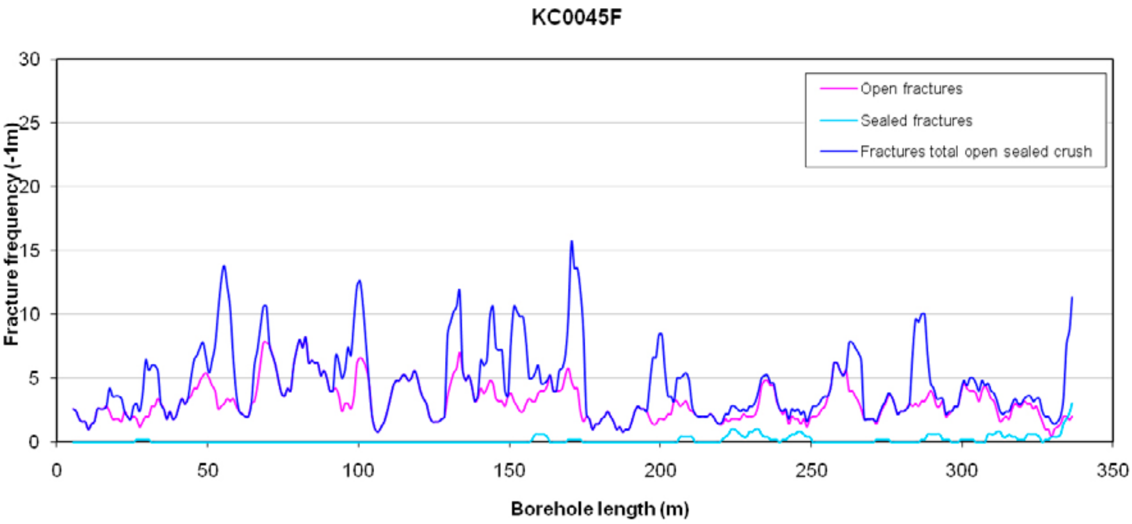

***Figure 2-8.** Fracture frequency plot for KC0045F. Moving average with a 5 m window and 1 m steps.*

2.3 Nonconformities

The geological mapping was initially made with the Petrocore system. In order to evaluate and present the geological data in question for the SHI in a similar way as during the Laxemar site investigation (SKB 2009), the Petrocore data was converted into Boremap.

Fracture orientation was not available in the boreholes KAS07, KA1755A and KC0045F. This is shown as blank sections in the columns *Open Frac Orientation/sealed Frac Orientation* and *Broken Frac Orientation/unbroken Frac Orientation* and as void stereograms in the Appendices.

Borehole TV (BIPS) was not available at the time for measurements of the boreholes, and therefore, the geological mapping was solely based on inspection of the drill core. However, borehole KC0045F was logged with BIPS during 2010, but the core was not remapped.

Geophysical logging was not performed in the underground boreholes KA1755A and KC0045F drilled from the tunnel.

The borehole radar measurement in KAS07 was performed with the first generation of radar antennas and the evaluation of radar data was at that time performed more or less manually by using different programs for the different steps of evaluation. Directional antenna was not available during the measurements in KAS07. The interpretation of radar reflectors in the report for KAS07 was at that time focused on association with interpretation of deformation zones, i.e. interpretation was made only in selected sections of the borehole. However, remaining data has been collected from Sicada. The borehole radar measurement in KC0045F was made with directional antenna. The alternative orientations have been collected from Sicada and not from the report. Strike is related to Äspö96 North.

Borehole radar measurement was not performed in KA1755A.

3 Results

The detailed result of the single-hole interpretation is presented as print-out from the software WellCAD (Appendix 1 for KAS07, Appendix 2 for KA1755A and Appendix 3 for KC0045F). Orientations are related to Äspö96 North.

3.1 KAS07

3.1.1 Rock units

The borehole consists of four rock units (RU1–RU4). However, due to repetition of RU1 (RU1a, RU1b and RU1c), RU2 (RU2a, RU2b, RU2c and RU2d) and RU3 (RU3a, RU3b, RU3c and RU3d) the borehole can be divided into twelve sections. The confidence in the interpretation of a rock unit is assigned according to three classes: 3 = high, 2 = medium and 1 = low.

1.55–13.62 m

RU1a: Totally dominated by Ävrö granodiorite (501056). Confidence level = 3.

13.62–24.24 m

RU2a: Totally dominated by gabbroid-dioritoid (508107). Subordinate rock types comprise fine-grained granite (511058) and very sparse occurrence of pegmatite (501061). Confidence level = 3.

24.24–71.20 m

RU1b: Totally dominated by Ävrö granodiorite (501056). Subordinate rock types comprise fine-grained granite (511058), pegmatite (501061) and very sparse occurrence of gabbroid-dioritoid (508107). Confidence level = 3.

71.20–191.54 m

RU3a: Dominated by Äspö diorite (501037). Subordinate rock types comprise Ävrö granodiorite (501056), fine-grained granite (511058), gabbroid-dioritoid (508107) and pegmatite (501061). Confidence level = 3.

191.54–215.20 m

RU2b: Totally dominated by gabbroid-dioritoid (508107). Subordinate rock types comprise fine-grained granite (511058) and pegmatite (501061). Confidence level = 3.

215.20–243.57 m

RU3b: Dominated by Äspö diorite (501037). Subordinate rock types comprise fine-grained granite (511058), gabbroid-dioritoid (508107) and sparse occurrence of pegmatite (501061). Confidence level = 3.

243.57–264.06 m

RU4: Totally dominated by fine-grained granite (511058). Subordinate rock type comprises Äspö diorite (501037), Ävrö granodiorite (501056) and pegmatite (501061). Confidence level = 3.

264.06–376.82 m

RU3c: Dominated by Äspö diorite (501037). Subordinate rock types comprise fine-grained granite (511058), gabbroid-dioritoid (508107) and sparse occurrence of pegmatite (501061). Confidence level = 3.

376.82–383.59 m

RU2c: Totally dominated by gabbroid-dioritoid (508107). Subordinate rock type comprises fine-grained granite (511058). Confidence level = 3.

383.59–529.65 m

RU3d: Dominated by Äspö diorite (501037). Subordinate rock types comprise fine-grained granite (511058), gabbroid-dioritoid (508107) and pegmatite (501061). Confidence level = 3.

529.65–565.61 m

RU2d: Dominated by gabbroid-dioritoid (508107). Subordinate rock type comprises fine-grained granite (511058), Äspö diorite (501037) and pegmatite (501061). There is a general tendency to increased frequency open fractures outside the possible deformation zones (DZ13–17). Confidence level = 3.

565.61–603.88 m

RU1c: Totally dominated by Ävrö granodiorite (501056). Subordinate rock types comprise fine-grained granite (511058), pegmatite (501061) and very sparse occurrence of gabbroid-dioritoid (508107). There is a general tendency to increased frequency open fractures outside the possible deformation zones (DZ18–19). Confidence level = 3.

3.1.2 Possible deformation zones

Nineteen possible deformation zones have been recognized in KAS07 (DZ1–DZ19). The confidence in the interpretation of a possible deformation zone is assigned according to three classes: 3 = high, 2 = medium and 1 = low.

6.30–6.60 m

DZ1: Brittle deformation zone characterized by one crush at 6.34-6.53 m. The magnetic susceptibility is decreased along the section. There are no other geophysical data available along this section of the borehole. The host rock is totally dominated by Ävrö granodiorite (501056). Confidence level = 3.

10.00–14.40 m

DZ2: Brittle deformation zone characterized by increased frequency of open fractures, oxidation and two crush at 12.37–12.45 m and 13.04–13.57 m. The single point resistance (SPR) and magnetic susceptibility are decreased along the section. There are also short intervals with significantly decreased p-wave velocity. The host rock is dominated by Ävrö granodiorite (501056) and to a lesser extent gabbroid-dioritoid (508107). Confidence level = 3.

95.55–95.86 m

DZ3: Brittle deformation zone characterized by increased frequency of open fractures and oxidation. There is a significant anomaly in the vertical temperature gradient data that indicates water-bearing fractures. There is also a major positive anomaly in the p-wave velocity in the section. A positive anomaly would normally indicate solid rock, but the shape of this particular anomaly suggests that it may be related to a misinterpretation or erroneous picks of the first arrival time of the seismic wave. The sonic data could thus indicate a low velocity zone. The host rock is totally dominated by Äspö diorite (501037). Confidence level = 3.

112.44–113.96 m

DZ4: Brittle deformation zone characterized by increased frequency of open fractures, sealed network (based on inspection of the drillcore during SHI), oxidation and one crush at 112.68–112.81 m. The section 110–114 m is characterized by decreased magnetic susceptibility. At c. 112.5 m the single point resistance (SPR) amplitude and p-wave velocity are clearly decreased, and there is also an anomaly in the vertical temperature gradient data that indicates a water-bearing fracture. The host rock is totally dominated by Äspö diorite (501037). Confidence level = 3.

112.44–113.96 m

DZ4: Brittle deformation zone characterized by increased frequency of open fractures, sealed network (based on inspection of the drillcore during SHI), oxidation and one crush at 112.68–112.81 m. The section 110–114 m is characterized by decreased magnetic susceptibility. At c. 112.5 m the single point resistance (SPR) amplitude and p-wave velocity are clearly decreased, and there is also an anomaly in the vertical temperature gradient data that indicates a water-bearing fracture. The host rock is totally dominated by Äspö diorite (501037). Confidence level = 3.

125.90–128.70 m

DZ5: Brittle deformation zone characterized by increased frequency of open fractures and oxidation. The entire section is characterized by decreased magnetic susceptibility and single point resistance (SPR) amplitude. There is also an anomaly in the vertical temperature gradient data that indicates a water-bearing fracture. One non-oriented radar reflector of medium strength occurs at 128 m with an angle of 40° to the borehole axis. The host rock consists of almost equal amounts of gabbroid-dioritoid (508107), Äspö diorite (501037) and fine-grained granite (511058). Confidence level = 3.

241.00–242.13 m

DZ6: Brittle deformation zone characterized by one crush at 241.20–242.13 m. In the section there is a distinct caliper anomaly, decreased single point resistance (SPR) amplitude and a significant p-wave low velocity anomaly. There is also a minor anomaly in the vertical temperature gradient data that may indicate a water-bearing fracture. The host rock is totally dominated by Äspö diorite (501037). Confidence level = 3.

383.98–389.62 m

DZ7: Brittle deformation zone characterized by increased frequency of open fractures, oxidation and three crush at 384.85–384.99 m, 387.22–387.53 m and 387.89–387.97 m. The single point resistance (SPR) amplitude and the p-wave velocity are partly decreased and there is a minor caliper anomaly at c. 390 m that could be related to the deformation zone. One non-oriented weak radar reflector occurs at 384 m with an angle of 55° to the borehole axis. The host rock is dominated by Äspö diorite (501037) and to a lesser extent fine-grained granite (511058). Subordinate rock type comprises sparse occurrence of gabbroid-dioritoid (508107). Confidence level = 3.

394.05–395.47 m

DZ8: Brittle deformation zone characterized by slightly increased frequency of open fractures, sealed network (based on inspection of the drillcore during SHI) and one crush at 394.71–395.23 m. The magnetic susceptibility is clearly decreased along the section, but there are no anomalies in the other geophysical logging data. The host rock is dominated by gabbroid-dioritoid (508107) and to a lesser extent Äspö diorite (501037). Confidence level = 3.

398.61–400.62 m

DZ9: Brittle deformation zone characterized by increased frequency of open fractures, breccia (based on inspection of the drillcore during SHI), oxidation and two crush at 398.86–399.00 m and 399.72–400.18 m. At c. 400 m there is a distinct decrease in the single point resistance (SPR) amplitude, the p-wave velocity and the magnetic susceptibility. The host rock is dominated by Äspö diorite (501037) and to a lesser extent fine-grained granite (511058). Subordinate rock type comprises gabbroid-dioritoid (508107). Confidence level = 3.

412.00–435.17 m

DZ10: Brittle deformation zone characterized by increased frequency of open fractures, oxidation and eleven crush which in total constitute 5.25 m of the deformation zone. The entire section is generally characterized by significant anomalies in the magnetic susceptibility, single point resistance (SPR), p-wave velocity and caliper data. The most prominent geophysical anomalies occur in the section 412–423 m. One non-oriented strong radar reflector occurs at 420 m with an angle of 50° to the borehole axis. The direct radar amplitude is reduced in the section 411–435 m. The host rock is totally dominated by Äspö diorite (501037). Subordinate rock types comprise sparse occurrence gabbroid-dioritoid (508107) and very sparse occurrence of pegmatite (501061). Confidence level = 3.

446.43–449.50 m

DZ11: Brittle deformation zone characterized by increased frequency of open fractures, oxidation and one crush at 447.62–447.70 m. The magnetic susceptibility is partly decreased along the section and there are some minor anomalies in the caliper data. The host rock is totally dominated by Äspö diorite (501037). Subordinate rock type comprises sparse occurrence of gabbroid-dioritoid (508107). Confidence level = 3.

469.48–469.96 m

DZ12: Brittle deformation zone characterized by increased frequency of open fractures, a thin breccia (based on inspection of the drillcore during SHI), oxidation and one crush at 469.69–469.76 m. There are minor anomalies of decreased p-wave velocity and magnetic susceptibility along the section. The host rock is totally dominated by Äspö diorite (501037). Confidence level = 3.

538.29–538.42 m

DZ13: Brittle deformation zone characterized by one crush at 538.29–538.42 m. In the section there are minor anomalies of decreased p-wave velocity and single point resistance (SPR) amplitude, and the magnetic susceptibility is significantly decreased along the interval 533–539 m. The host rock is totally dominated by gabbroid-dioritoid (508107). Confidence level = 3.

541.96–542.07 m

DZ14: Brittle deformation zone characterized by one crush at 541.96–542.07 m. There are significant anomalies in the p-wave velocity and single point resistance (SPR) amplitude and there is also a distinct caliper anomaly. One non-oriented radar reflector of medium strength occurs at 542 m with an angle of 50° to the borehole axis. The host rock is totally dominated by gabbroid-dioritoid (508107). Confidence level = 3.

548.60–548.72 m

DZ15: Brittle deformation zone characterized by epidotization and one crush at 548.60–548.72 m. There are no significant anomalies in the geophysical logging data. The host rock is totally dominated by gabbroid-dioritoid (508107). Confidence level = 3.

549.79–549.87 m

DZ16: Brittle deformation zone characterized by epidotization and one crush at 549.79–549.87 m. There are no significant anomalies in the geophysical logging data. The host rock is totally dominated by gabbroid-dioritoid (508107). Confidence level = 3.

552.90–553.25 m

DZ17: Brittle deformation zone characterized by one crush at 552.90–553.25 m. There is a distinct decrease in the p-wave velocity and in the single point resistance (SPR) amplitude. The magnetic susceptibility is also decreased. The host rock is totally dominated by Äspö diorite (501037). Confidence level = 3.

578.81–579.01 m

DZ18: Brittle deformation zone characterized by oxidation and one crush at 578.81–579.01 m. There is a distinct decrease in the p-wave velocity and in the single point resistance (SPR) amplitude. There are also minor caliper anomalies. The host rock is totally dominated by Ävrö granodiorite (501056). Confidence level = 3.

590.03–590.89 m

DZ19: Brittle deformation zone characterized by oxidation and one crush at 590.03–590.89 m. There is a distinct decrease in the p-wave velocity and in the single point resistance (SPR) amplitude. There are also minor caliper anomalies and decreased magnetic susceptibility. The host rock is totally dominated by Ävrö granodiorite (501056). Confidence level = 3.

3.2 KA1755A

3.2.1 Rock units

The borehole consists of four rock units (RU1–RU4). However, due to repetition of RU1 (RU1a, RU1b, RU1c, RU1d and RU1e), RU3 (RU3a and RU3b) and RU4 (RU4a and RU4b) the borehole can be divided into ten sections. The confidence in the interpretation of a rock unit is assigned according to three classes: 3 = high, 2 = medium and 1 = low.

0.00–98.35 m

RU1a: Dominated by Äspö diorite (501037). Subordinate rock types comprise fine-grained granite (511058) and very sparse occurrences of mylonite (508004), pegmatite (501061) and quartz-dominated hydrothermal vein/segregation (508021). The rock unit is inhomogeneously foliated. Confidence level = 3.

98.35–150.50 m

RU2: Dominated by fine-grained granite (511058). Subordinate rock types comprise sparse occurrences of mylonite (508004) and breccia (508002), cf. DZ1. Confidence level = 3.

150.50–188.55 m

RU3a: Dominated by Ävrö granodiorite (501056). Subordinate rock types comprise fine-grained granite (511058) and sparse occurrences of pegmatite (501061). Confidence level = 3.

188.55–214.48 m

RU1b: Dominated by Äspö diorite (501037). Subordinate rock types comprise fine-grained granite (511058), gabbroid-dioritoid (508107), mylonite (508004), breccia (508002), cf. DZ2, and pegmatite (501061). Confidence level = 3.

214.48–236.04 m

RU3b: Dominated by Ävrö granodiorite (501056). Subordinate rock types comprise sparse occurrences of Äspö diorite (501037) and pegmatite (501061). Confidence level = 3.

236.04–255.92 m

RU1c: Dominated by Äspö diorite (501037). Subordinate rock types comprise Ävrö granodiorite (501056) and sparse occurrences of gabbroid-dioritoid (508107) and pegmatite (501061). Confidence level = 3.

255.92–264.58 m

RU4a: Totally dominated by gabbroid-dioritoid (508107). Confidence level = 3.

264.58–289.43 m

RU1d: Dominated by Äspö diorite (501037). Subordinate rock types comprise fine-grained granite (511058), Ävrö granodiorite (501056), gabbroid-dioritoid (508107) and sparse occurrences of pegmatite (501061). Confidence level = 3.

289.43–308.88 m

RU4b: Dominated by gabbroid-dioritoid (508107). Subordinate rock types comprise breccia (508002), mylonite (508004), cf. DZ3, fine-grained granite (511058), sparse occurrences of pegmatite (501061) and very sparse occurrence of quartz-dominated hydrothermal vein/segregation (508021). Confidence level = 3.

308.88–320.58 m

RU1e: Dominated by Äspö diorite (501037). Subordinate rock types comprise gabbroid-dioritoid (508107) and very sparse occurrence of pegmatite (501061). Confidence level = 3.

3.2.2 Possible deformation zones

Three possible deformation zones have been recognized in KA1755A (DZ1–DZ3). The confidence in the interpretation of a possible deformation zone is assigned according to three classes: 3 = high, 2 = medium and 1 = low.

95.35–123.05 m

DZ1: Low-grade ductile to brittle-ductile deformation zone overprinted by brittle deformation. The deformation zone is characterized by protomylonitic to mylonitic foliation, increased frequency of open fractures, sparse oxidation, epidotization, sparse occurrence of breccia and 10 crush which in total constitute 2.54 m of the deformation zone. The deformation is most intense in the section between 95.35 and 105.00 m. The section 123.05–150.50 m has been documented as brittle-ductile shear zone in Sicada, but was considered as a misinterpretation based on inspection of the drillcore during SHI. The host rock is dominated by fine-grained granite (511058) and to a lesser extent Äspö diorite (501037). Note! The lower limit of the deformation zone is difficult to define due to the grain size and leucocratic character of the host rock. Confidence level = 3.

203.42–213.64 m

DZ2: Low-grade ductile to brittle-ductile deformation zone overprinted by brittle deformation. The deformation zone is characterized by protomylonitic to mylonitic foliation, increased frequency of open fractures, breccia, oxidation, epidotization and one crush at 207.52–208.65 m. The host rock is dominated by Äspö diorite (501037) and to a lesser extent fine-grained granite (511058) and gabbroid-dioritoid (508107). Confidence level = 3.

295.09–299.44 m

DZ3: Low-grade ductile to brittle-ductile deformation zone overprinted by brittle deformation. The deformation zone is characterized by protomylonitic to mylonitic foliation, increased frequency of open fractures, breccia, epidotization and two crush at 295.33–295.84 m and 297.60–297.75 m. The section 299.44–308.88 m has been documented as brittle-ductile shear zone in Sicada, but was considered as a misinterpretation based on inspection of the drillcore during SHI. The host rock is totally dominated by gabbroid-dioritoid (508107). Confidence level = 3.

3.3 KC0045F

3.3.1 Rock units

The borehole consists of three rock units (RU1–RU3). However, due to repetition of RU1 (RU1a, RU1b and RU1c) and RU2 (RU2a and RU2b) the borehole can be divided into six sections. The confidence in the interpretation of a rock unit is assigned according to three classes: 3 = high, 2 = medium and 1 = low.

2.52–102.00 m

RU1a: Dominated by fine-grained granite (511058). Subordinate rock types comprise Äspö diorite (501037) and very sparse occurrence of pegmatite (501061). The fracture frequency is locally increased also outside the possible deformation zones (DZ1–DZ2) due to occurrence of fractures that are subparallel to the core axis. Confidence level = 3.

102.00–131.72 m

RU2a: Dominated by Äspö diorite (501037). Subordinate rock types comprise fine-grained granite (511058) and one occurrence of a thin pegmatite (501061). Confidence level = 3.

131.72–147.36 m

RU1b: Totally dominated by fine-grained granite (511058). Subordinate rock type comprises one occurrence of a thin pegmatite (501061). Confidence level = 3.

147.36–164.40 m

RU3: Totally dominated by Ävrö granodiorite (501056). Confidence level = 3.

164.40–173.03 m

RU1c: Totally dominated by fine-grained granite (511058). Confidence level = 3.

173.03–336.70 m

RU2b: Dominated by Äspö diorite (501037). Subordinate rock types comprise pegmatite (501061), fine-grained granite (511058) and gabbroid-dioritoid (508107). Confidence level = 3.

3.3.2 Possible deformation zones

Six possible deformation zones have been recognized in KC0045F (DZ1–DZ6). The confidence in the interpretation of a possible deformation zone is assigned according to three classes: 3 = high, 2 = medium and 1 = low.

54.67–57.90 m

DZ1: Brittle deformation zone characterized by slightly increased frequency of open fractures and two crush at 54.62–56.54 m and 57.70–57.79 m which constitute a major part of the deformation zone. The host rock is totally dominated by fine-grained granite (511058). Subordinate rock type comprises sparse occurrence of Äspö diorite (501037). Confidence level = 3.

98.48–102.99 m

DZ2: Brittle deformation zone characterized by increased frequency of open fractures, sealed network (based on inspection of the drillcore during SHI) and three crush at 98.74–99.17 m, 99.34–99.50 m and 100.76–100.92 m. One oriented strong radar reflector occurs at 103 m with the orientation 311°/69° or 230°/36°. The host rock is dominated by fine-grained granite (511058) and to a lesser extent Äspö diorite (501037). Confidence level = 3.

116.24–139.94 m

DZ3: The deformation zone has been divided in a central section (core) surrounded by damage zones, based on inspection of the drillcore during SHI. Confidence level = 3.

116.24–126.83 m – damage zone: Increased frequency of sealed network and alteration (based on inspection of the drillcore during SHI). One oriented radar reflector of medium strength occurs at 119 m with the orientation 130°/12° or 008°/55°. The host rock is dominated by Äspö diorite (501037) and to a lesser extent fine-grained granite (511058).

126.83–133.05 m – core: low-grade mylonitic foliation, fine-grained. One crush occurs at 131.49–131.72 m. Two oriented radar reflectors of medium strength occur at 130 m and 132 m with the orientation 300°/73° or 259°/55° and 008°/59° or 143°/14°, respectively. The host rock is dominated by Äspö diorite (501037) and to a lesser extent fine-grained granite (511058).

133.05–139.94 m – damage zone: Increased frequency of sealed network and alteration (based on inspection of the drillcore during SHI). One oriented radar reflector of medium strength occurs at 136 m with the orientation 118°/61° or 048°/89°. The host rock is totally dominated by fine-grained granite (511058).

169.88–173.10 m

DZ4: Brittle deformation zone characterized by slightly increased frequency of open fractures and two crush that occur at 171.27–171.46 m and 171.98–173.03 m. One oriented weak and uncertain radar reflector occurs at 172 m with the orientation 286°/20° or 330°/44°. The host rock is totally dominated by fine-grained granite (511058). Subordinate rock type comprises Äspö diorite (501037). Confidence level = 2.

264.15–264.86 m

DZ5: Brittle deformation zone characterized by slightly increased frequency of open fractures, oxidation and one crush located at 264.31–264.86 m. The host rock is totally dominated by Äspö diorite (501037). Confidence level = 3.

285.61–286.46 m

DZ6: Brittle deformation zone characterized by one crush at 285.61–286.24 m. One oriented radar reflector of medium strength occurs at 286 m with the orientation 220°/79° or 132°/66°. The host rock is totally dominated by Äspö diorite (501037). Confidence level = 3.

4 Discussion

The geological mapping was initially performed with the Petrocore system. The Petrocore data was converted into the Boremap system in order to evaluate and present the geological data in question for the geological single-hole interpretation in a similar way as performed during the Laxemar site investigation (SKB 2009).

Important input data are the results from the borehole TV (BIPS) investigation of the boreholes, which give the best possible location and true orientation (strike and dip) of fractures intersecting the core drilled borehole and when fractures also are visible in the drill core a very good observation of the location and orientation of the fractures is given. However, lack of borehole TV (BIPS)-images, inconclusiveness in the geological documentation and lack of certain parameters such as fracture frequency, along with the fact that geophysical logging data only exist for some or in some parts of the boreholes KAS07, KA1755A and KC0045F is too sparse to allow the full application of the established and complete SHI methodology. When borehole TV (BIPS) was not available the geological mapping was only based on inspection of the drill core.

The geophysical borehole logging measurements was performed after the reaming of the upper 100 m telescope drilled part of the core drilled boreholes KAS07. The increased borehole diameter at the reamed part generates in a decreased geophysical signal strength and decreased resolution in many of the geophysical logging parameters, which affects the result and interpretation of the logging data in the reamed part of the borehole. Density logging (gamma-gamma) was available in KAS07. The boreholes KA1755A and KC0045F were not logged with geophysical tools.

The borehole radar measurements was performed with the first generation of radar equipment and the evaluation of radar data was at that time performed more or less manually by using different programs for the different steps of evaluation. Furthermore, the radar directional antenna was not available during the measurements in boreholes KAS07 and in KC0045F only the directional antenna was used. The occurrence of radar data is listed in the description of each deformation zone (DZ) unit in Section 3.1.2, 3.2.2 as well as in the Section 3.3.2. The correlation between radar reflectors and geological structures has been studied elsewhere (see for example Carlsten et al. 1995).

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Appendices

Geological single-hole interpretation of KAS07, KA1755A and KC0045F

The results from the geological single-hole interpretation of KAS07, KA1755A and KC0045F are presented in WellCAD plots (Appendices 1 to 3). The WellCAD plots consist of the following columns:

Boremap data	1: Length (Length along the borehole)
	2: Rock type
	3: Rock alteration
	4: Sealed fractures (frequency)
	5: Open and partly open fractures (frequency)
	6: Crush
Generalized geophysical data	7: Silicate density
	8: Magnetic susceptibility
	9: Natural gamma radiation
	10: Estimated fracture frequency
Interpretations	11: Description: Rock unit
	12: Stereogram for sealed fractures in rock unit (Wulff projection, blue symbols)
	13: Stereogram for open and partly open fractures in rock unit (Wulff projection, red symbols)
	14: Description: Possible deformation zone
	15: Stereogram for sealed fractures in possible deformation zone (Wulff projection, blue symbols)
	16: Stereogram for open and partly open fractures in possible deformation zone (Wulff projection, red symbols)

Appendix 1

Geological single-hole interpretation of KAS07

Title SINGLE HOLE INTERPRETATION KAS07

Site	ÄSPÖ	**Inclination [°]**	-59.09	**Elevation [m.a.s.l.]**	4.58
Borehole	KAS07	**Date of mapping**	1989-01-26 00:00:00	**Drilling Start Date**	1988-12-01 00:00:00
Diameter [mm]	56	**Coordinate System**	ÄSPÖ96	**Drilling Stop Date**	1988-12-01 00:00:00
Length [m]	603.880	**Northing [m]**	7229.66	**Surveying Date**	
Bearing [°]	217.60	**Easting [m]**	2215.40	**Plot Date**	2015-06-08 02:01:34

ROCKTYPE ÄSPÖ
- Fine-grained granite 511058
- Pegmatite 501061
- Ävrö granodiorite 501056
- Äspö diorite 501037
- Gabbroid-dioritoid 508107

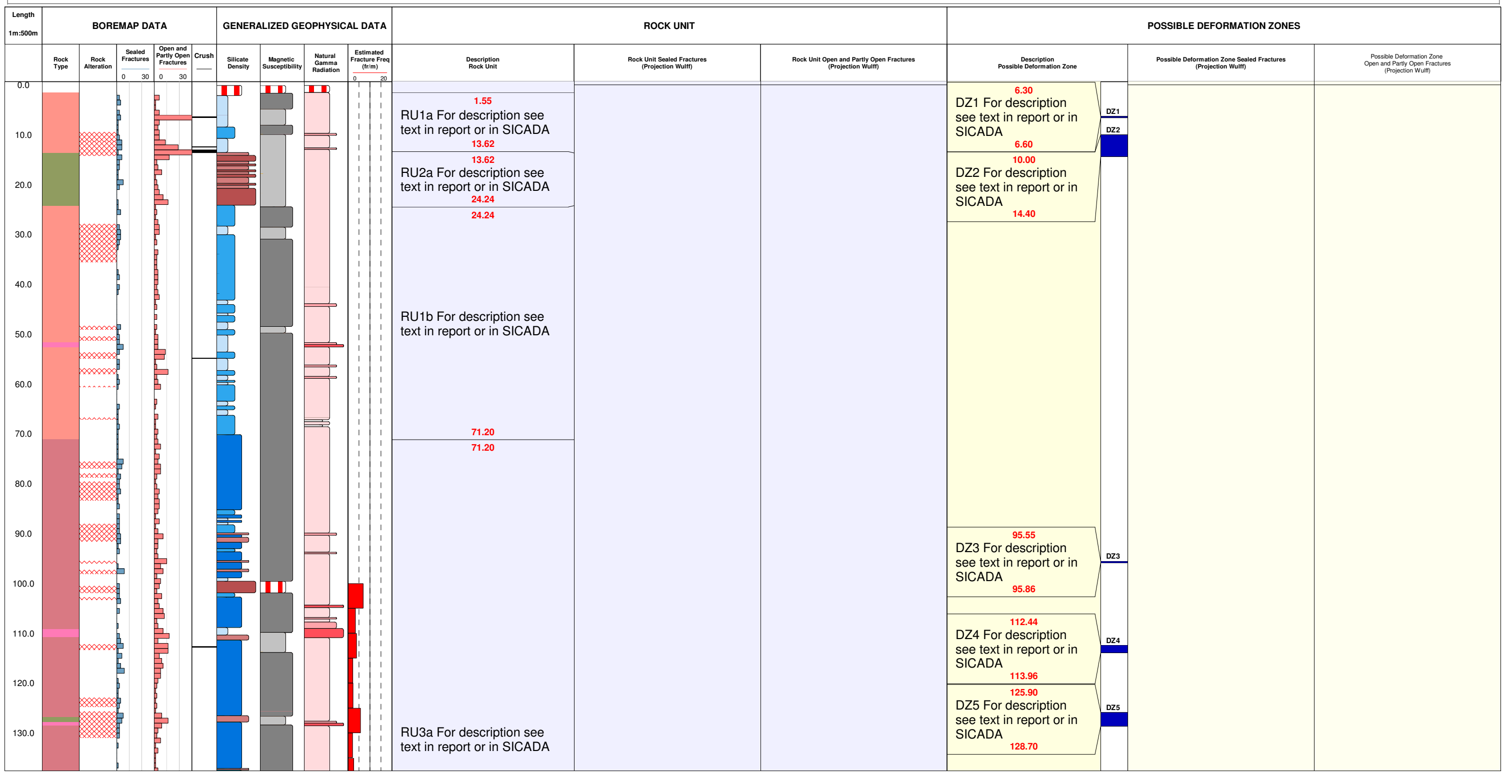
ROCK ALTERATION
- Oxidized
- Epidotisized

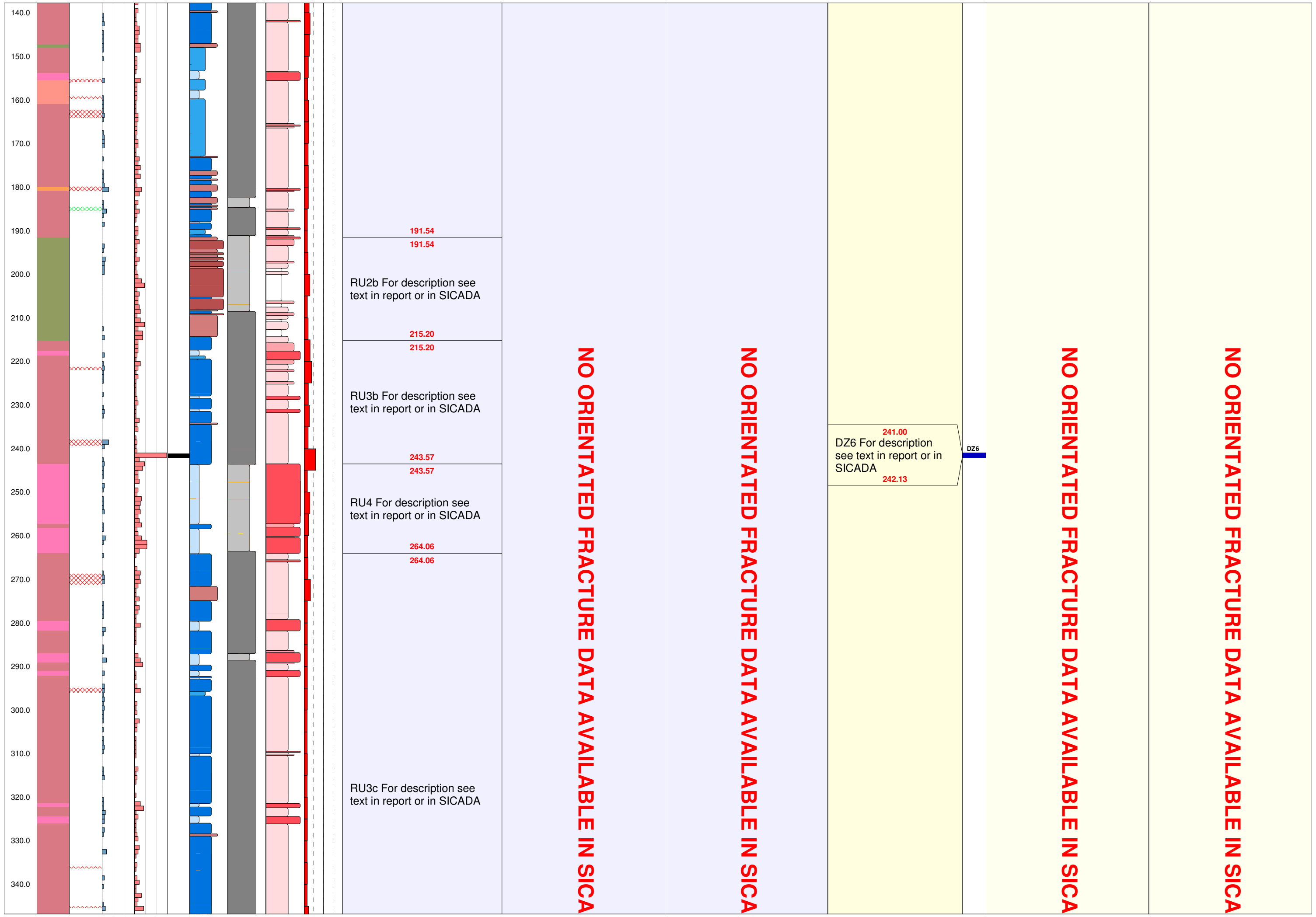
SILICATE DENSITY
- unclassified
- dens<2680
- 2680<dens<2730
- 2730<dens<2800
- 2800<dens<2890
- dens>2890

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

NATURAL GAMMA
- unclassified
- gam<10
- 10<gam<20
- 20<gam<30
- gam>30

DZ CONFIDENCE
- Confidence 3

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RU4 For description see text in report or in SICADA
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RU3c For description see text in report or in SICADA
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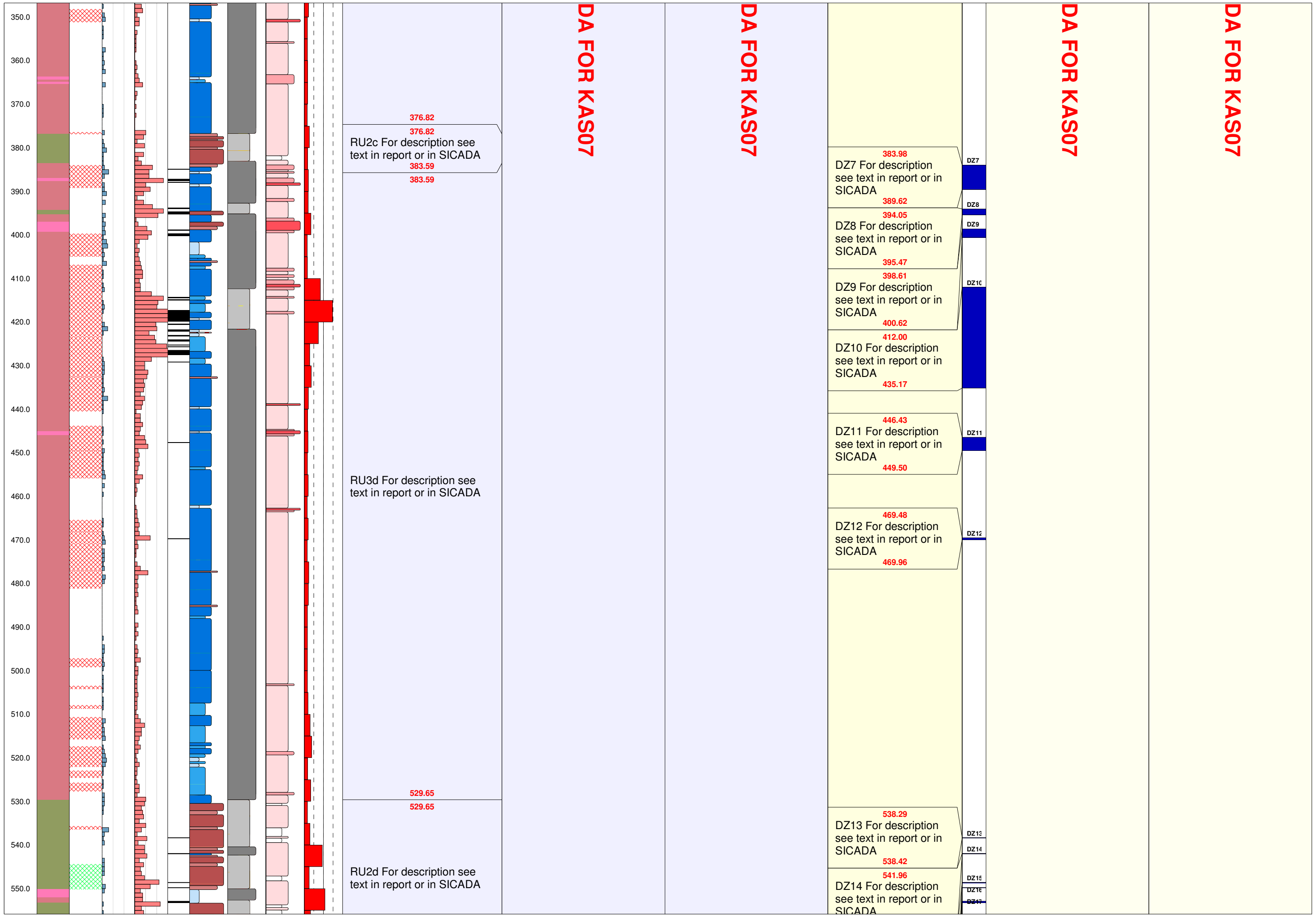
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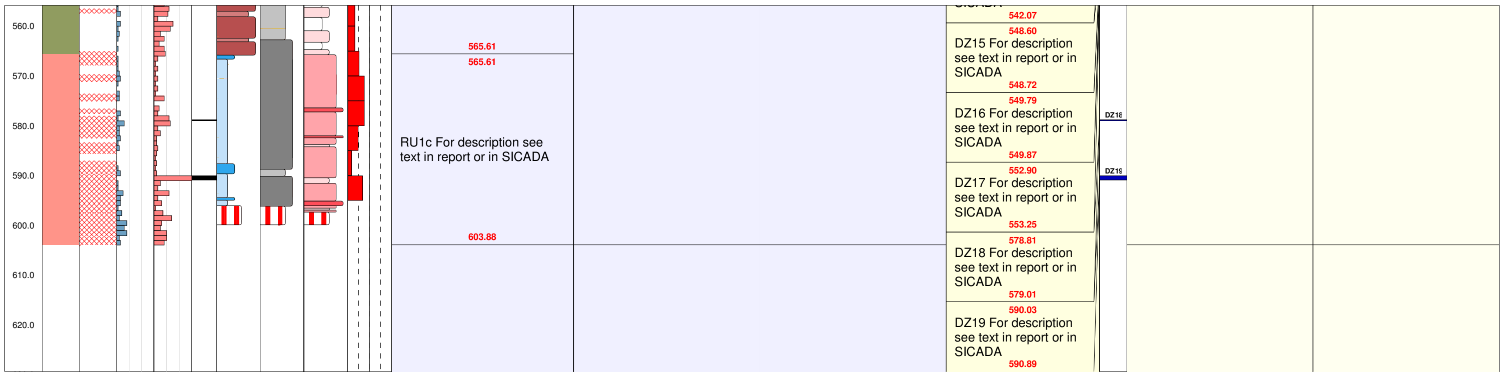
DA FOR KAS07

Page 3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Appendix 2

Geological single-hole interpretation of KA1755A

Title	SINGLE HOLE INTERPRETATION KA1755A				
Site	ÄSPÖ	**Inclination [°]**	0.00	**Elevation [m.a.s.l.]**	-237.79
Borehole	KA1755A	**Date of mapping**	1994-04-28 00:00:00	**Drilling Start Date**	1994-03-13 17:25:00
Diameter [mm]	56	**Coordinate System**	ÄSPÖ96	**Drilling Stop Date**	1994-04-06 14:05:00
Length [m]	320.580	**Northing [m]**	7389.81	**Surveying Date**	
Bearing [°]	0.00	**Easting [m]**	2060.87	**Plot Date**	2015-06-08 02:01:34

ROCKTYPE ÄSPÖ
- Fine-grained granite 511058
- Ävrö granodiorite 501056
- Äspö diorite 501037
- Gabbroid-dioritoid 508107
- Mylonite 508004
- Breccia 508002

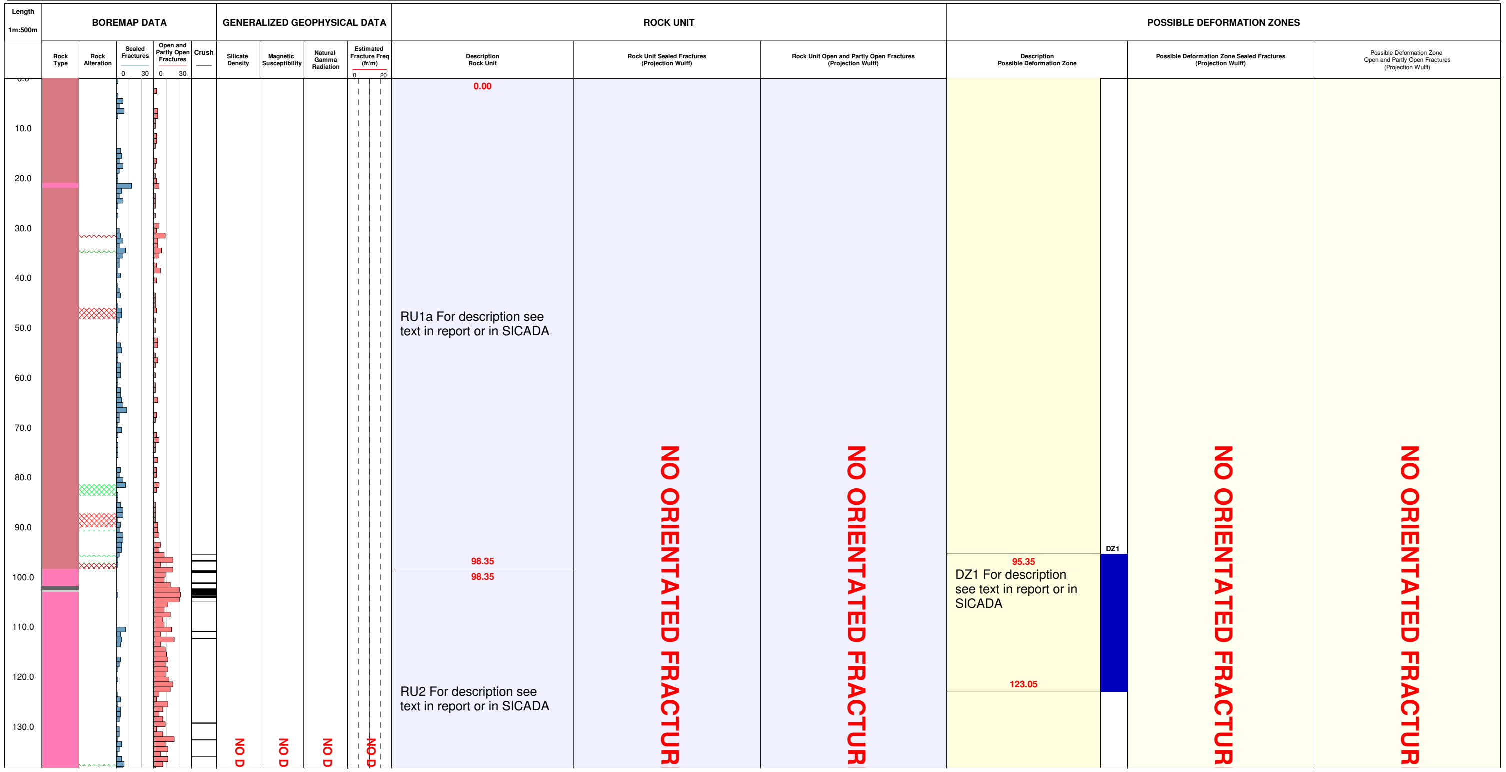
ROCK ALTERATION
- Oxidized
- Chloritisized
- Epidotisized

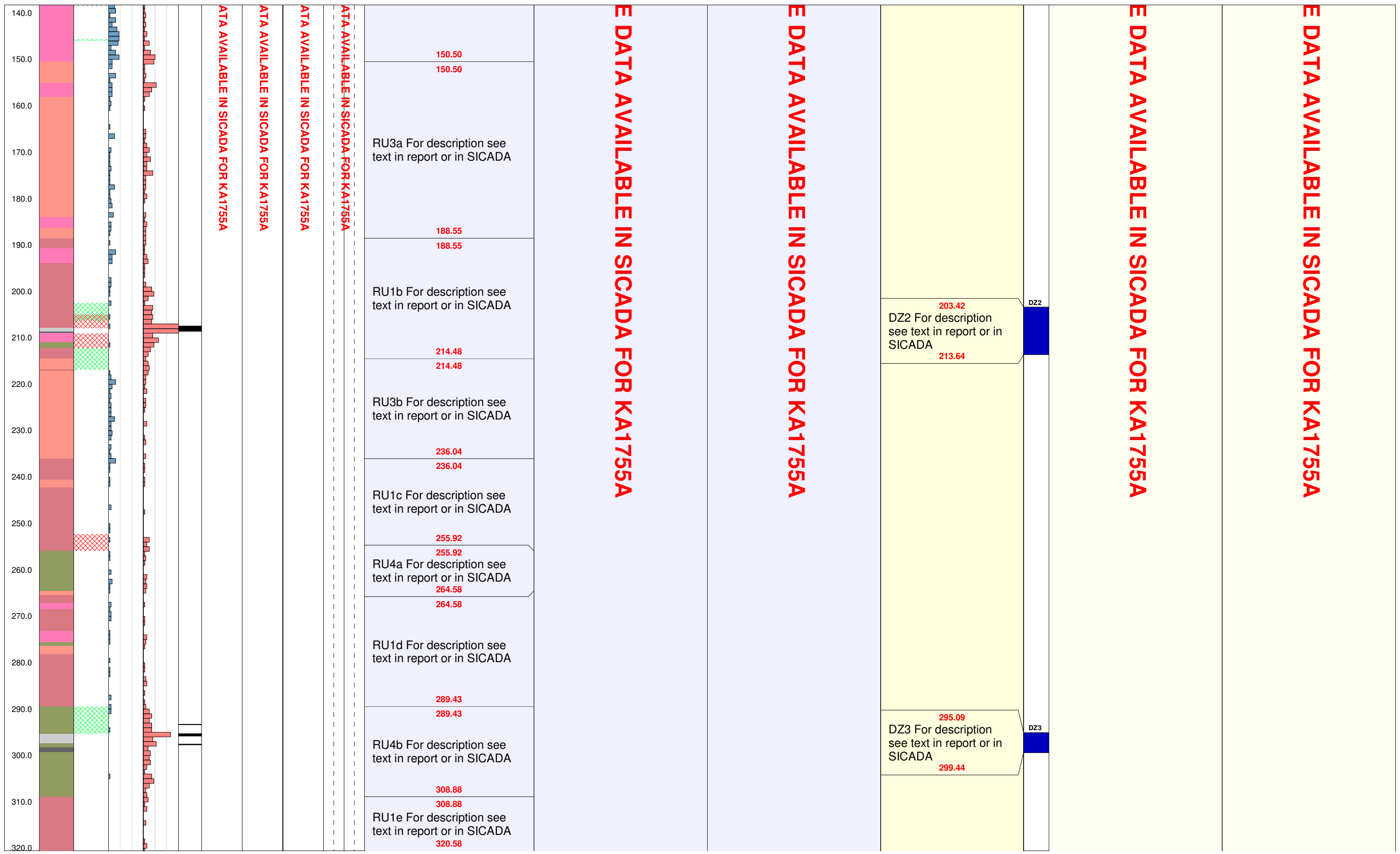
SILICATE DENSITY

SUSCEPTIBILITET

NATURAL GAMMA

DZ CONFIDENCE
- Confidence 3

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E DATA AVAILABLE IN SICADA FOR KA1755A

Appendix 3

Geological single-hole interpretation of KC0045F

Title	SINGLE HOLE INTERPRETATION KC0045F				
Site	ÄSPÖ	Inclination [°]	22.80	Elevation [m.a.s.l.]	-341.52
Borehole	KC0045F	Date of mapping	1993-10-08 00:00:00	Drilling Start Date	1993-09-20 13:10:00
Diameter [mm]	56	Coordinate System	ÄSPÖ96	Drilling Stop Date	1993-10-17 01:03:00
Length [m]	336.700	Northing [m]	7288.40	Surveying Date	
Bearing [°]	85.00	Easting [m]	2084.11	Plot Date	2015-06-08 02:01:34

ROCKTYPE ÄSPÖ
- Fine-grained granite 511058
- Pegmatite 501061
- Ävrö granodiorite 501056
- Äspö diorite 501037
- Gabbroid-dioritoid 508107

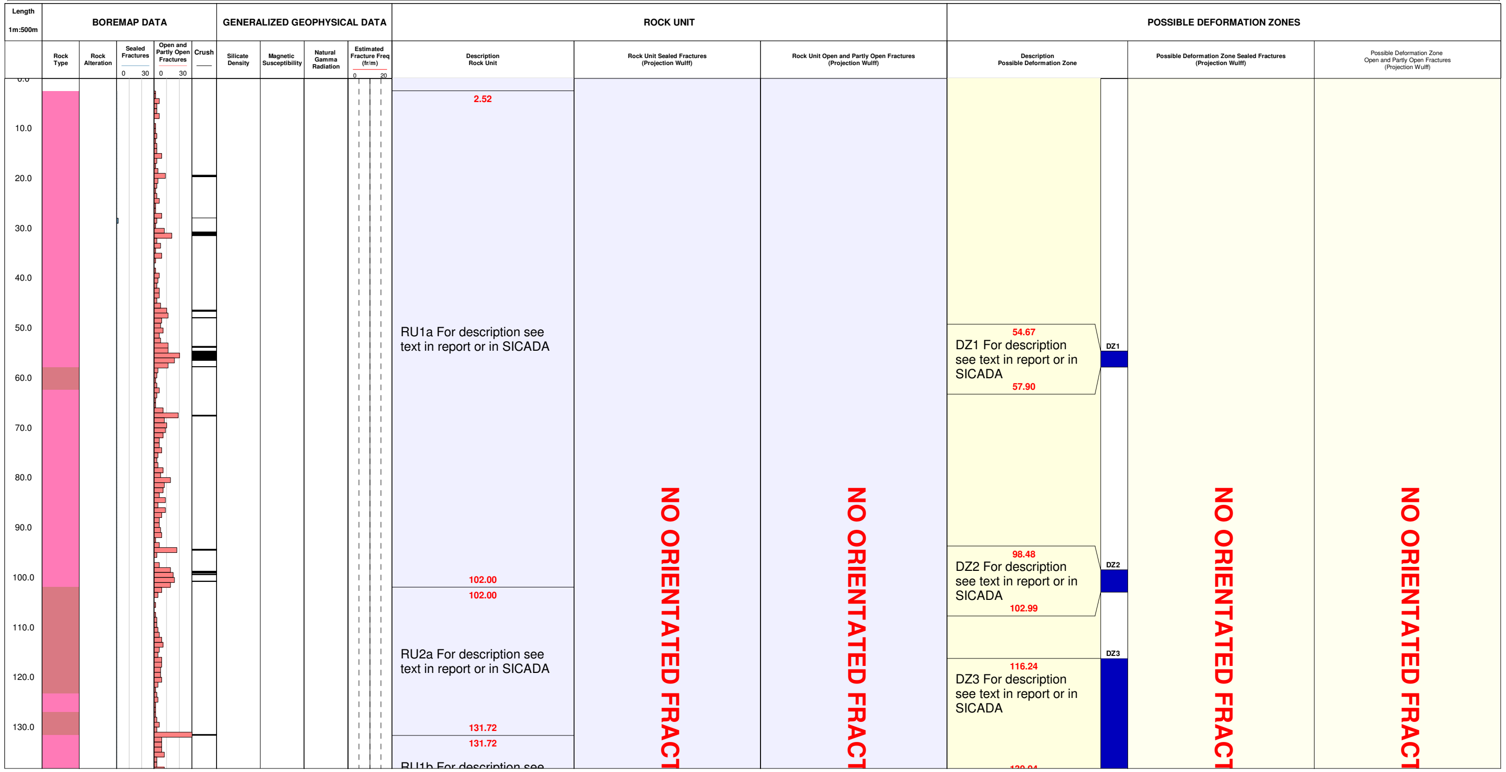
ROCK ALTERATION
- Oxidized
- Chloritisized
- Epidotisized

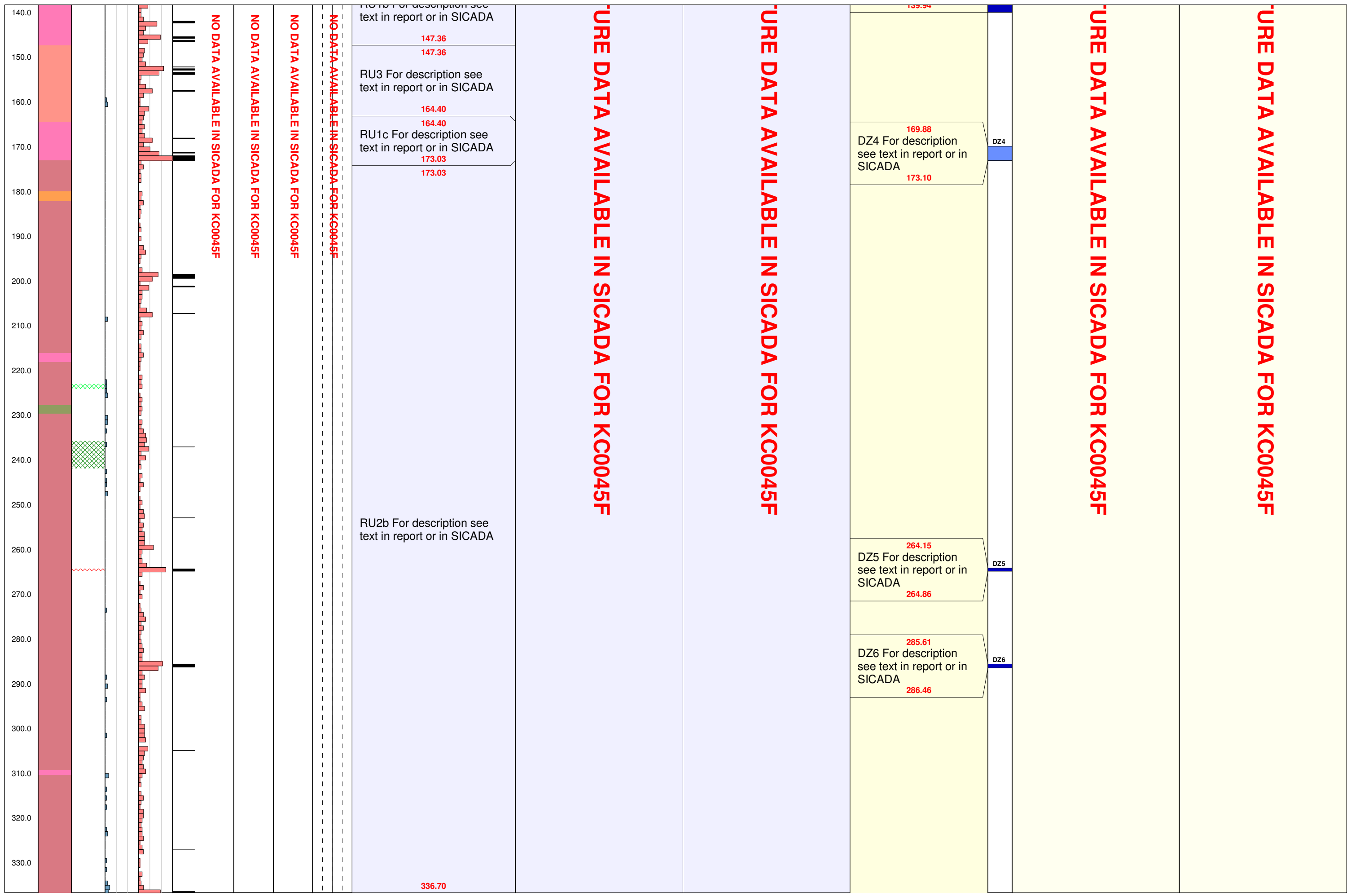
SILICATE DENSITY

SUSCEPTIBILITET

NATURAL GAMMA

DZ CONFIDENCE
- Confidence 2
- Confidence 3

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URE DATA AVAILABLE IN SICADA FOR KC0045F
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DZ4
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DZ5
285.61
DZ6 For description see text in report or in SICADA
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DZ6
URE DATA AVAILABLE IN SICADA FOR KC0045F
URE DATA AVAILABLE IN SICADA FOR KC0045F