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Abstract

This report presents the outcome from geological single-hole interpretation of the core drilled borehole KAS02 located on Äspö. The geological single-hole interpretation (SHI) is part of the work for the Äspö Site descriptive model, Äspö SDM. The aim of the work is from data from geological core mapping, interpreted geophysical logs, and borehole radar measurements identify different rock unit distribution in the boreholes and to identify the location and distribution of possible deformation zones in the borehole.

The geological mapping was initially performed with ABC800 Core Mapping system and afterwards converted into the Petrocore system. 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 parts of the borehole KAS02, a complete geological single-hole interpretation as was made in the Laxemar site investigations (SKB 2009) could not be performed.

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 the borehole KAS02.

The geological single-hole interpretation shows that the upper part (c. 300 m) of the borehole KAS02 is dominated by Ävrö granodiorite (501056). Several sections with mixture of gabbroid-dioritoid (508107), fine-grained granite (511058) and hybrid rock (505105) occur in this part of the borehole. The lower part (c. 600 m) of the borehole is dominated by Äspö diorite (501037) and some larger sections with fine-grained granite (511058) and one section with Ävrö granodiorite (501056). Subordinate rock types comprise occurrences of gabbroid-dioritoid (508107) and pegmatite (501061).

Eighteen possible deformation zones are identified in KAS02 (DZ1–DZ18).

Sammanfattning

Denna rapport presenterar resultatet från geologisk enhålstolkning av kärnborrhålet KAS02 beläget på Äspö. 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 med ABC800 kärnkarteringssystem och data överfördes till 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 KAS02 genomfördes inte en komplett geologisk enhålstolkning på det sätt den genomfördes under platsundersökningarna i Laxemar (SKB 2009).

Borrhålsradar genomfördes med den första generationen av radarantenner och utvärderingen och tolkningen av radardata genomfördes manuellt med fristående program och i olika steg. Radar riktantenn var inte heller tillgänglig vid tiden för undersökningarna.

Den geologiska enhålstolkningen visar att övre delen (ca 300 m) av kärnborrhålet KAS02 domineras av Ävrögranodiorit (501056). Ett antal sektioner med en blandning av gabbroid-dioritoid (508107), finkornig granit (511058) och hybridbergart (505105) förekommer i denna övre del av borrhålet. Den nedre delen (ca 600 m) av borrhålet domineras av Äspödiorit (501037) och en del större sektioner med finkornig granit (511058) och en sektion med Ävrögranodiorit (501056). Underordnade bergarter utgörs av gabbroid-dioritoid (508107) och pegmatit (501061).

Arton möjliga deformationszoner har identifierats i KAS02 (DZ1–DZ18).

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 exist for some parts of the borehole KAS02, complete input data for the geological single hole interpretation is not available as for the site investigations at 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 borehole KAS02 at Äspö (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 F140-08-037. The controlling documents for performing this activity are listed in Table 1-1. Activity plan, method description and method instruction are SKB's internal controlling documents. The original lithological mapping and its used nomenclature was translated into an updated SKB nomenclature based on merging Äspö nomenclature with Laxemar-Simpevarp nomenclature and was converted into the Boremap system. The used rock Rock type nomenclature is presented in Table 1-2 that has been used is in accordance with method instruction SKB MD 132.004.

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

Activity plan	Number	Version
Geologisk enhålstolkning av KAS02	AP TD F140-10-07	1.0
Method description	**Number**	**Version**
Metodbeskrivning för geologisk enhålstolkning	SKB MD 810.003	3.0

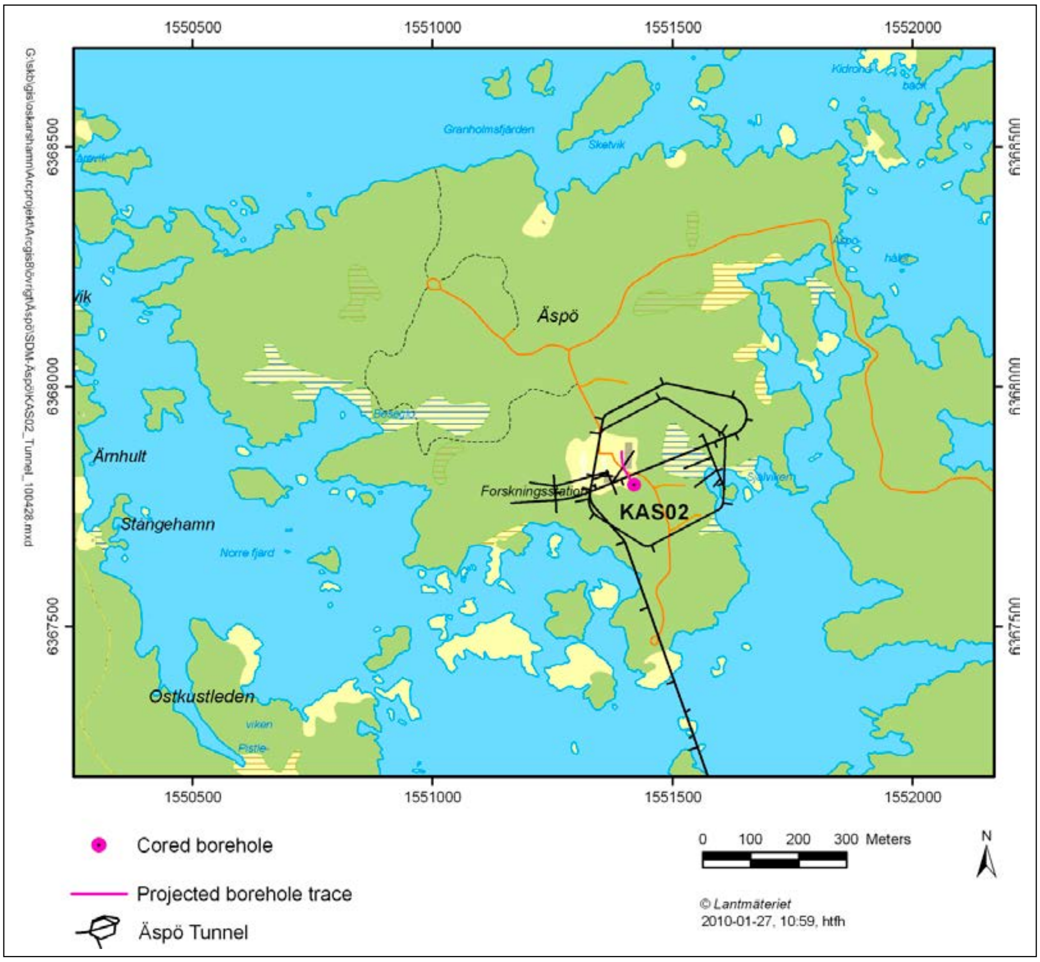

__Figure 1-1.__ Map showing the position of the cored borehole KAS02.

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 Objectives

This report presents the outcome from geological single-hole interpretation of the core drilled borehole KAS02 located on Äspö. The geological single-hole interpretation (SHI) is part of the work for the Äspö Site descriptive model SDM. The aim of the work is from data from geological core mapping, interpreted geophysical logs, and borehole radar measurements identify different rock unit distribution in the boreholes and to identify possible deformation zones location and distribution in the borehole.

The geological mapping of the cored boreholes involves a documentation of the character of the bedrock in the drill core with help of a mapping program developed on the platform/computer system ABC800 during the 1980:s, later converted into Petrocore system developed for PC, which was then converted to the Boremap system, the latter developed for SKB. The work involved an integrated interpretation of data from the geological mapping, different borehole geophysical logs and borehole radar data available for the core drilled borehole KAS02. The methodology for geological single-hole interpretation has been developed during the site investigations at 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 in a borehole.

The result from the geological single-hole interpretation is presented in a WellCAD plot (Appendix 1) and described in this report.

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 borehole KAS02:

- Boremap data converted from geological mapping performed in ABC800 Core Mapping system which was converted into the Petrocore system (Stråhle 1989).
- Generalized geophysical logs and their interpretation (Sehlstedt and Triumf 1988, Mattsson 2011).
- Radar data and their interpretation (Niva and Gabriel 1988).

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, 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: Open alteration
2.1: Rock type	4.2: Sealed 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: Open total	6.3: Natural gamma radiation
3.2: Sealed total	6.4: Estimated fracture frequency (fr/m)
3.3: Fracture orientation open/sealed	**7: Geophysics**
3.4: Fracture orientation broken/unbroken	7.1: Magnetic susceptibility
3.5: Total fractures	7.2: Sonic
3.6: RQD	7.3: Radar directional primary/radar dipole 1
	7.4: Radar directional alternative

The geophysical logs 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.

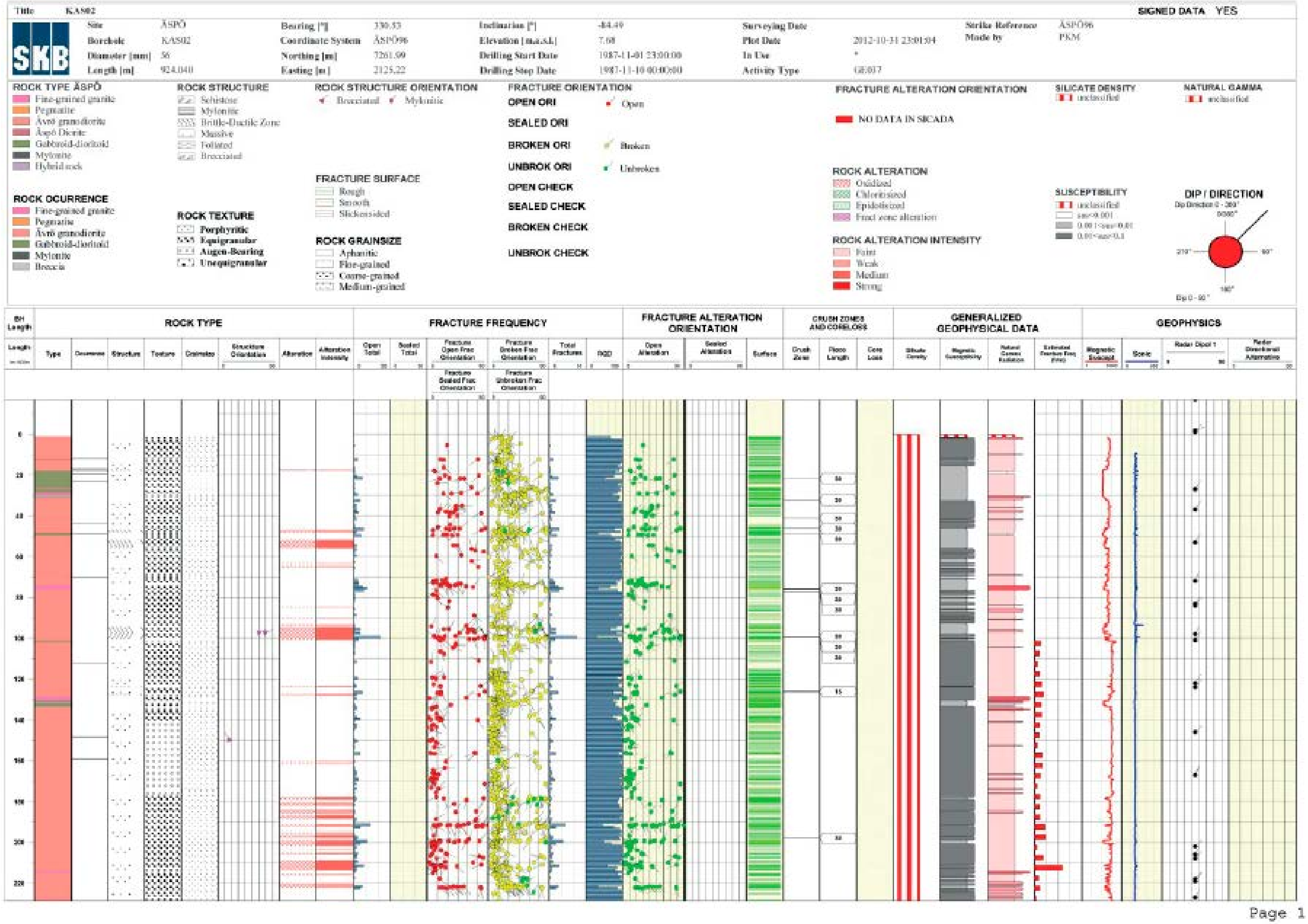

Figure 2-1. Example of WellCAD plot (from borehole KAS02 at Äspö) used as a basis for the geological single-hole interpretation.

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 of radar anomalies and the orientation of radar reflectors, e.g. their alpha angle against the borehole axis within the possible deformation zones are commented upon in the text that describes these deformation 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. 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.

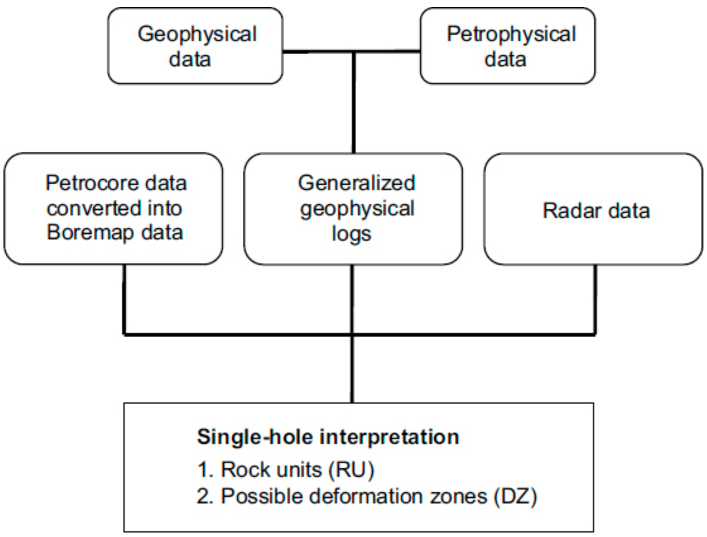

Figure 2-2. *Schematic block-scheme for data used in the geological single-hole interpretation.*

The procedure to identify possible deformation zones is primarily based on inspection of the drill cores. Each identified possible deformation zone is defined in terms of the borehole length interval and provided with a brief description, which includes information of the rock types affected by the possible deformation zone, fracture character and frequency in general terms, as well as the existence of breccias, mylonites, cataclasites and bedrock alteration. A reassessment of each interval was done at the basis of the digital drill core images during the data compilation for this report. If judged necessary, the descriptions are adjusted. The confidence in the interpretation of a possible deformation zone is assigned according to three classes: 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 the interpreted units above. 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 description (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, have all assisted in the identification of the deformation zones.

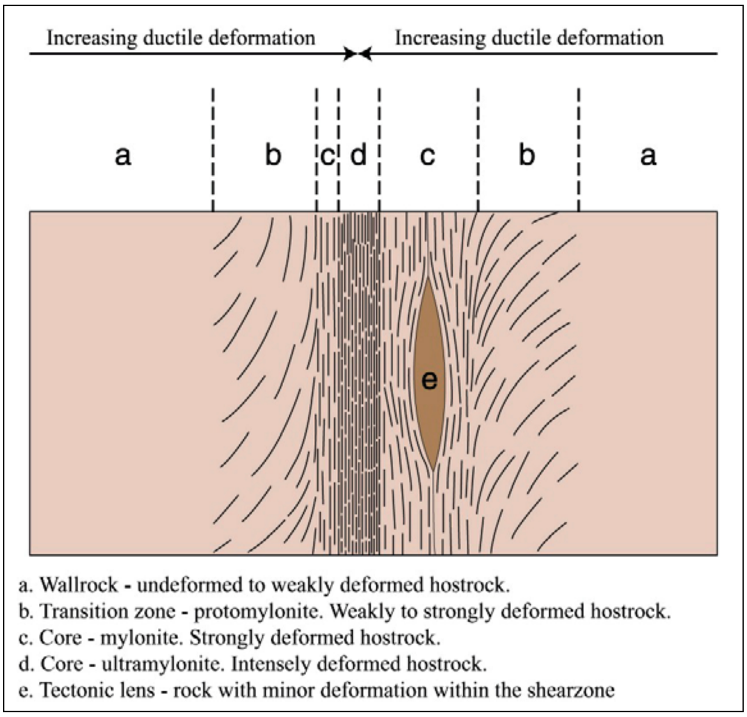

Figure 2-3. *Schematic example of a ductile shear zone. Homogeneous rock which is deformed under low- to medium-grade metamorphic conditions (after Munier et al. 2003).*

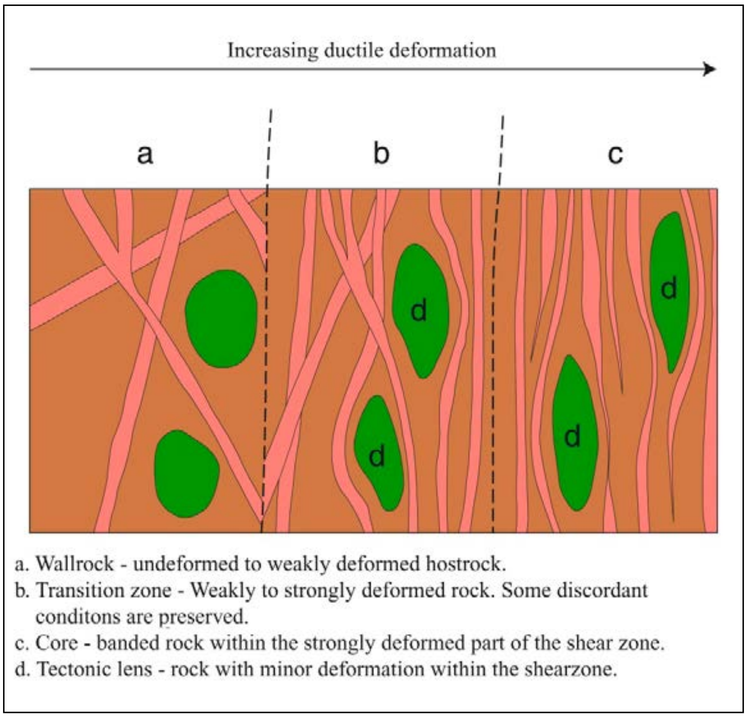

Figure 2-4. *Schematic example of a ductile shear zone. Heterogeneous rock which is deformed under low- to high-grade metamorphic conditions (after Munier et al. 2003).*

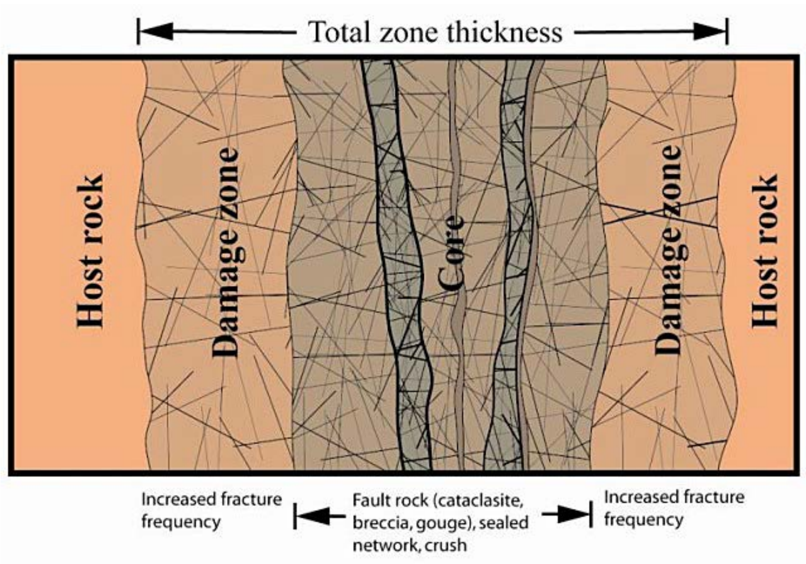

Figure 2-5. *Schematic example of a brittle deformation zone (modified from Munier et al. 2003).*

Since the frequency of fractures is of key importance for the definition of the possible deformation zones, a moving average plot for this parameter is shown for the cored borehole KAS02 (Figure 2-6). 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 a diagram (Figure 2-6).

Observation of occurrence of radar anomalies was used during the identification of deformation zones.

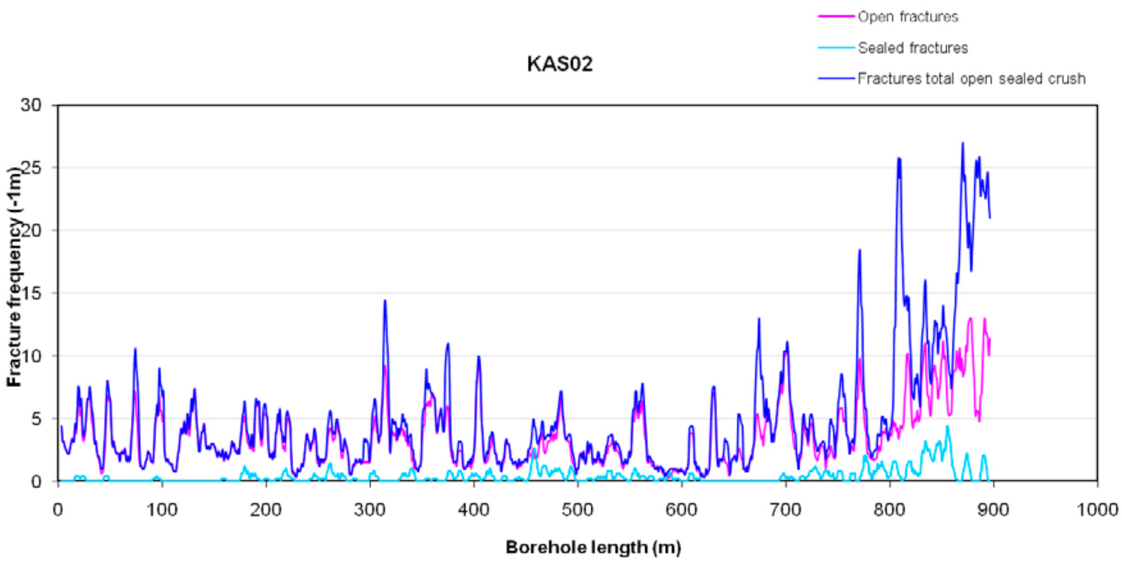

Figure 2-6. *Fracture frequency plot for KAS02. Moving average with a 5 m window and 1 m steps.*

2.3 Nonconformities

The geological mapping was made with ABC800 Core Mapping and afterwards converted into the Petrocore system. In order to evaluate and present the geological data in question for the Single-hole Geological Interpretation (SHI) in a similar way as during the Laxemar site investigation (SKB 2009), the Petrocore data was converted into the Boremap system.

Borehole TV (BIPS) was not available at the time for measurements of the borehole, and therefore, the geological mapping was solely based on inspection of the drill core.

The geophysical logging measurements were performed after the reaming of the upper 100 m of KAS02. The increased borehole diameter has caused decreased signal strength and decreased resolution in many of the measured parameters, which affects the result and interpretation of the logging data in the reamed part of the borehole. Note that the density data is based on sampling of the drill core and not logging of the borehole.

Density logging (gamma-gamma) was not performed in KAS02. However, a database comprising density measurements on 121 core samples was used to support the rock type classification.

The borehole radar measurements were performed with the first generation of radar antenna and evaluation of radar data was at that time performed more or less manually by using different programs for the different steps of evaluation. Furthermore, directional antenna was not available during these measurements.

3 Results

The detailed result of the single-hole interpretation is presented as print-out from the software WellCAD (Appendix 1 for KAS02). Orientations are related to Äspö96 North.

3.1 KAS02

3.1.1 Rock units

The borehole consists of four rock units (RU1–RU4). However, due to repetition of RU1 (RU1a, RU1b, RU1c, RU1d and RU1e), RU2 (RU2a, RU2b, RU2c and RU2d), RU3 (RU3a, RU3b and RU3c) and RU4 (RU4a, RU4b and RU4c) the borehole can be divided into fifteen sections. The confidence in the interpretation of a rock unit is assigned according to three classes: 3 = high, 2 = medium and 1 = low.

0.90–17.92 m

RU1a: Totally dominated by Äspö diorite (501037). Subordinate rock types comprise fine-grained granite (511058) and a thin mylonite (508004). The Äspö diorite (501037) has a density of c. 2,760 kg/m^3 (1 sample). Confidence level = 3.

17.92–31.55 m

RU2a: Totally dominated by gabbroid-dioritoid (508107). Subordinate rock types comprise fine-grained granite (511058), hybrid rock (505105) and sparse occurrence of Ävrö granodiorite (501056). Confidence level = 3.

31.55–269.12 m

RU3a: Totally dominated by Ävrö granodiorite (501056). Subordinate rock types comprise fine-grained granite (511058), gabbroid-dioritoid (508107), hybrid rock (505105) and pegmatite (501061). The Ävrö granodiorite has a density of c. 2,693 ± 25 kg/m^3 (30 samples). Confidence level = 3.

269.12–280.34 m

RU2b: Similar lithological association as in RU2a, i.e mixture of gabbroid-dioritoid (508107), fine-grained granite (511058) and hybrid rock (505105), but slightly dominated by fine-grained granite (511058). Furthermore, Ävrö granodiorite (501056) is more abundant than in RU2a. Confidence level = 3.

280.34–303.10 m

RU3b: Totally dominated by Ävrö granodiorite (501056). Subordinate rock type comprises fine-grained granite (511058). The Ävrö granodiorite has a density of c. 2,683 ± 6 kg/m^3 (3 samples). Confidence level = 3.

303.10–318.87 m

RU2c: Similar lithological association as in RU2a and RU2b, i.e mixture of gabbroid-dioritoid (508107), fine-grained granite (511058) and hybrid rock (505105), but more or less equal amounts of fine-grained granite (511058) and gabbroid-dioritoid (508107). Subordinate rock type comprises very sparse occurrences of pegmatite (501061). Confidence level = 3.

318.87–352.97 m

RU1b: Totally dominated by Äspö diorite (501037). Subordinate rock types comprise pegmatite (501061), gabbroid-dioritoid (508107) and very sparse occurrence of fine-grained granite (511058). The Äspö diorite has a density of c. 2,813 ± 59 kg/m^3 (4 samples). Confidence level = 3.

352.97-375.47 m

RU4a: Totally dominated by fine-grained granite (511058). The fine-grained granite is characterized by an increased fracture frequency (outside DZ9) and is locally foliated. Confidence level = 3.

375.47–395.77 m

RU1c: Totally dominated by Äspö diorite (501037). Subordinate rock type comprises fine-grained granite (511058) and sparse occurrences of pegmatite (501061). The Äspö diorite has a density of c. 2,775 ± 35 kg/m^3 (2 samples). Confidence level = 3.

395.77–414.73 m

RU2d: Similar lithological association as in RU2a, RU2b and RU2c, i.e gabbroid-dioritoid (508107) and fine-grained granite (511058) are important components. Furthermore, Äspö diorite (501037) is an important lithological component and constitutes c. 45 % of the rock unit. Subordinate rock types comprise Ävrö granodiorite (501056) and pegmatite (501061). Confidence level = 3.

414.73–654.45 m

RU1d: Totally dominated by Äspö diorite (501037). Subordinate rock types comprise sparse occurrences of pegmatite (501061), fine-grained granite (511058), Ävrö granodiorite (501056) and gabbroid-dioritoid (508107). The Äspö diorite has a density of c. 2,775 ± 26 kg/m^3 (18 samples). Confidence level = 3.

654.45–709.01 m

RU4b: Totally dominated by fine-grained granite (511058). The fine-grained granite is characterized by an increased fracture frequency (outside DZ16). Subordinate rock type comprises very sparse occurrence of pegmatite (501061). Confidence level = 3.

709.01–865.34 m

RU1e: Totally dominated by Äspö diorite (501037). Subordinate rock types comprise fine-grained granite (511058), pegmatite (501061), gabbroid-dioritoid (508107) and one short section (739.170–742.620 m) of hybrid rock (505105) with intercalated short sections of Ävrö granodiorite (501056). Very sparse occurrence of Ävrö granodiorite (501056) also occurs outside the hybrid rock (505105). The Äspö diorite has a density of c. 2,746 ± 19 kg/m^3 (14 samples). Confidence level = 3.

865.34–909.50 m

RU4c: Totally dominated by fine-grained granite (511058). Confidence level = 3.

909.50–924.04 m

RU3c: Totally dominated by Ävrö granodiorite (501056). The Ävrö granodiorite has a density of c. 2,680 kg/m^3 (1 sample). Confidence level = 3.

3.1.2 Possible deformation zones

Eighteen possible deformation zones have been recognized in KAS02 (DZ1–DZ18). The confidence in the interpretation of a possible deformation zone is assigned according to three classes: 3 = high, 2 = medium and 1 = low.

48.12–49.57 m

DZ1: Low-grade ductile shear zone slightly increased frequency of open fractures and one crush (48.37–48.38 m). The geophysical logging data show a distinct decrease in p-wave velocity at 49.4 m and decreased magnetic susceptibility along the entire section. The host rock is dominated by gabbroid-dioritoid (508107). Subordinate rock type comprises Ävrö granodiorite (501056). Confidence level = 3.

73.88–76.06 m

DZ2: Brittle deformation zone characterized by increased frequency of open fractures and two crush at 75.61–75.86 m and 75.95–76.06 m. The section is characterized by three distinct anomalies of decreased p-wave velocity and generally decreased magnetic susceptibility. The host rock is dominated by fine-grained granite (511058). Subordinate rock type comprises very sparse occurrence of Ävrö granodiorite (501056). Confidence level = 3.

94.43–100.05 m

DZ3: Brittle deformation zone characterized by increased frequency of open fractures, oxidation and three crush at 99.18–99.27 m, 99.39–99.48 m and 99.55–99.59 m. At 99.5 m there is a distinct decrease in the p-wave velocity. The entire section shows decreased magnetic susceptibility and there is an anomaly in the vertical temperature gradient, which indicates a water-bearing fracture. One non-oriented radar reflector of medium strength occurs at 98 m with an angle of 22° to the borehole axis. The host rock is totally dominated by Ävrö granodiorite (501056). Confidence level = 3.

191.37–192.23 m

DZ4: Brittle deformation zone characterized by increased frequency of open fractures and oxidation. The geophysical logging data show decreased magnetic susceptibility, resistivity and p-wave velocity. The host rock is totally dominated by Ävrö granodiorite (501056). Confidence level = 3.

199.20–200.51 m

DZ5: Brittle deformation zone characterized by increased frequency of open fractures and oxidation. The geophysical logging data show decreased magnetic susceptibility, resistivity and p-wave velocity. The host rock is totally dominated by Ävrö granodiorite (501056). Confidence level = 3.

211.40–211.59 m

DZ6: Brittle deformation zone characterized by slightly increased frequency of open fractures and oxidation. The deformation is concentrated at 211.44–211.51 m. The geophysical logging data show a strong decrease in resistivity and p-wave velocity and partly decreased magnetic susceptibility. The host rock is totally dominated by Ävrö granodiorite (501056). Confidence level = 3.

309.68–317.00 m

DZ7: Brittle deformation zone characterized by increased frequency of open fractures and four crush at 312.99–313.03 m, 315.01–315.36 m, 316.21–316.41 m and 316.77–316.81 m. The section is characterized by narrow but distinct anomalies of decreased p-wave velocity and significantly decreased resistivity and magnetic susceptibility. There is also a major anomaly in the vertical temperature gradient, which indicates water-bearing fractures. The caliper data show that the borehole diameter is increased along the section. One non-oriented radar reflector of medium strength occurs at 316 m with an angle of 35° to the borehole axis. The host rock is dominated by gabbroid-dioritoid (508107) and to a lesser extent fine-grained granite (511058). Confidence level = 3.

352.46–356.74 m

DZ8: Brittle to ductile deformation zone (based on inspection of drillcore during SHI). Two crush at 352.80–352.97 m and 356.14–356.28 m. The geophysical logging data show decreased magnetic susceptibility, resistivity and p-wave velocity. One non-oriented radar reflector of medium strength occurs at 355 m with an angle of 30° to the borehole axis. The host rock is dominated by fine-grained granite (511058). Subordinate rock types comprise gabbroid-dioritoid (508107) and Äspö diorite (501037). Confidence level = 3.

374.90–375.72 m

DZ9: Brittle deformation zone characterized by slightly increased frequency of open fractures and one crush at 375.35–375.41 m. The magnetic susceptibility is decreased. There are no other anomalies in the geophysical logging data. One non-oriented radar reflector of medium strength occurs immediately below the DZ at 376 m with an angle of 40° to the borehole axis. The host rock is dominated by fine-grained granite (511058) and to a lesser extent Äspö diorite (501037). Confidence level = 3.

7403.07–406.82 m

DZ10: Brittle deformation zone characterized by increased frequency of open fractures. The geophysical logging data indicate slightly decreased magnetic susceptibility, p-wave velocity and resistivity. The host rock is dominated by fine-grained granite (511058). Subordinate rock types comprise gabbroid-dioritoid (508107) and Äspö diorite (501037). Confidence level = 3.

455.80–456.00 m

DZ11: Low-grade ductile shear zone. There are no significant anomalies in the geophysical logging data along the section. The host rock is dominated by mylonite (508004) and to a lesser extent Äspö diorite (501037). Confidence level = 3.

464.10–466.75 m

DZ12: Low-grade ductile to brittle-ductile shear zone. Inhomogeneous alteration, oxidation and sparse occurrence of sealed network (based on inspection of drillcore during SHI). The magnetic susceptibility is partly decreased but there are no other significant anomalies in the geophysical logging data. One non-oriented radar reflector of medium strength occurs immediately below the DZ at 467 m with an angle of 25° 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 pegmatite (501061). Confidence level = 3.

533.60–534.60 m

DZ13: Brittle deformation zone characterized by slightly increased frequency of open fractures and some oxidation. The geophysical logging data show decreased resistivity and p-wave velocity. The host rock is totally dominated by Äspö diorite (501037). Confidence level = 3.

557.00–564.15 m

DZ14: Brittle deformation zone characterized by slightly increased frequency of open fractures, inhomogeneously distributed sealed network with a small angle to the borehole axis (based on inspection of drillcore during SHI), some epidotization and oxidation and two crush at 562.48–562.53 m and 564.01–564.07 m. The geophysical logging data show partly decreased magnetic susceptibility and resistivity. The host rock is totally dominated by Äspö diorite (501037). Confidence level = 3.

629.92–631.45 m

DZ15: Brittle deformation zone characterized by increased frequency of open fractures and oxidation. The geophysical logging data show significantly decreased magnetic susceptibility, resistivity and p-wave velocity. One non-oriented radar reflector of medium strength occurs immediately below the DZ at 632 m with an angle of 40° to the borehole axis. The host rock is totally dominated by Äspö diorite (501037). Confidence level = 3.

672.50–674.00 m

DZ16: Brittle deformation zone characterized by slightly increased frequency of open fractures and two crush at 672.67–672.90 m and 673.58–673.71 m. The geophysical logging data show partly decreased magnetic susceptibility, resistivity and p-wave velocity. The host rock is totally dominated by fine-grained granite (511058). Confidence level = 3.

766.00–773.30 m

DZ17: Brittle deformation zone characterized by slightly increased frequency of open fractures, schistosity, some oxidation and six crush at 769.10–769.16 m, 769.43–769.59 m, 769.76–769.86 m, 771.28–771.60 m, 771.68–772.02 m, 772.44–772.52 m. A significant low resistivity anomaly is centered at 770.1 m. The entire section is characterized by partly decreased p-wave velocity and magnetic susceptibility. One non-oriented strong radar reflector occurs immediately below the DZ at 774 m with an angle of 7° to the borehole axis. The radar reflector is considered to be one of the strongest radar reflectors in the borehole. 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.

806.00–924.04 m

DZ18: The deformation zone has been divided into five sections depending on varying geological character, see below. The geophysical logging data show that the entire section 806.00–924.04 is characterized by various degrees of decreased magnetic susceptibility, p-wave velocity and generally decreased bulk resistivity. There are also several significant anomalies in the vertical temperature gradient (indicating in- or outflow of water) and a number of distinct caliper anomalies. The radargram shows an abrupt decrease in radar range and decrease in radar amplitude from about 790 m and below, with its most intense part between 860 m to 905 m. This indicates increased conductivity in the rock surrounding the borehole, i.e. increased salinity or increased fracturing of the rock. Confidence level = 3.

806.00–819.30 m: The section is characterized by increased frequency of open fractures, oxidation and sixteen crush which in total constitute 4.63 m of this part of the deformation zone. The resistivity is greatly decreased (below 1,000 ohm-m) in the interval 809–813 m, which indicates heavily crushed rock. One caliper anomaly is located at 813.5 m and there is a distinct vertical temperature gradient anomaly, which indicates water-bearing fractures. There are several narrow intervals with decreased p-wave velocity and the magnetic susceptibility is partly decreased. One non-oriented weak radar reflector occurs at 811 m with an angle of 35° to the borehole axis. The host rock is totally dominated by Äspö diorite (501037). Subordinate rock type comprises very sparse occurrence of pegmatite (501061).

819.30–835.56 m: The section is characterized by slightly increased frequency of open fractures, oxidation (but to a lesser extent than in the section 806.00–819.30 m) and five crush which in total constitute 0.71 m of this part of the deformation zone. The resistivity is decreased, but not as much as along the section 809–813 m. In the interval 819–826 m there are several distinct low p-wave velocity anomalies and an anomaly in the vertical temperature gradient, which indicates water-bearing fractures. In the interval 826–835.56 m there are only minor anomalies in the geophysical logging data. The host rock is totally dominated by Äspö diorite (501037). Subordinate rock types comprise sparse occurrences of Ävrö granodiorite (501056), fine-grained granite (511058) and pegmatite (501061).

835.56–865.34 m: The section is characterized by inhomogeneously distributed low-grade, ductile shear foliation (based on inspection of drillcore during SHI) , slightly increased frequency of open fractures, oxidation and six crush which in total constitute 0.69 m of this part of the deformation zone. The section is characterized by partly decreased resistivity, p-wave velocity and magnetic susceptibility. Close to the end of this section, in the interval 864.0–866.0 m, the p-wave velocity and resistivity are significantly decreased and there is a major caliper anomaly. The resistivity decreases down below100 ohm-m. There is also a significant anomaly in the vertical temperature gradient. The combination of physical properties indicates heavily crushed rock and the occurrence of significant water-bearing fracture(s). One non-oriented weak radar reflector occurs at 863 m with an angle of 45° to the borehole axis. The host rock is dominated by Äspö diorite (501037). Subordinate rock types comprise sparse occurrences of mylonite (508004), gabbroid-dioritoid (508107) and pegmatite (501061).

865.34–914.10 m: The section is characterized by increased frequency of open fractures, oxidation, chloritization and 55 crush which in total constitute 16.78 m of this part of the deformation zone. The entire section is characterized by significantly decreased bulk resistivity, bulk p-wave velocity and magnetic susceptibility. Several narrow low resistivity and low p-wave velocity anomalies occur on top of the general bulk decrease in these parameters. At c. 879.0 m, 883.7 m and 899.4 m there are distinct caliper anomalies. There is also a major anomaly in the vertical temperature gradient. This combination of physical properties indicates heavily crushed rock and the occurrence of significant water-bearing fracture(s). Two non-oriented weak radar reflectors occur at 866 m and 912 m with angles of 25° and 40° to the borehole axis. The host rock is totally dominated by fine-grained granite (511058).

914.10–924.04 m: The section is characterized by somewhat increased frequency of open fractures, oxidation and seven crush which in total constitute 0.30 m of this part of the deformation zone. The geophysical logging data show decreased magnetic susceptibility and partly decreased resistivity and p-wave velocity. One non-oriented weak radar reflector occurs at 923 m with an angle of 40° towards the borehole axis. The host rock is totally dominated by Ävrö granodiorite (501056).

4 Discussion

The geological mapping was initially made with ABC800 Core Mapping system and afterwards converted into the Petrocore system. 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 (SHI) in a similar way as was 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, 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 borehole KAS02. The borehole documentation from the older boreholes at Äspö, like KAS02, is too sparse to allow the full application of the established and complete SHI methodology. When BIPS (borehole TV) 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 borehole KAS02. 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. Note that the absolute value of the density is based on sampling of the drill core and petrophysical measurements of the drill cores and is not based on geophysical logging in the borehole. Density logging (gamma-gamma) was not performed in KAS02. However, a database comprising density measurements on 121 core samples was used to support the rock type classification.

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 the borehole KAS02. The use of radar data is listed in the description of each deformation zone (DZ) unit in Section 3.1.2. The correlation between radar reflectors and geological structures has been studied elsewhere (see for example Carlsten et al. 1995).

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Appendix 1

Geological single-hole interpretation of KAS02

The result from the geological single-hole interpretation of KAS02 is presented in a WellCAD plot (Appendix 1). The WellCAD plot consists 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).

Title SINGLE HOLE INTERPRETATION KAS02

Site	ÄSPÖ	**Inclination [°]**	-84.49	**Elevation [m.a.s.l.]**	7.68
Borehole	KAS02	**Date of mapping**	1988-02-05 00:00:00	**Drilling Start Date**	1987-11-01 23:00:00
Diameter [mm]	56	**Coordinate System**	ÄSPÖ96	**Drilling Stop Date**	1987-11-10 00:00:00
Length [m]	924.040	**Northing [m]**	7261.99	**Surveying Date**	
Bearing [°]	330.53	**Easting [m]**	2125.22	**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
- Mylonite 508004
- Hybrid rock 505105

ROCK ALTERATION
- Oxidized
- Chloritisized
- Epidotisized
- Fract zone alteration

SILICATE DENSITY
- unclassified

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

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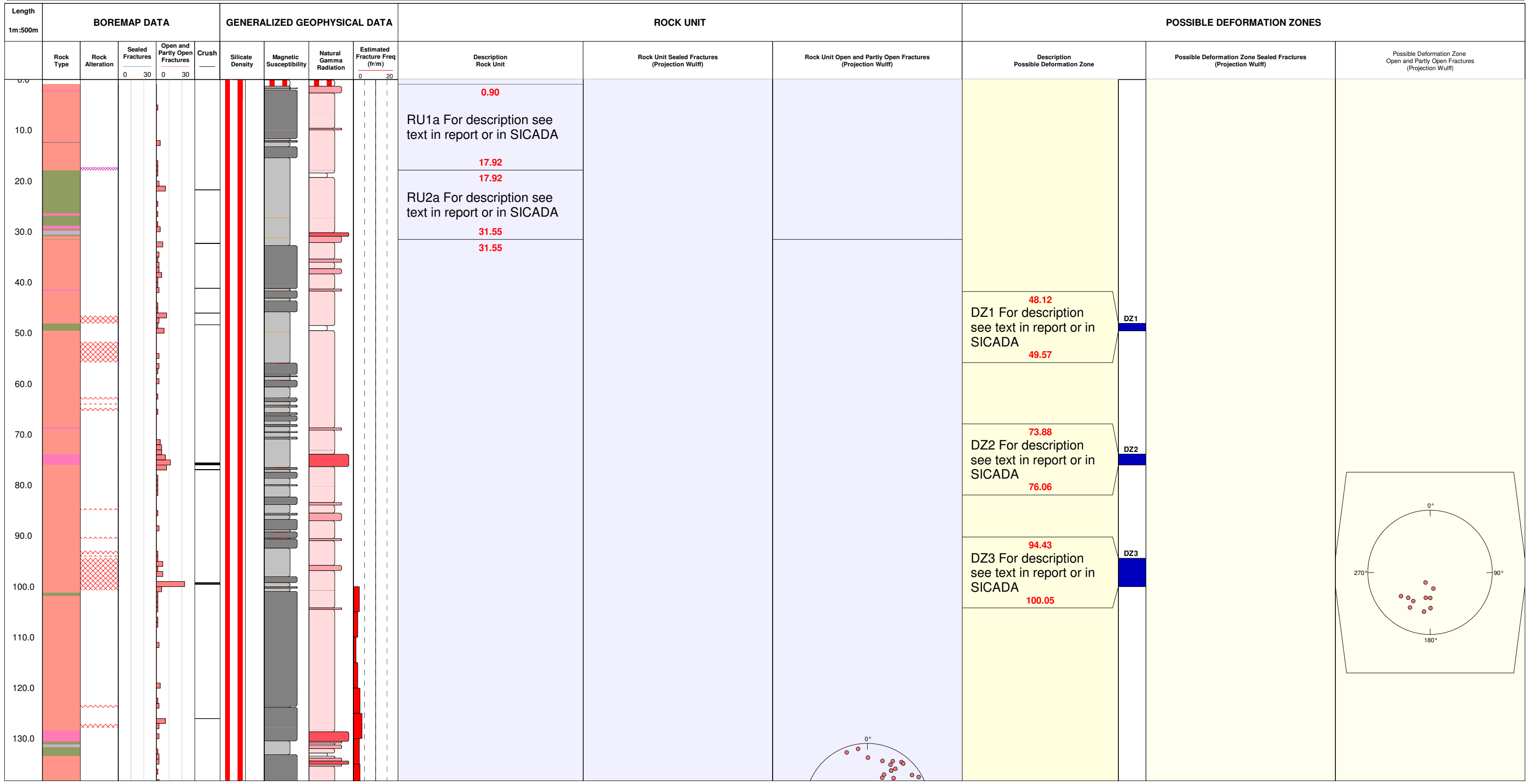
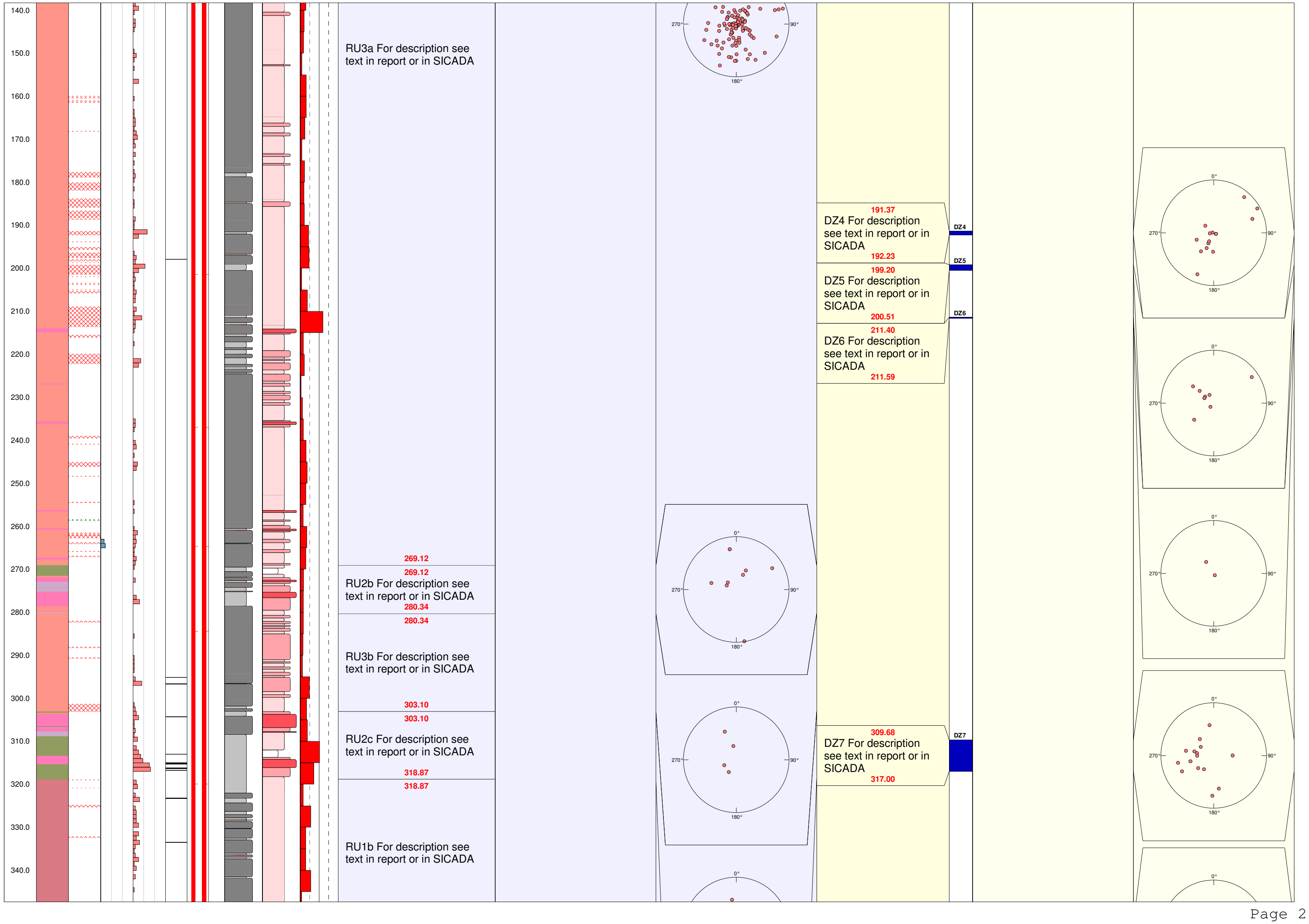
- gam<10
- 10<gam<20
- 20<gam<30
- gam>30

DZ CONFIDENCE
- Confidence 3

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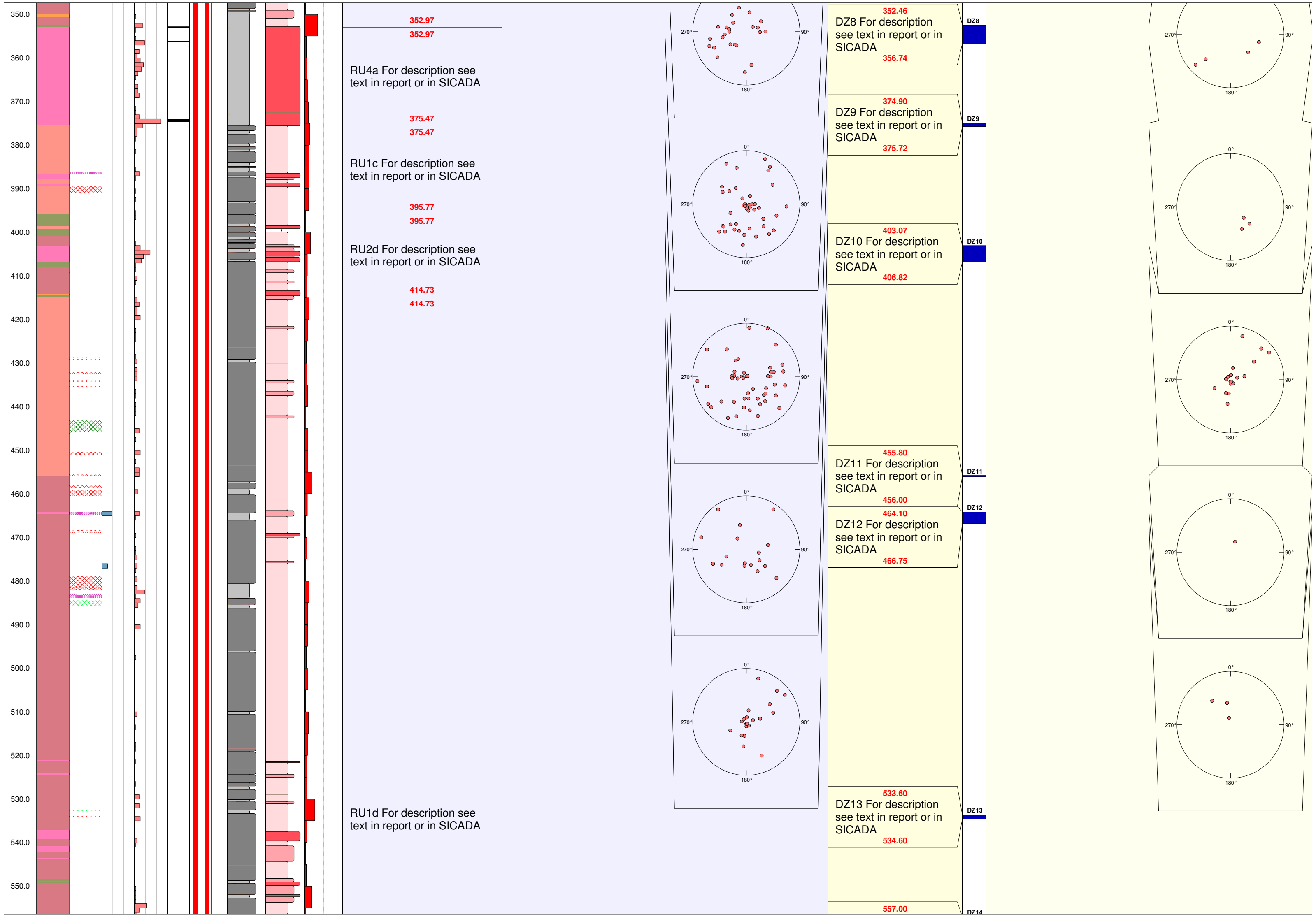
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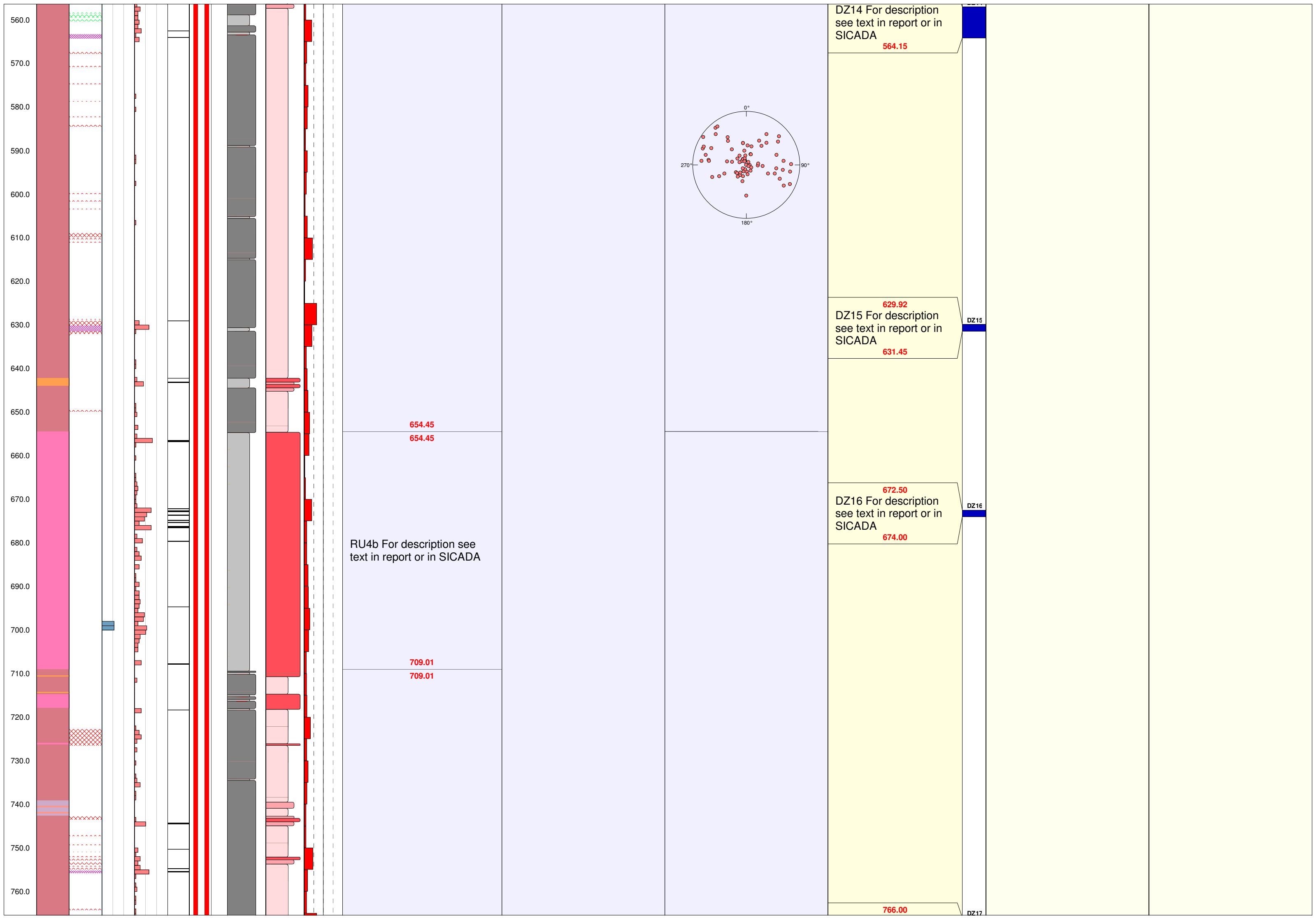
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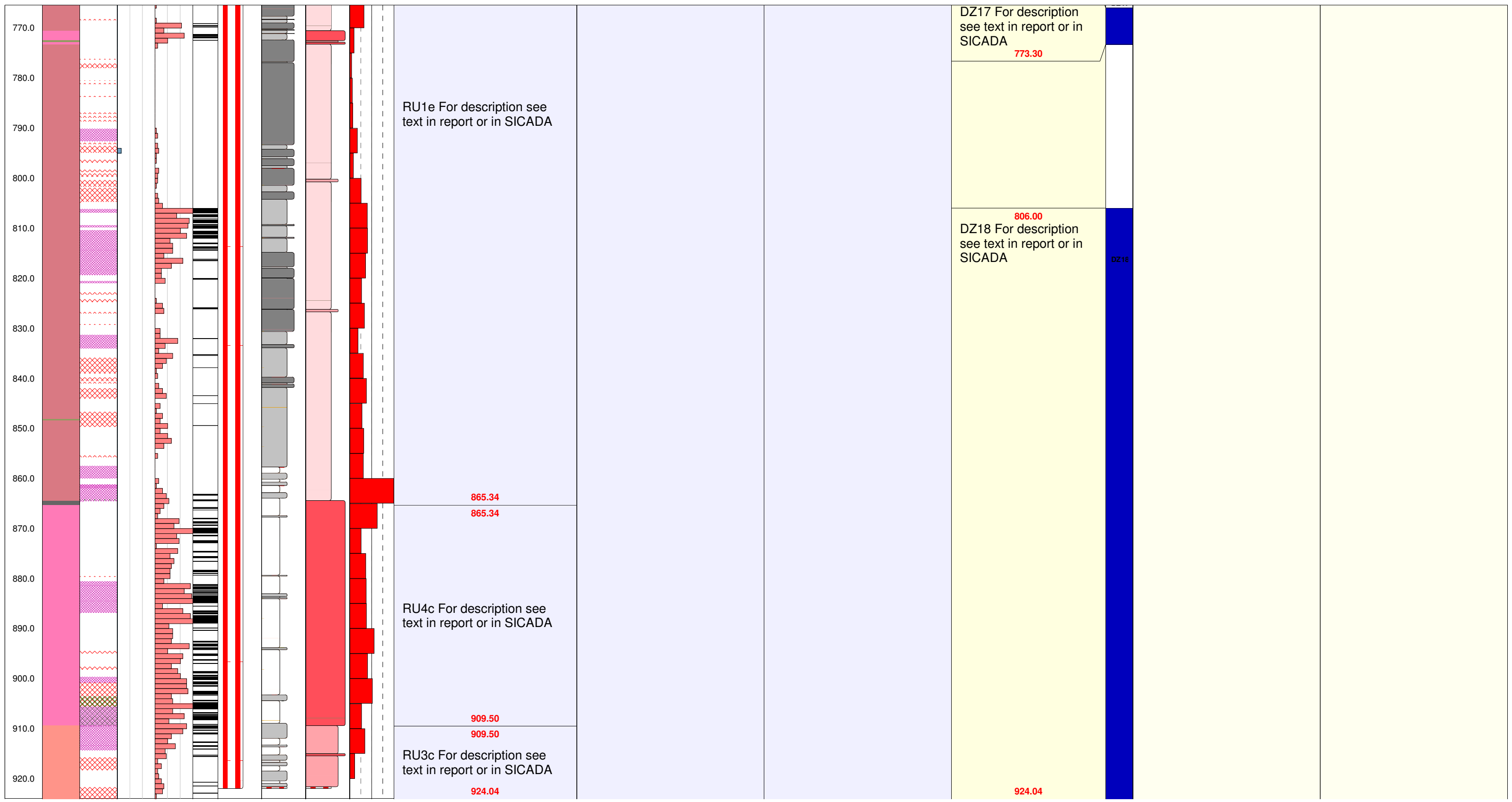
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