P-06-117

Review of existing information from the Äspö HRL area, with focus on hydraulically important minor structures

Roy Stanfors, Roy Stanfors Consulting AB

November 2006

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

ISSN 1651-4416
SKB P-06-117

Review of existing information from the Äspö HRL area, with focus on hydraulically important minor structures

Roy Stanfors, Roy Stanfors Consulting AB

November 2006

Keywords: Deformation zones, MDZ, Distance between water-bearing structures, Grouting experiences, Identification, Geological characteristics.

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

Summary

During construction of the Äspö HRL water inflow was the most significant problem experienced. In order to limit the water inflow pre-grouting was performed along many sections of the tunnel. Passage of the major deformation zones NE-1, NE-3 and NE-4 caused the most difficulty. These zones, which were identified prior to the construction, consumed about 45% of the total grout volume. However, it is important to note that minor deformation zones, only partly identified, consumed more than 50% of the total grout volume.

During construction all water-bearing structures were documented and all information was stored in the database GEOTAB. A great number of detailed investigations concerning water-bearing structures were later performed. The main results are presented in this report.

The main aim of this study is to summarise what has been learned in general about water-bearing minor structures in Äspö and to point out to what extent the experiences from Äspö are applicable to the Laxemar site.

The classification of minor structures in "minor zones" (length 100–1,000 m, thickness 0.1–5 m) and "single open fractures" (length 10–100 m, thickness < 0.1 m) has proved impractical as the subdivision assumes a minimum thickness of a "minor zone".

As an alternative it is proposed to use the term "minor deformation zone" (MDZ) for all deformation zones with a thickness of < 5 m and extents in the range of 10–1,000 m.

One question of importance is whether there is a correlation between minor deformation zones (MDZs) mapped on the surface, in boreholes and in the tunnel regarding their frequency and spacing? Based on data assembled from different studies the distance between MDZs mapped on surface is in the order of 40–100 m, with variation linked to orientation. In the deep boreholes at Äspö the equivalent distance is 75–200 m though there is a great variation between different boreholes.In the tunnel the distance between highly conductive MDZs (often pre-grouted) is approximately 75–100 m and 25–35 m between less conductive structures. However, there is great variation between different sections of the tunnel. In the section c 700–1,300 m, between the major deformation zones, there is an increased frequency of MDZs.

In summary, it can be said that there is a clear correlation between surface and borehole data regarding frequency and spacing with conditions at a depth of 400–450 m but it is important to perform detailed geological and geophysical surface investigations complemented with borehole data from BIPS, Boremap, geophysical logging and borehole radar in order to more clearly define this correlation.

Sammanfattning

I samband med utsprängning av Äspötunnlarna var inläckande vatten det klart största problemet ur byggnadsteknisk synpunkt. För att begränsa inläckningen utfördes förinjektering i stor omfattning längs delar av tunneln och senare även efterinjektering.

Passagen av de större deformationszonerna, NE-1, NE-3 och NE-4, utgjorde de största problemen och svarade för ca 45 % av injekterad cementvolym. Dessa större zoner var dock väl kända redan från förundersökningsstadiet såväl avseende läge, bredd som förväntad vattenföring. För övriga vattenförande strukturer, mindre deformationszoner och långa uthålliga sprickor, fanns kunskap om dessa strukturers existens och vattenföring men ingen mera exakt kunskap om läge och antal. Av intresse är att dessa mindre zoner svarade för mer än hälften av den injekterade cementvolymen.

I samband med tunneldrivningen utfördes kontinuerligt dokumentation av bl a alla vattenförande strukturer. Dessa uppgifter lagrades i databasen Geotab. Efter utbyggnadsfasen har ett stort antal detaljundersökningar utförts avseende vattenförande strukturer för olika forskningsprojekt. I denna rapport redovisas resultat från ett antal av dessa projekt.

Huvudsyftet med denna rapport – som av naturliga skäl endast behandlar en mycket begränsad del av den stora mängd data om vattenförande strukturer i ÄHRL som föreligger – är närmast att belysa vilka erfarenheter som kan vara av intresse för pågående förundersökningar främst då i Laxemar.

En av de frågor som bedöms vara av intresse är huruvida det finns en korrelation mellan vattenförande mindre zoner karterade på ytan, i borrhål och i tunnlarna avseende frekvens och inbördes avstånd?

Sammanfattningsvis kan sägas att avståndet mellan de mindre zoner som karterats på Äspö, geologiskt och geofysiskt, är i storleksordningen 40–100 m med variation avseende strukturernas orientering. I de djupa kärnborrhålen från ytan på Äspö är motsvarande avstånd 75–200 m med stor variation mellan olika borrhål.

I tunneln noterar vi avstånd i storleksordningen 75–100 m mellan mindre zoner med relativt stor vatteninläckning (som ofta krävt förinjektering) och zoner (långa sprickor) med inbördes avstånd på ca 25–35 m som i regel har ringa vattenföring. Det bör dock framhållas att variation finns mellan olika delar av underjordsanläggningen. Inom tunnelavsnittet 700–1 300 m, mellan de större zonerna, är frekvensen mindre zoner större än i övriga delar av tunneln.

Slutsatsen av ovanstående är att det finns en god korrelation mellan yt-borrhålsdata och de förhållanden avseende betydelsefulla mindre zoners frekvens och inbördes avstånd som kan förväntas på djup av 400–500 m. För en god förutsägelse krävs dock detaljerade ytundersökningar – geologiska och geofysiska – kompletterade med borrhålsundersökningar där kombinationen BIPS, Boremap, borrhålsradar och hydraulisk diff. log bedöms vara speciellt värdefull.

Contents

1 Introduction

The ground investigations for the Äspö HRL prior to construction involved extensive field measurements aimed at characterising the rock formations with regard to geology, geohydrology, groundwater chemistry and rock mechanics /Rhén et al. 1997/.

During construction of the tunnel continuous mapping and documentation provided an extensive amount of data and experiences.

The geological site characterization in the Laxemar area has so far been focused mainly on the general structural pattern including the most important regional structures. As a basis for more detailed groundwater flow modelling, engineering design and construction it is also necessary to describe the pattern and character of the minor deformation zones (MDZs) that lie in between the major deformations zones.

Experience gained from the investigation and construction of the Äspö hard rock laboratory (HRL) should provide valuable input to the planning of the detailed characterization of other sites – especially the Laxemar site since it lies so close to Äspö. The work was carried out in accordance with activity plan AP PS 400-05-101. In Table 1-1 controlling documents for performing this activity are listed. Activity plan are SKB's internal controlling documents.

1.1 Project area

The project area is shown in Figures 1-1 and 1-2 and encompasses the following parts of Äspö HRL

- Äspö – surface.
- Deep boreholes from Äspö surface.
- Ventilation shaft.
- Tunnel.

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

Activity plan	Number	Version
Sammanställning av data avseende lokala mindre strukturer i Äspötunneln	AP PS 400-05-101	1.0

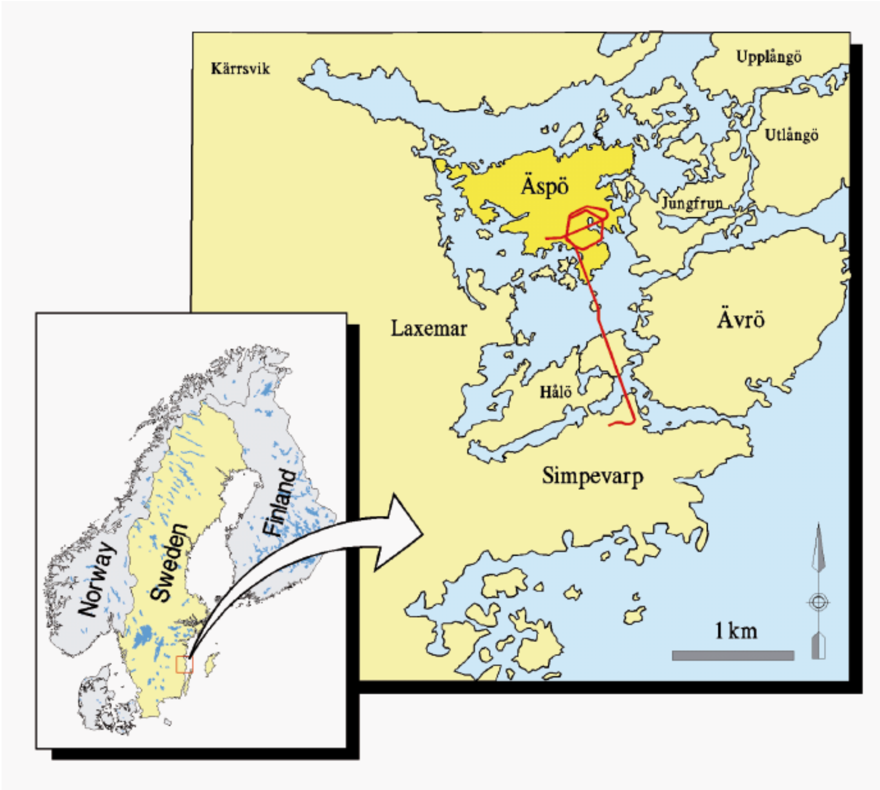


Figure 1-1. *Project area.*

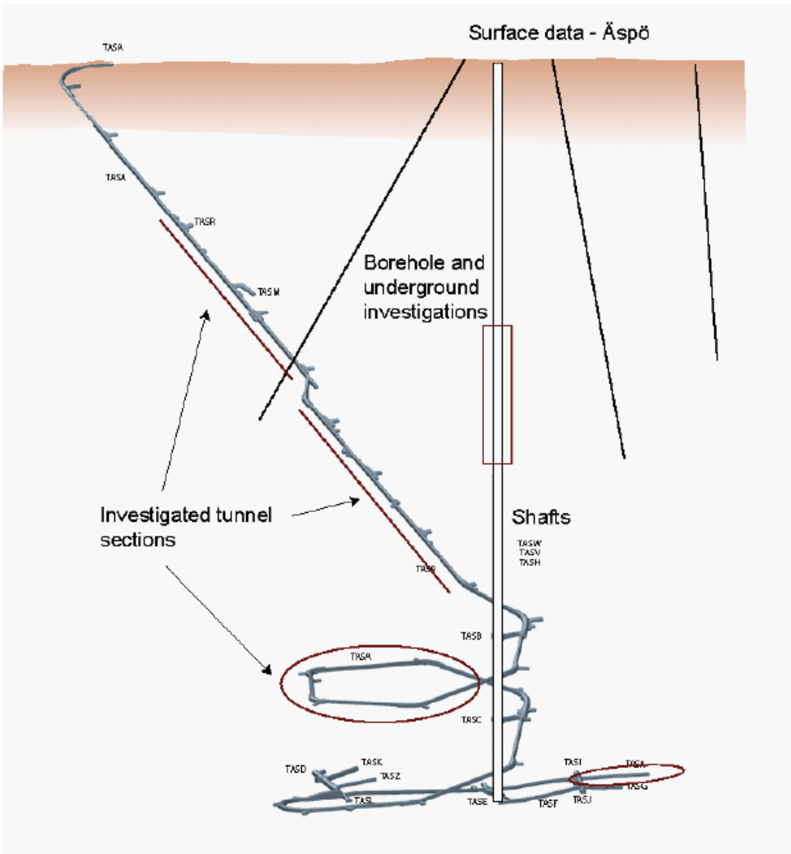


Figure 1-2. *Overview of the project.*

2 Objective and scope

The current study aims to review data from the Äspö HRL and evaluate the applicability of findings and experiences to other sites. The study focuses on water-bearing minor deformation zones and single persistent fractures.

The key questions to be addressed are:

- What has been learned in general about water-bearing minor structures at Äspö?
- Can ground surface and borehole investigations provide sufficient data for characterization of MDZs at repository level?
- To what extent are experiences from Äspö applicable to the Laxemar site?
- Which are the most useful investigation methods for identification and characterization of MDZs?

3 Background information, terminology and available data base

Information in the current report is based on tunnel mapping data, both geological and hydrogeological, processed and stored in the Tunnel Mapping System (TMS) along with supplementary investigations performed after construction. TMS data were transferred to the SKB database GEOTAB.

3.1 Terminology used in the Äspö project

In the Äspö project the following definitions concerning brittle structures were applied during pre investigations and tunnel documentation /Bäckblom 1989/.

Major fracture zone

The term major fracture zone was used for a feature > 5 m thick and extending for more than c 1,000 m, with the characteristics that the intensity of natural fractures is at least twice as high as for the surrounding rock. Completely disintegrated and/or chemically altered rock is included in the definition of a fracture zone as well as any kinematic marker. Some examples of major fracture zones are presented in Appendix A. (Regional deformation zone and local major deformation zone according to current terminology in Laxemar).

Minor fracture zone

The term minor fracture zone was used for a feature < 5 m thick and extending for ca 100–1,000 m. (Local minor zone according to current terminology in Laxemar).

Single open fracture

Persistent, several m (10–100 m) long fractures, less than 0.1 m thick, mostly steep and estimated to be significant hydraulic conductors were called “single open fractures”. (Local minor zone – except for discrete fracture – according to current terminology in Laxemar).

Fracture swarm

A fracture swarm is defined as a zone with relatively high fracture frequency, but not so high as a proper fracture zone with fractures essentially parallel to the orientation of the swarm boundary /Hermansson 1995/.

/Mazurek et al. 1996/ used the following definitions in a later study on water-bearing features in the Äspö Tunnel.

Simple fracture

Simple fractures consist of a single master fault and sets of diverging splay cracks (joints) on both sides. Examples were observed where the geometry remains constant over at least 15 m along the strike. Water inflows from the splay cracks cannot be located in the master fault, but inflows from the splay cracks cannot be discounted at present.

Complex fractures

Complex fractures are fault zones consisting of interconnected networks of 1–5 sub-parallel master faults and sets of converging splay cracks. The width of the fault zones may exceed 1 m.

3.2 Examples of minor fracture zones and single open fractures (minor deformation zones according to present terminology)

More than one hundred minor fracture zones and single open fractures have been mapped and documented in the Äspö HRL.

Structures that display indicators, such as increased fracturing, slickensides, mylonitic fabrics or faults were mapped in the tunnel as minor fracture zones.

Most of them are generally not wider than 1 m. Most consist of a single or up to a handful of faults that generally contain gouge. The host rock is generally mylonitized granite or sheets of fine-grained granite.

The minor deformation zone NE-2 is an example of a topographically significant zone that is also indicated geophysically by low-magnetism and decreased resistivity along almost its entire length). Geological indications were found in the SW part of zone NE-2 including intense fracturing and alteration of outcrops in the trench (Figure 3-1). Borehole indications in the form of mylonite and crushed and highly altered rock, as well as vertical seismic profiling (VSP) and borehole radar data confirm the extent of the zone at depth.

***Figure 3-1**. Fracure zone NE-2 at Äspö surface.*

Tunnel intersections of fracture zones at ch. 1,605 m, 1,844 m and 2,480 m probably represent different branches of NE-2. Measured strikes vary between 015° and 036° and measured dips cluster around 75 ± 5°. However, the width of the most intensely foliated portion of the mylonite varies between 1 and 5 m (Figures 3-2) /Munier 1995/.

The water-bearing zone NNW-4W is another example of a minor fracture zone mapped on the surface. At the surface it is represented by a number of longer fractures and narrow (some decimetres wide) fracture zones. In the tunnel it is interpreted as intersecting, at ch. 2,018 m, 2,116 m (Figure 3-3) and at 2,940 m. Some 5–10 cm wide and open fractures in this metre-wide section of cataclastic granite are filled with grout.

Combined results from tunnel mapping and drilling show a characteristic pattern for the "NNW-system". They mostly occur in a complex pattern of steeply dipping fractures (fracture swarms) and some decimetre-wide "fracture zones".

Many of the narrow fracture zones are associated with veins or dikes of fine-grained granite. It seems possible to correlate a number of decimetre-wide fracture zone indications in the tunnel to observations in boreholes. The character of many of these structures as "fracture zones" is not very evident. They should rather be described as a 10–30 m wide swarm of mostly sub vertical conductive fractures trending WNW to N where the WNW trending fractures are normally the most frequent and hydraulically important.

Figure 3-2. *Fracture zone NE-2 at 1,605 m in the Äspö Tunnel.*

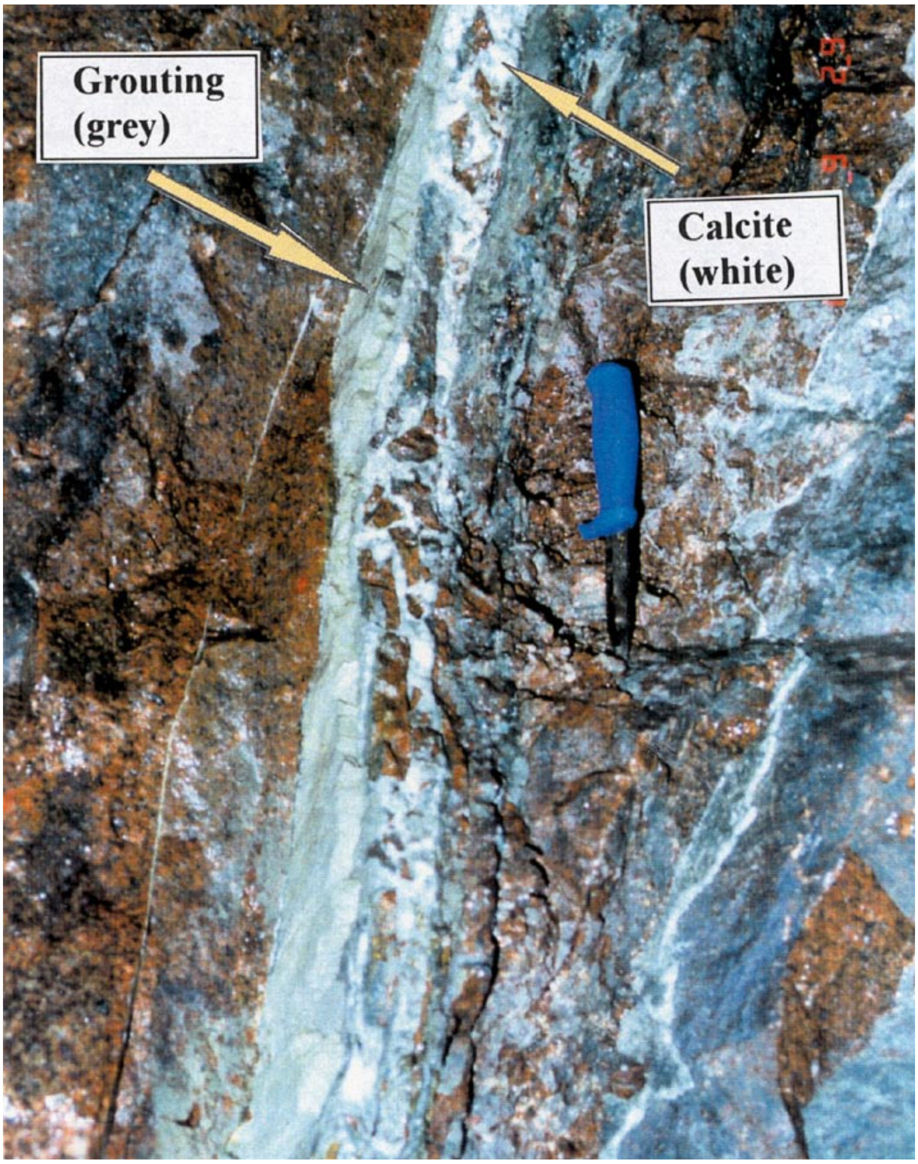


Figure 3-3. *Fracture zone NNW-4. Intersection in the Äspö tunnel at 2,116 m.*

4 Summary of investigation data

There has been considerable work carried out during and after construction of the Äspö HRL concerning water–bearing structures. Due to the limited scope of the current study it was considered most useful to select data from a limited number of investigations for evaluation focused on the main goals of the current report.

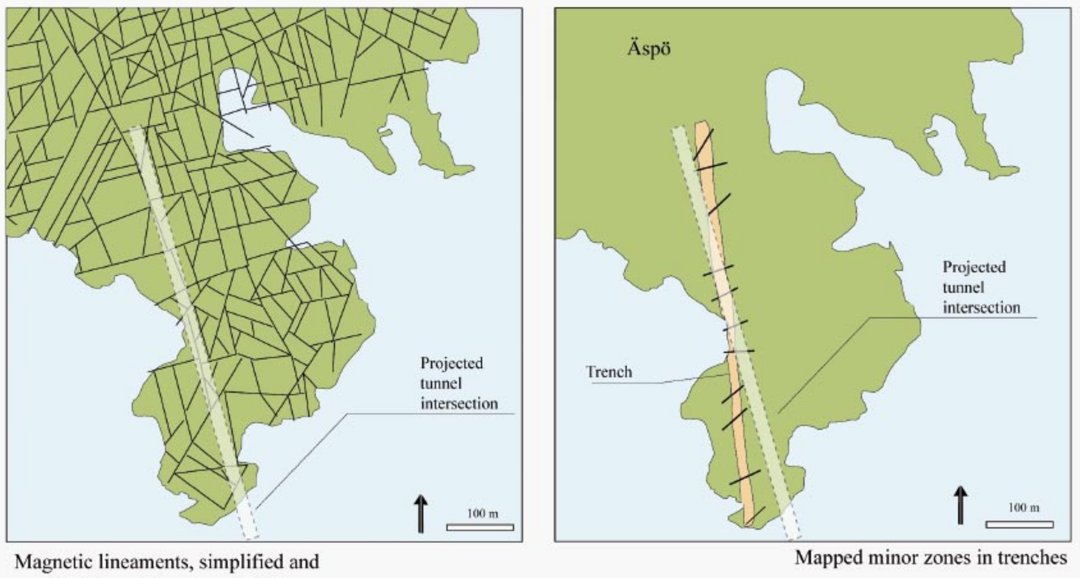
4.1 Surface investigations

The investigations of minor fracture zones on the Äspö surface was aided by lineament maps /Tirén and Beckholmen 1987/ and detailed magnetic and electrical investigations /Nisca and Triumf 1989/ (Figure 4-1).

According to /Talbot and Munier 1989/ steep faults trending NNW are the most common orientation on Äspö. These are normally spaced 50–100 m apart. Other clear orientation sets are subvertical NE-trending and NW-trending faults having spacings of about 10–40 m. Steep N-trending fractures are typically c 50 m long and generally appear about 50 m apart. Some of these fractures were estimated to be very significant hydraulic conductors /Nisca and Triumf 1989/. Some fractures and fracture zones trending NE are associated with scarps .

A successful correlation between ground magnetic lineaments with lengths of ca 20–100 m and structures identified on the ground, showed that it was possible to identify some geological structure on the ground with a similar orientation and location for about 80% of the magnetic lineaments /Talbot and Munier 1989/.

A mapping study along a N-S oriented profile on Äspö indicated a 60–75 m spacing between minor fracture zones /Ericsson 1988/. A more detailed investigation in a cleaned trench on southern Äspö, close to the tunnel direction, indicated a 30–35 m spacing between minor structures /Kornfält and Wikman 1988/. The deviation between the two investigations was probably due to the increased possibility to map "single fractures" on the cleaned bedrock surface in the trenches (Figures 4-1 and 4-2).



Magnetic lineaments, simplified and modified from Nisca et al (1988)

Mapped minor zones in trenches

Figure 4-1. *Interpreted magnetic lineaments on surface and mapped minor zones in the trenches.*

Figure 4-2. *Cleaned trench on south Äspö.*

A great number of fractures and narrow, decimetre to a few m thick, subvertical fracture zones striking approximately north have been mapped on outcrops on Äspö. They seem to branch out in an enéchelon pattern across the island. Only a few of them are topographically significant and normally too narrow to be geologically unambiguously indicated. Vertical Seismic Profiling and borehole information support the notion of steep, mostly easterly dips. All these fractures and fracture zones were described under the designation "NNW-system" in the predictive studies.

4.2 Boreholes on Äspö

During the site-investigations for the Äspö HRL a great number of boreholes were used to detect and characterize minor fracture zones (MDZs) and single open fractures (MDZs).

An estimate of minor deformation zones (MDZ) in some core boreholes (Figure 4-3) – based on core mapping, borehole radar, geophysical logging and hydraulic data – is presented in Table 4-1.

Table 4-1.

Borehole	Length	Estimated number of MDZ (water-bearing)	Estimated spacing of MDZ
KAS02	924	18 (11)	51(84)
KAS05	550	6(5)	92(110)
KAS06	602	10(8)	60(75)
KAS07	604	11(4)	55(151)
KAS08	601	5(3)	120(200)
KAS09	450	9(4)	50(113)
KAS12	380	7(3)	54(127)
KAS13	406	6(2)	68(203)

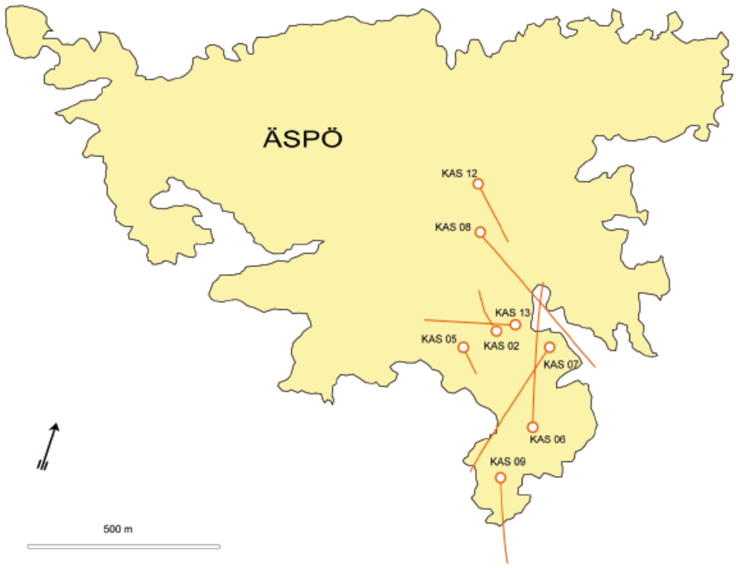


***Figure 4-3**. Investigated core boreholes.*

4.3 Tunnel investigations

In this chapter brief summaries of a number of studies, performed after construction, are presented.

4.3.1 Fracture classification and characterization project /Mazurek et al. 1996/

The objectives of the Fracture Classification and Characterization Project performed by /Mazurek et al. 1996/ were:

- to classify water-conducting features that occur in the Äspö HRL,
- to characterize and conceptualise these features with respect to radionuclide transport properties,
- to develop and apply a methodology for the characterization of water-conducting features in crystalline rocks.

Within the framework of this project, only water-conducting features whose traces were mappable along the whole tunnel cross-section were considered for mapping and detailed characterization. This geometrical limitation implies that only fractures with trace lengths of at least 7 m i.e. ≥ tunnel section, were considered. Given this definition of scale, all water-conducting features turned out to be faults. Depending on the intersection angle between the tunnel and the fault, the observable trace lengths were in the range 7–25 m.

The full characterization included 88 water-conducting features. Many of the faults follow pre-existing structural inhomogeneities, such as ductile shear-zones or lithified cataclastic shear-zones.

The investigation was performed between tunnel chainage 600 m and 3,050 m, i.e. in the deeper parts of the access ramp and into the spiral loops of the Äspö HRL. 1,100 m of straight access ramp (600–1,700 m) were included in order to increase the representativity of the investigated features with respect to spatial distribution and this section contains 44 mapped water-conducting features. The remaining 44 structures are situated in the spiral loops, where no sampling bias with respect to the strike direction affects the observations.

Main results

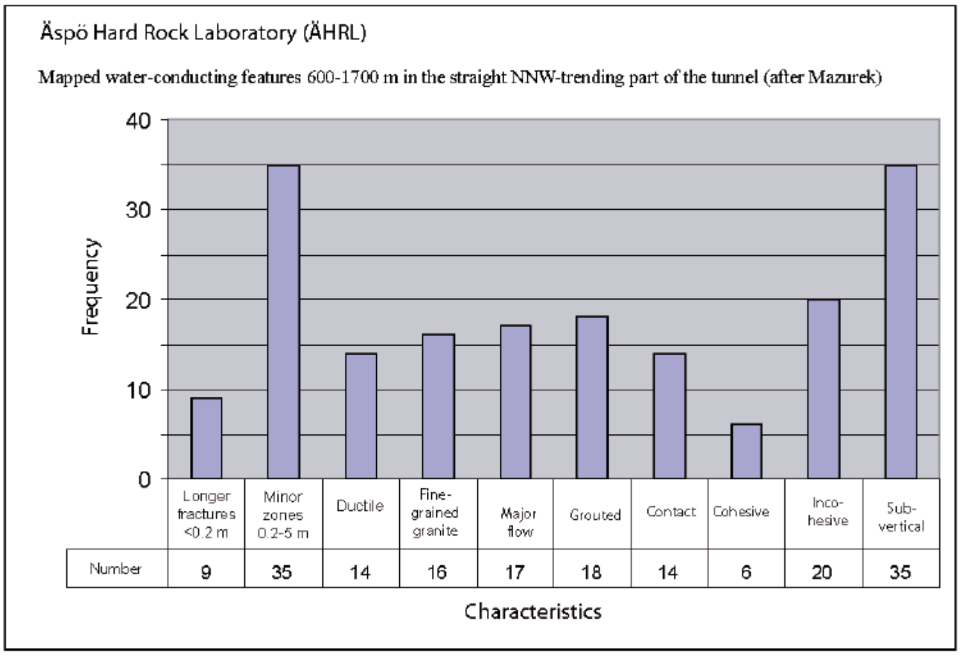
- The only clear difference between individual water-conducting features is the internal fault geometry. No other distinguishing criteria such as the arrangement of lithologic domains, mineralogy of fracture infills, transmissivity etc. were identified and probably do not exist.
- On the basis of the geometric arrangement 5 types of water-conducting features are distinguished:
  – Type 1 – single fault.
  – Type 2 – swarm of single faults.
  – Type 3 – fault zone.
  – Type 4 – fault zone with rounded geometries.
  – Type 5 – parallel fault zones with long connecting splays.
- The strike of the majority of the mapped water-conducting features is roughly NW to WNW, with an approximately vertical dip. No flat-lying water-conducting features were observed in the tunnel (Figure 4-4).
- There is essentially no difference in the preferred orientation of the water-conducting features classified as simple and complex. Both structural types are principally oriented WNW-ESE with predominately vertical dips.
- The orientations of water-conducting features with ductile precursors fall into two clusters. They are fairly steep and strike WNW and NNE, respectively. The latter set is thus parallel to the trend of ductile shear-zones observed on the surface. There is no difference in intensity, persistence or width of the deformed zones between the two clusters.
- In total 39 water-conducting features contain cohesive fault rock (ductile or brittle), which implies that about 45% of the water-conducting features are partly or wholly reactivated pre-existing shear/fault zones.
- 12 water-conducting features contain cohesive (lithified) brittle fault rock along the fault plane. These cataclasites generally consist of fairly thin (average ca 4 cm), epidote-prehnite-quartz-cemented micobreccias.
- In total, 45 (51%) water-conducting features have some incohesive fault rock (fault gouge, fault breccia and fault crush) along the fault plane. The incohesive fault rock commonly occurs in zones or lenses of highly variable thickness (max 0.3 m) or as more irregular masses along the fault plane.
- The majority (56 out of 88) of the water-conducting features exhibit some macroscopically identifiable hydrothermal alteration, seen as oxidised red colouration or, as observed along 4 features, as chloritisation of the wallrock.
- In total, 36 of the 88 investigated water-conducting features were pre-grouted. In addition to these, 7 have been partly sealed off by shotcrete.
- Characteristics of water-conducting features in section 600–1,700 m are presented in Figure 4-4.

4.3.2 TRUE Block Scale Project /Andersson et al. 2002/

According to /Andersson et al. 2002/ the principal aim of the TRUE Block Scale project was to build a robust hydro-structural model of major deterministic conductive structures to serve as a basis for planning tracer tests in a block scale.

The identification of hydraulic structures in the TRUE Block Scale rock volume has been made with a number of methods such as:

- use of pressure responses and associated flow anomalies for early information on existence and location of hydraulic structures,
- use of various flow logging techniques for verification of hydraulic conductors,



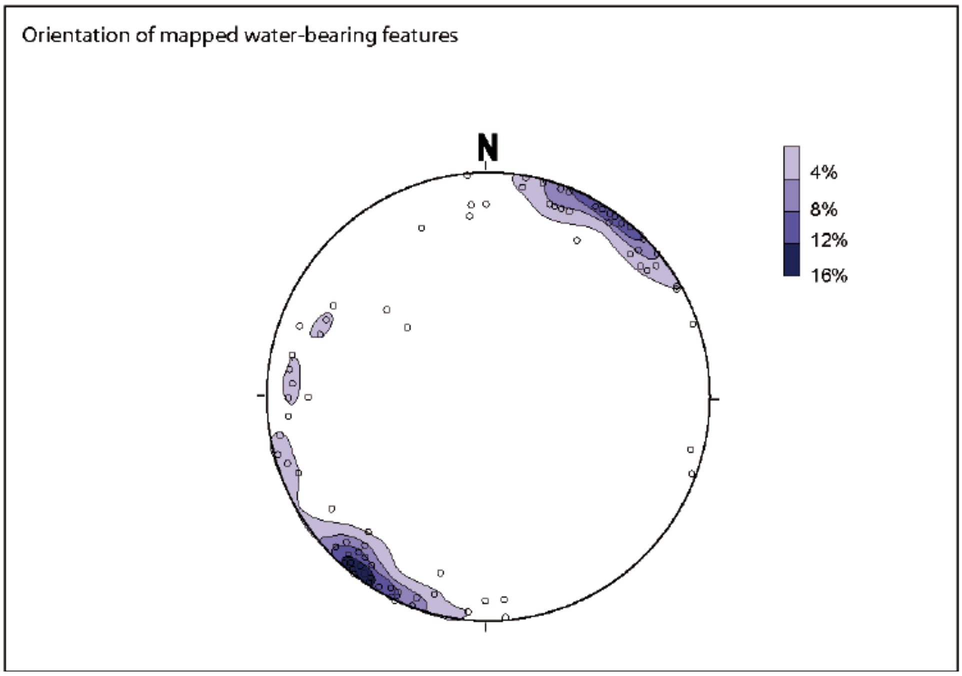


Figure 4-4. *Above: Histogram showing frequency of different characteristics of water-conductive features in section 600–1,700 m of Äspö HRL. Below: Equal area projections of poles to water-conducting features. (Lower hemisphere).*

- BIPS and Boremap for correlation of a hydraulic flow anomaly to a geological feature,
- RAMAC borehole radar for assessment of the geometry of larger structures,
- USP and HSP seismic cross-hole techniques for identification of bounding larger structures.

The final hydro-structural model of the TRUE Block Scale volume is illustrated in plan view in Figure 4-5 at a level of –450 m above sea level The investigation comprised seven core boreholes.

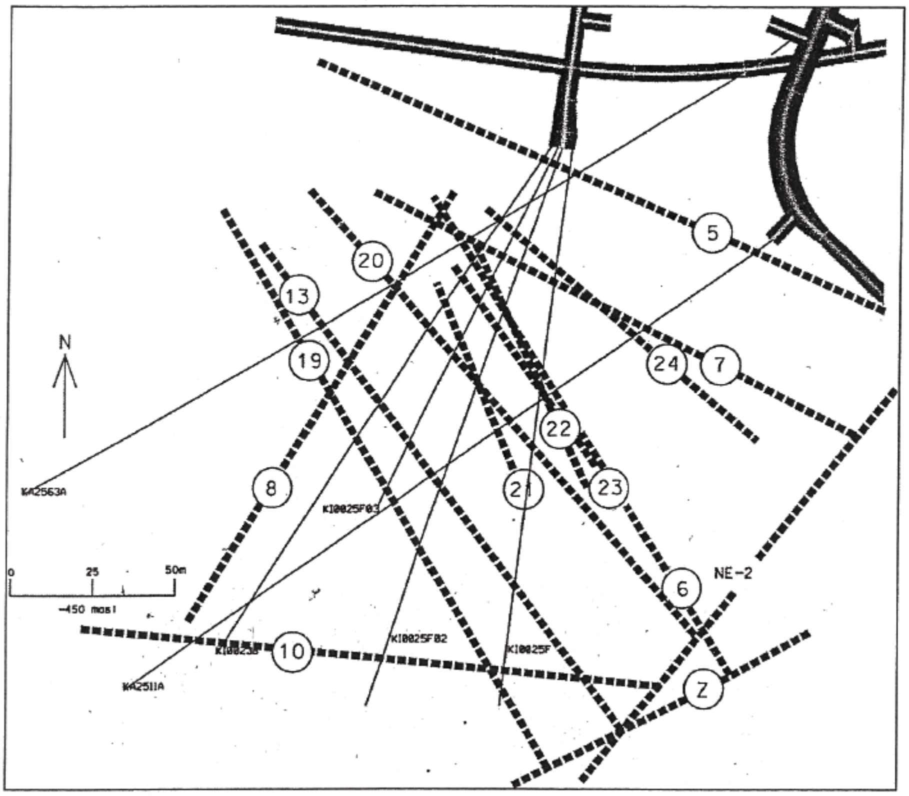


Figure 4-5. Hydro-structural model of the TRUE Bock Scale volume /Andersson et al. 2002/.

Main results

- structure #20 is the major structure located in the centre of the tracer test area. It constitutes the core of a network that includes Structures #6, #23, #22, #13 and #21,
- structure #19 intersects all boreholes except KA2511A. It has possible connections to the Structure #20 network, possibly indirectly through structure #13,
- structure #13 has its strongest geological appearance in boreholes KA2563A and KI0023B,
- structure #21 is part of the Structure #20 network with interpreted intersections in boreholes KI0025F02, KI0025F03, KI0023B and possibly in KA2563A,
- structures #22 and #23 are confirmed by the data from KI0025F03,
- the responses due to the drilling of KI0025F03 strongly suggest an additional structure, #24, which is located north of structures #6 and #7,
- it seems evident that most of the hydraulic structures described can be correlated to single open fractures/faults and fracture swarms rather than minor deformation zones according to the Äspö HRL nomenclature,
- the horizontal distance between the hydraulic structures varies from c 25 to 50 m.

4.3.3 Definition and characterization of the N-S fracture system in tunnel section 1,600–2,400 m /Kickmaier 1995/

The main aim of Kickmaier's study was to investigate the predicted NNW-striking fracture system in Äspö HRL. The "NNW"-fractures (minor fracture zone or MDZ using current terminology) was suggested to be one of the major hydraulic conductors, based on surface investigations. The study was focused on "NNW"-striking fractures in the first tunnel spiral (ca 1,600 m to 2,400 m), and particularly on strike directions between 340° and 10°.

The data were analysed in order to answer the following basic questions:

- what does the distribution pattern of the "NNW"-fracture system look like and is it possible to define minor deformation zones?
- is there a relationship between the highly water-bearing (grouted) zones and the "NNW"-fracture system?

Main results

- it was suggested that the term "NNW" should not be used any more. Instead the term N-S fracture system should be introduced,
- it was concluded that "single" fractures with an average spacing of approx 1–2 m are dominating in the N-S fracture system,
- within tunnel sections 1,600 m to 2,400 m no evidence for N-S striking fracture zones can be found. Two sections are characterized by increased N-S fracturing, but there is no reason to call them fracture zones,
- it seems that the zones of increased N-S fracturing can be traced over a distance of at least 200 m along strike, indicated by the correspondence of frequency maxima on tunnel legs A and E,
- generally the direct correlation between high water inflows and the occurrence of the N-S fracture system is weak,
- the frequency of N-S striking fractures in the grouted zones is comparable to the tunnel average,
- the width of an increased N-S fracturing in fracture swarms varies between 20 and 50 m. The horizontal distance is estimated approx 100 m.

4.3.4 Structural geology of water-bearing fractures /Hermansson 1995/

A mapping campaign of major larger water-bearing fractures in the tunnel spiral showed that all mapped fractures either had a substantial water inflow and/or grout and often gouge, brecciation or ductile precursors /Hermanson 1995/. They were not in any case classified as zones and their width ranged from millimetres to centimetres. Figure 4-6 shows the mapped fractures. The fractures shown were mainly subvertical. The fault system trending NW and NNW generally appears as sub-planar fractures with a central water-bearing fault plane that often contains fault breccia and/or fault gouge as well as a mineral assemblage. Some of the larger fractures appear in fracture swarms.

According to /Hermanson 1995/ two well-defined gently dipping fracture zones were found in the tunnel. The width of the zones is less than a metre. Except for the two gently dipping fracture zones seven sub horizontal fracture swarms were identified in the HRL. The swarms together with the two minor fracture zones intersect the tunnel system within a distance of just below 100 m.

Main results

- Most of the major water-conducting structures are larger fractures or fracture swarms rather than minor fracture zones.
- Gently dipping fracture zones and fracture swarms seem to be of minor hydraulic importance in Äspö HRL.
- The mean distance between major water-bearing structures in the spiral tunnel is estimated to be c 35 m.

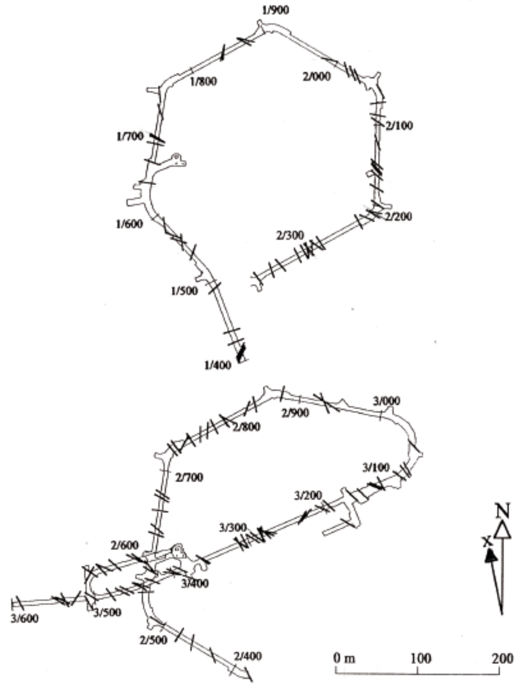


Figure 4-6. *Mapped large, single open, water-bearing fractures in the spiral of the Äspö HRL.*

4.3.5 Distance between structures with a specified transmissivity in the Äspö HRL /Rhén et al. 1997, Rhén and Forsmark 2001/

The block scale model comprised a description of the expected distance between hydraulic conductors with transmissivities (T) greater than a given value or within a given range. The purpose was to give a generic description of hydraulic characteristics of blocks at the site scale.

In the text below both arithmetic mean and median values are given. As the expected distance between structures with a certain transmissivity or greater than a specified value is log/normally distributed, the median value is less than the arithmetic mean value. The median value and the standard deviation are useful for estimating where the next structure will probably turn up. The arithmetic mean value gives expected numbers of structures on a longer part of the tunnel.

The distance reported in /Rhén et al. 1997/ between hydraulic conductors has been estimated based on injection tests with 3 m packer spacing in KAS02, KAS04 and KAS08; 30 m packer spacing in KAS02, KAS03 and KLX01along with pressure build-up tests in the tunnel with a test scale of approximately 15 m.

For the 3 and 30 m tests the evaluated transmissivity and position of each test section were used for the statistics.

During the drilling of the probe holes, the drill depth at which any increase in the amount of water inflow was recorded. The flow rate out of the borehole was also estimated and documented. The number of increasing flow-rate-steps was generally 1–6, but in a few of the probe holes it was not possible to define any position for the flow rate increase.

Statistics for the injection tests with 30 m packer spacing in KAS02, KAS03 and KLX01 are documented. These holes are all more or less vertical. The transmissivity (T) should more or less always be expected to be greater than 10^{-10} m^2/s for each 30 m section and the expected distance (median value) for $T > 10^{-6}$ m^2/s is around 100 m based on rather few boreholes with test scale 3 m. The arithmetic mean for the 3 m tests is around 20 m. One reason for this difference is that the samples are not from the same boreholes but if the data from KAS02 are compared the difference between 3 and 30 m tests can be studied. In KAS02 the expected distance (median value) for $T > 10^{-6}$ m^2/s is around 10 m for the 3 m tests and around 60 m for the 30 m tests.

Statistics for pressure build-up tests in the tunnel, which were performed in more or less horizontal boreholes are also available. As for the injection tests, results are probably biased to some extent for $T > 10^{-4}$ m^2/s as the sample is small and for low transmissivities. The method used to identify transmissive structures in probe holes during drilling lead to an underestimation of low-conductivity structures, since they were masked by higher flow rates. This probably affects the statistics for low-transmissive structures. The statistics are probably not relevant for $T < 10^{-7}$ m^2/s. Secondly, it was not possible to drill probeholes every fourth round, which cause false "long distances".

Main results

The expected distance (median value) for $T > 10^{-6}$ m^2/s is 10–20 m. The arithmetic mean is 35–55 m. The rock mass is probably anisotropic due to most of the water-bearing fractures being sub vertical. One could therefore expect to find shorter distances between conductive features with a specified transmissivity using probe hole data than with the data from the sub vertical boreholes. In Table 4-2 the results are summarized. As can be seen in the table, the distance in the probeholes are longer than in the coreholes. The reason is partly because of what mentioned above as "false long distance".

In the Prototype Repository project, at 450 depth in Äspö HRL, several core holes were drilled horizontally, inclined and vertically around the tunnel for the Prototype Repository /Rhen and Forsmark 2001/. There, the distance between features exceeding a predefined magnitude of transmissivity was studied.

Features exceeding six different orders of magnitude of the transmissivity were analysed: $T > 10^{-11}$, 10^{-10}, 10^{-9}, 10^{-8}, 10^{-7} and 10^{-6} m^2/s. In the analysis all boreholes drilled during the Prototype Repository Project were used, totally 34 bore holes. The evaluation is based on the transmissivity evaluated for the 1 m and 3 m sections assigning the midpoint of the section as a feature. The result is presented in Figure 4-7.

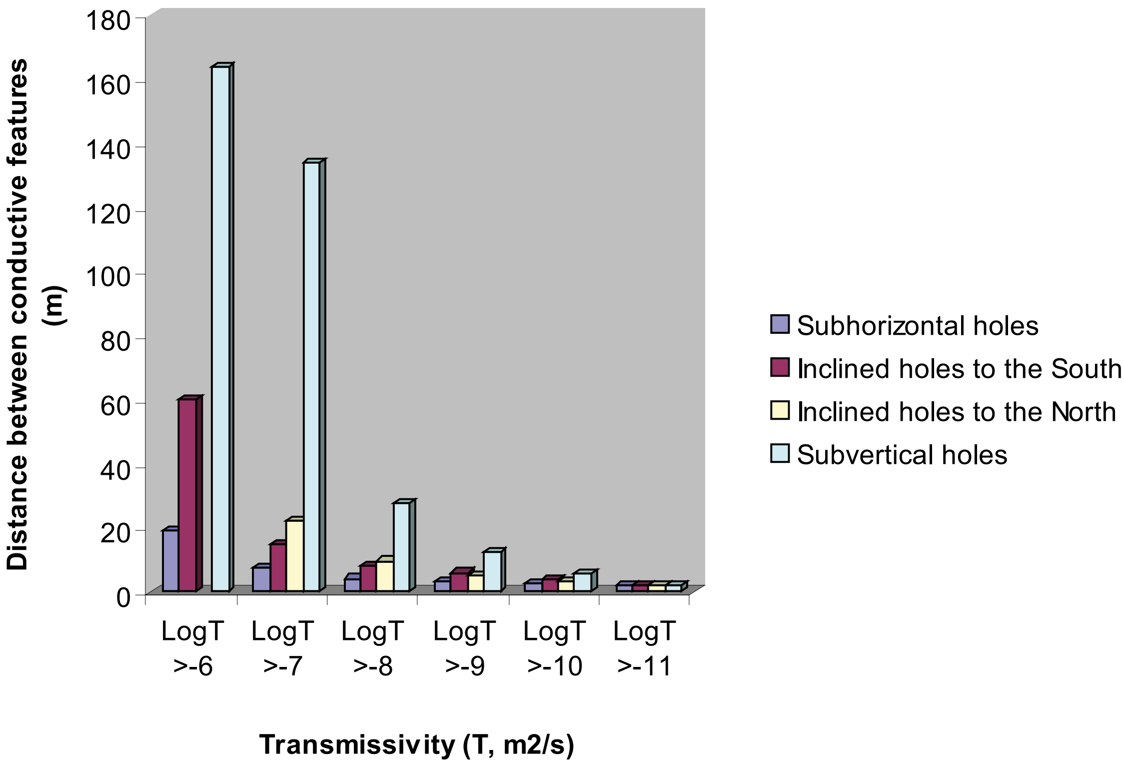


Figure 4-7. *Arithmetic mean distances between conductive features near the Prototype Repository tunnel.*

Table 4-2. The arithmetic mean distance between hydraulic conductors with a transmissivity (T) greater than a specified value of the transmissivity (Tj) is presented below. Results for cored boreholes based on injection tests with 3 m packer spacing.

Probe holes Tj (m^2/s)	Arithmetic mean distance Da (m^2/s)
$T > 10^{-5}$	70
$T > 10^{-7}$	35
$T > 10^{-9}$	(20)*
Cored boreholes Tj (m^2/s)	**Arithmetic mean distance Da (m^2/s)**
$T > 10^{-5}$	45
$T > 10^{-7}$	14
$T > 10^{-9}$	8

*uncertain value.

Main results

The results from Äspö HRL show that:

- The distance between conductors with a transmissity (T) greater than a specified value of the transmissivity is lognormal distributed.
- The arithmetic mean distance between conductors with a transmissivity greater than 10^{-5} and 10^{-7} m^2/s are 45–70 and 14–35 m respectively looking at the entire Äspö HRL. Locally, and at 450 m depth the arithmetic mean distance between conductors with a transmissivity greater than 10^{-7} m^2/s are c 7 m in horizontal boreholes and c 130 m in vertical boreholes.

4.3.6 Grouting experiences from the construction of Äspö HRL /Stille and Olsson 1996/

The experiences from the grouting work in the tunnel have been evaluated in detail and the results are presented in two separate reports /Stille et al. 1993, 1994/.

The difficult hydrogeological conditions for the tunnelling work with high water pressure and large water aquifers in the rock mass, made the grouting important for the tunnelling operation.

A total of 150 grouting operations were performed along the tunnel section 0–3,137 m – mainly as pre-grouting in parts of the tunnel were probe holes indicated water inflow in the order of $T=10^{-6}$ or Q > 10 l/min. As grouting was only performed in tunnel sections with high water inflow they are estimated to be good indicators of major hydraulic structures. Grouting data is presented in Table 4-3.

It is interesting to notice that minor zones, with a thickness of less than 5 m and single open fractures have consumed 56% of the total consumed grouted volume.

Table 4-3. Grouting data from tunnel section 0+–3/137 m.

Structure	Grouted volume	Total length of grout holes	Grouted volume l/m
Major DZ (> 5 m)	205.000 l	14,400 m	14.2
Minor DZ (< 5 m)	76.500 l	2,400 m	32.0
Remaining parts of tunnel(single open fractures < 0.1 m)	189.500 l	7,000 m	27.0
Total	471.000 l	23,800 m	19.8

4.3.7 Localization of experimental sites and layout of turn 2 /Olsson 1994/

Four cored boreholes were drilled from the tunnel section (Figure 4-8) ch. 2,050 m, 2,511 m, 2,598 m and the C-tunnel at the ca –450 m above sea level. The aim of the boreholes was to identify sites providing suitable conditions for planned experiments and to define a tentative layout for the extent in the tunnel.

The boreholes KAS2050A and KC0045F also gave information about a suitable location of the assembly hall for the tunnel boring machine.

During the drilling, water outflow from the holes was measured for each run of the core. Radar measurements using a directional antenna were performed along the boreholes and core logging was performed using the Petro Core System. Data concerning estimated hydraulic structures are presented in Table 4-4.

4.3.8 Results of the Select project /Winberg et al. 1996/

Several experiments were performed during the Operation Phase of the Äspö HRL. These experiments need sites, which meet specific requirements with respect to rock conditions and groundwater properties. A separate project (SELECT) was initiated to provide base data and recommendations for locating experiments /Olsson 1994/. Based on this work a provisional allocation was made of experimental sites for the Radionuclide Retention Experiment (RNR), the Redox Experiment on a local scale (REX) and the Tracer Retention Understanding Experiment (TRUE). It was decided that access to the allocated rock volume would be facilitated by drilling 20–30 m long boreholes from the existing niches along the tunnel spiral.

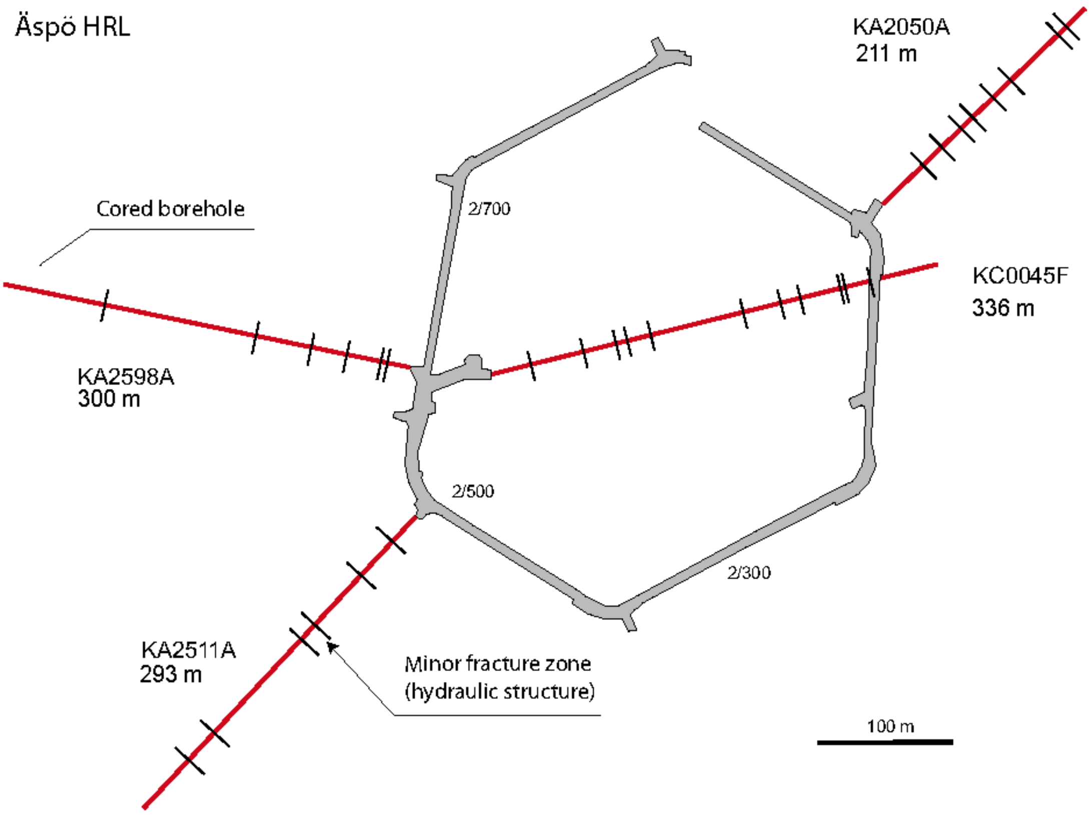


Figure 4-8. *Locations of the core boreholes at – 450 m above sea level.*

Table 4-4. Hydraulic structures and borehole radar indications in core boreholes located at –450 m above sea level in the Äspö HRL.

Borehole	Reflector ID	Bore-hole length (m)	Orientation	Distance from borehole (m)	Geological character	Inflow during drilling, (l/min)
KAS2598A	–	15	–	–	Fractured	10
	–	20	–	–	Fractured	12
	1	45	87/251	10	Crushed, lithological contact	4
	2	74	84/346	13	Fractured, crushed	3
	–	95	–	–	Fractured	3
	3	113	84/173	11	Lithological contact?	–
	7	226	37/054	10	Tectonisation	–
KAS2511A	–	25	–	–	Fractured	30
	2	58	76/164	15	Fractured, crushed, lithological contact	36
	5	106	78/153	10	Fractured, crushed, lithological contact	60
	6	121	71/248	10	Fractured, crushed	–
	–	215	–	–	Fractured	23
	10	241	85/111	10	Fractured, crushed	110
KC0045F	–	30	–	–	Crushed	20
	–	57	–	–	Crushed	25
		95			Fractured, crushed	18
		103			Fractured, crushed	75
		119			Fractured	30
		191			Fractured	43
	–	217	–	–	Fractured	100
		231			Crushed	255
		262			Fractured	840
		266			Fractured, crushed, alteration	200
	–	285	–	–	Crushed	110
KA2050A	22	41	21/314	8	Crushed	6
	5	60	33/008	10	Oxidised, fractured	14
	–	80	–	–	Fractured	30
	9	92	77/120	15	Fractured	66
	–	112	–	–	Fractured	12
	13	129	68/110	8	Fractured	250
	17	178	45/222	12	Crushed and oxidised	300
	19	187	27/225	10	Fractured, oxidised	500

One of the main objectives for the SELECT project was to perform geological, hydrogeological and hydrogeochemical characterization of the designated experimental volumes.

The general strategy for characterising the allocated volumes and identifying suitable sites for experiments within the volumes included:

- complementary geological and structural mapping of the niches from which drilling into allocated experimental volumes will be performed,
- drilling of 8 pilot boreholes into the allocated experimental volumes,
- core logging, borehole TV inspection and borehole radar,
- borehole flowmeter measurements and pressure build up tests.

The results from the integration of the collected data are presented for four rock blocks. The ambition was to account for the main lithological units, the main fracture sets and main fractures zones identified in the defined model blocks. In addition, the descriptive models integrated the collected hydraulic information in order to define hydraulic units. The degree of connectivity within and between blocks and associated degree of sensitivity to outer disturbances was also discussed.

The following rock blocks are discussed:

A) the "REX Block" which focuses on a potential site for the REX experiment centred on boreholes KA2858A and KA2862A,

B) the "TRUE-1 Block" which focuses on a potential site for the experiments planned for the First TRUE Stage, centred on borehole KA3005A and in part on KA3010A,

C) the "TRUE-F Block" which focuses on potential sites for future experiments within the TRUE programme,

D) the "RNR Block" which focuses on a potential site for experiments on radionuclide retention using the so-called Chemlab sonde.

A general observation is that a set of fault zones with associated splays trending NW with a separation of approximately 40 m crosses all the defined blocks. The faults are interpreted as being hydraulically active with estimated transmissivities in the order of $1 \cdot 10^{-6}$ m^2/s. The fault zones consist of one master fault with ca 1 cm thick fault gouge or fault breccia. The master faults are near vertical, dipping from 80° SW to 80° NE and are accompanied by splay cracks contained within 2–3 m off the master fault. These splay cracks occur more frequently on the NE side of the master fault. The splay cracks dip 60–70° to SW. Generally, the master faults are strike slip faults, i.e. the blocks have moved clock-wise along the strike direction. A vertical component of movement, i.e. dip slip, is also observed, but is generally less frequent. These fractures, master faults and splay cracks are mostly filled with calcite and chlorite ± FeOOH.

Ductile fracture swarms trending NNE occur in all the defined rock blocks. The ductile fractures are the oldest formed fractures, most often filled with epidote and chlorite. These fractures have low transmissivities. Often these fractures are surrounded by a few cm-wide red oxidation rims. Thus, water at high temperature has circulated along these fractures. The darker minerals in the granite matrix, most often biotite, are frequently reoriented to the NNE, parallel to these ductile fractures. Comprehensive studies performed in the Äspö HRL site indicate that the schistosity (foliation, or orientation of the darker minerals, is oriented in NE /Munier 1995/.

5 Investigation methods

The investigation methods, which were found to be most useful for identification and characterization of MDZs in the Äspö HRL are presented below.

5.1 Seismic refraction

As a complement to the electric and magnetic measurements, which were partly severely disturbed by man-made installations and saline water, seismic refraction has been used to locate minor fracture zones on Äspö /Sundin 1988/, /Rydström and Gereben 1989/. The investigations on southern Äspö were performed with geophones at 2.5 m centres and shot points at about 12.5 m centres, especially in order to detect minor, narrow fracture zones (MDZs).

5.2 Detailed geomagnetic and geoelectric mapping

As a part of the investigation of the structural pattern on Äspö, detailed ground magnetic and electric mapping were carried out. Magnetic measurements were made every fifth metre along profiles in an east-west direction, with profiles at 10 m centres in the geomagnetic survey and at 40 m centres in the geoelectric survey. Different geometrical arrangements of currents and potential electrodes can be used in geoelectrical mapping. In order to effectively map relatively narrow zones (< 2 m thick), and low-resistivity zones near the surface, a 5–10–5 m dipole-dipole configuration was used.

A combined analysis of the geomagnetic and geoelectic data was carried out, especially with respect to fracture zone delineation /Nisca and Triumf 1989/. The combination of detailed geoelectric and geomagnetic data provided very good basic information concerning the possible extent and orientation of minor fracture zones, but it is very important to try and correlate the geophysical indications with geological features in the field. Most VLF measurements were strongly disturbed by the saline water and man-made installations in the Äspö area have for this reason not been very useful.

To check the correlation between ground geophysical indications (magnetic and resistivity) and structures seen on the ground, a systematic investigation was performed along the trenches. A very good correlation (83%) was found, especially between magnetic indications and different geological minor structures. The correlations between magnetic indications and minor fracture zones are in very good agreement with the results from a very detailed ground susceptibility study along the cleaned trench (see Section 5.3) on southern Äspö. Increased susceptibility values for zones up to a few metres wide were found in red stained zones close to these features, probably due to oxidation of the magnetite in the bedrock /Barmen and Stanfors 1988/.

5.3 Detailed geological mapping

Recognition of minor fracture zones and single open fractures, and their orientation within and near the site area on Äspö was achieved by means of detailed surface mapping along cleaned trenches across the island (Figure 4-2). The results of these investigations, complemented with subsurface information, have been very useful in the geological characterization of rock volumes in the site area.

A geological map in the scale 1:2000 was presented /Kornfält and Wikman 1988/.

5.4 Borehole investigations

The cored borehole KAS13 was drilled in a direction specially intended to locate NNW-trending minor fracture zones indicated on southern Äspö. Core mapping data and borehole radar measurements in KAS13 complemented the results from a VSP survey (KAS07) and confirmed the geological and geophysical indications from surface investigations /Sehlstedt et al. 1990/.

A number of geophysical borehole logs were used in order to detect and characterize minor fracture zones and single open fractures. To obtain their absolute orientation, TV-logging and Televiewer measurements were performed /Fridh and Stråhle 1989/.

Single hole radar reflections gave valuable information about the orientation of minor fracture zones – especially those intersecting the borehole at rather low angles. A number of prominent structures were indicated in the boreholes using the directional antenna and dipole antenna radar measurements that corroborated the presumed orientation of some of the minor zones interpreted /Niva and Gabriel 1988, Carlsten 1989/. Some examples of the usefulness of borehole radar are presented in Appendix B, C and D.

VSP results were found to be important as a complement to the borehole radar data, especially after 3D-processing using a new technique with Image Space Filtering, which has been developed for seismic studies in crystalline rock.

The results of the caliper log and electric logs were of greatest interest in detecting fractures and minor fracture zones.

The use of TV logging and Televiewer methods for absolute orientation of fractures in core boreholes was accompanied by many problems. It was for example, very difficult to identify the same feature in the core as in the TV log and Televiewer records, due to less exact depth measurements.

6 Discussion

There is a considerable body of knowledge on water-bearing structures in Äspö HRL. This report, however, addresses mainly MDZs as regards frequency and spacing.

Most of the major fracture zones intersecting the Äspö HRL proved to be highly or moderately water-bearing which resulted in very comprehensive grouting activities. It was also found that minor deformation zones (MDZ) could be very important as hydraulic conductors. More than 50% of the grout volume was consumed by the MDZs.

Field data – geological and geophysical – gave the first indications of a NNW-NNE-trending fracture swarm and minor MDZs. Interference hydraulic tests in boreholes from the ground water surface on southern Äspö revealed their hydraulic importance. During excavation of the tunnel, this kind of MDZs have been mapped and indicated and some have been found by drilling (core- and probeholes). This type of hydraulically significant MDZ is complicated to describe deterministically by means of geological and geophysical investigations. It is considered that this type of structure is likely to be rather common in the“rock blocks lying between the major fracture zones”

From Chapter 4 it's evident that mapped "water-bearing" or "water conducting fractures" in Äspö HRL can be related to a great variety of features such as "fractures", "single open fractures", "fracture zones", "fracture swarms", "faults" and "fault zones". In the following discussion the term MDZ (minor deformation zone) is used for all these structures.

The term "water-bearing" or "water conducting" are also used for very different amount of water inflow, normally divided into the following three groups: flow, drop and moisture. Transmissivity values are present from core boreholes and probeholes drilled prior to the tunnel excavation. In the following the terms "major flow" ($T > 10^{-5}$ or $Q > 10$ l/min) or "minor flow" are used.

Data from the different studies presented in Chapter 4 are summarised in Table 6-1.

From Table 6-1 we can see that the distance between geologically indicated MDZs on surface is estimated to be in the range of 50–100 m, except for a few E-W structures on Äspö. In the detailed trench study we have a shorter distance due to the fact that some of the mapped structures are "single fractures".

The 50–100 m spacing between magnetic lineaments correlates normally to MDZs with a thickness of > 2–3 m.

The interpretation of MDZs in deep boreholes from surface was based on core mapping, geophysical logging, radar and water inflow indications. No BIPS was available, which contributes to the uncertainty of detecting all the MDZs. A distance of 75–200 m between MDZs is estimated for most of the boreholes.

According to the results from tunnel investigations MDZs can be divided into two main groups. The first group has an estimated spacing of 75–200 m, with major water inflows and thicknesses from 0.5–c 3 m. This is confirmed by a mean spacing of grouting sections of c 65 m. The second group has a spacing of c 25–35 m probably corresponding to structures less than 0.5 m thick and associated with minor water inflows. Hydraulic data and detailed investigations in the TRUE Block Scale seem to confirm this assumption.

Vertical distance between mapped sub-horizontal fracture swarms in the tunnel is estimated to be c 100 m.

Table 6-1. Estimated distance between water-bearing minor structures (MDZs) in ÄHRL based on data from different geological studies.

Investigated part of ÄHRL	Geological study	Reference	Estimated mean distance between water-bearing minor structures	
Surface	Detailed investigation of minor fracture zones (single open fractures) based on lineaments and geophysical maps	/Talbot and Munier 1989/ PR 25-89-11	NNW steep faults	50–100 m
			NE and NW trending faults	10–40 m
			N-S trending fractures	ca 50 m
			E-W structures	200–300 m
Surface	Detailed magnetic investigation	/Nisca and Triumf 1989/ PR 25-89-01	Magnetic lineaments Different directions	50–100 m
Surface	Detailed geological mapping of 3 uncovered trenches	/Ericsson 1988/ PR 25-88-10 /Kornfält and Wikman 1988/ PR 25-88-12	Minor fracture zones	ca 75 m
			Minor fracture zones and single open fractures (more detailed mapping)	ca 35 m
Core bore-holes from surface	Interpretation of geological and geophysical logging in KAS02, KAS05-08, KBH02, KAS09, KAS12-13	/Sehlstedt and Triumf 1988/ PR 25-88-15	Interpretation of minor fracture zones (single open fractures) based on geological and geophysical and hydraulic borehole data	75–200 m
		/Sehlstedt and Stråhle 1989, Sehlstedt et al. 1990/ PR 25-89-09, PR 25-90-06		
		/Rhén et al. 1991/ PR 25-91-01		
Tunnel	Detailed investigation of water-conducting minor structures	/Mazurek et al. 1996/ PR 25-95-03	Heavy ($Q > 10$ l/min) and medium($Q < 10$ l/min) water inflow	68(28)
		TMS (SICADA)		61(36)
Tunnel	Investigation of predicted NNW minor fracture zone system	/Kickmaier 1995/ SKB ICR 95-02	N-S fracture swarms	ca 100 m
Tunnel	Structural geology of water-bearing fractures and fracture swarms in the tunnel spiral	/Hermansson 1995/ PR 25-95-23	Seven sub-horizontal fracture swarms were identified	ca 100 m
			Major water-bearing up to some cm-wide sub-vertical fractures	ca 35 m
Tunnel	Data from 4 sub-horizontal core boreholes at the 450 m level	/Olsson 1994/ PR 25-94-03	Major (minor) water inflow in sub-horizontal boreholes	ca 25–50 m
Tunnel	Distance between structures with a specified transmissivity	/Rhén et al. 1997/ TR 97-06	Hydraulic conductors in probe holes $T > 10^{-5}$ ($T > 10^{-7}$)	70 (35) m
		/Rhén and Forsmark 2001/ IPR-01-65	Hydraulic conductors in core boreholes $T > 10^{-5}$ ($T > 10^{-7}$)	45 (14) m
Tunnel	Grouting experience from Äspö HRL	/Stille and Olsson 1996/ PR HRL 96-07	Pre-grouted major water inflow in tunnel	c 65 m
Tunnel	TRUE Block scale project. Hydro-structural model based on seven core boreholes. Use of hydraulic tests, BIPS, borehole radar and VSP and HSP seismic cross-hole techniques	/Andersson et al. 2002/ TR-02-13	Hydraulic structures trending NW	25–50 m
Tunnel	The Select Project. Detailed geological and hydraulic investigations of four rock blocks	/Winberg et al. 1996/ HRL 96-01	Fault zones trending NW	c 40 m

Figure 6-1 shows an increased frequency of MDZs between the major zones NE-3 and NE-1. Almost all MDZs in the tunnel are water-bearing but only major inflows (W) are indicated. A comparison between the mean distance of MDZs on surface, in deep boreholes and underground shows a good agreement and it seems possible to make a fairly good judgement concerning frequency and spacing of MDZs at repository level based on surface and borehole pre-construction investigations.

Some MDZs e.g. NE-2 and NNW-4, have been possible to follow at different depths in HRL down to the –450 m above sea level (Figures 3-1, 3-2 and 3-3). However, normally it is very difficult to identify a certain surface indication of an MDZ in boreholes due to the lateral variation in character (Figure 6-2). There is normally no specific geological signature for an MDZ in Äspö but the lithology of the water-bearing MDZ has some bearing on the characteristics of these structures. The fracture density in the dikes and veins of fine-grained granite is much higher when compared with the main granitoids. Figure 6-1 shows a correspondence between many MDZs and fine-grained granite.

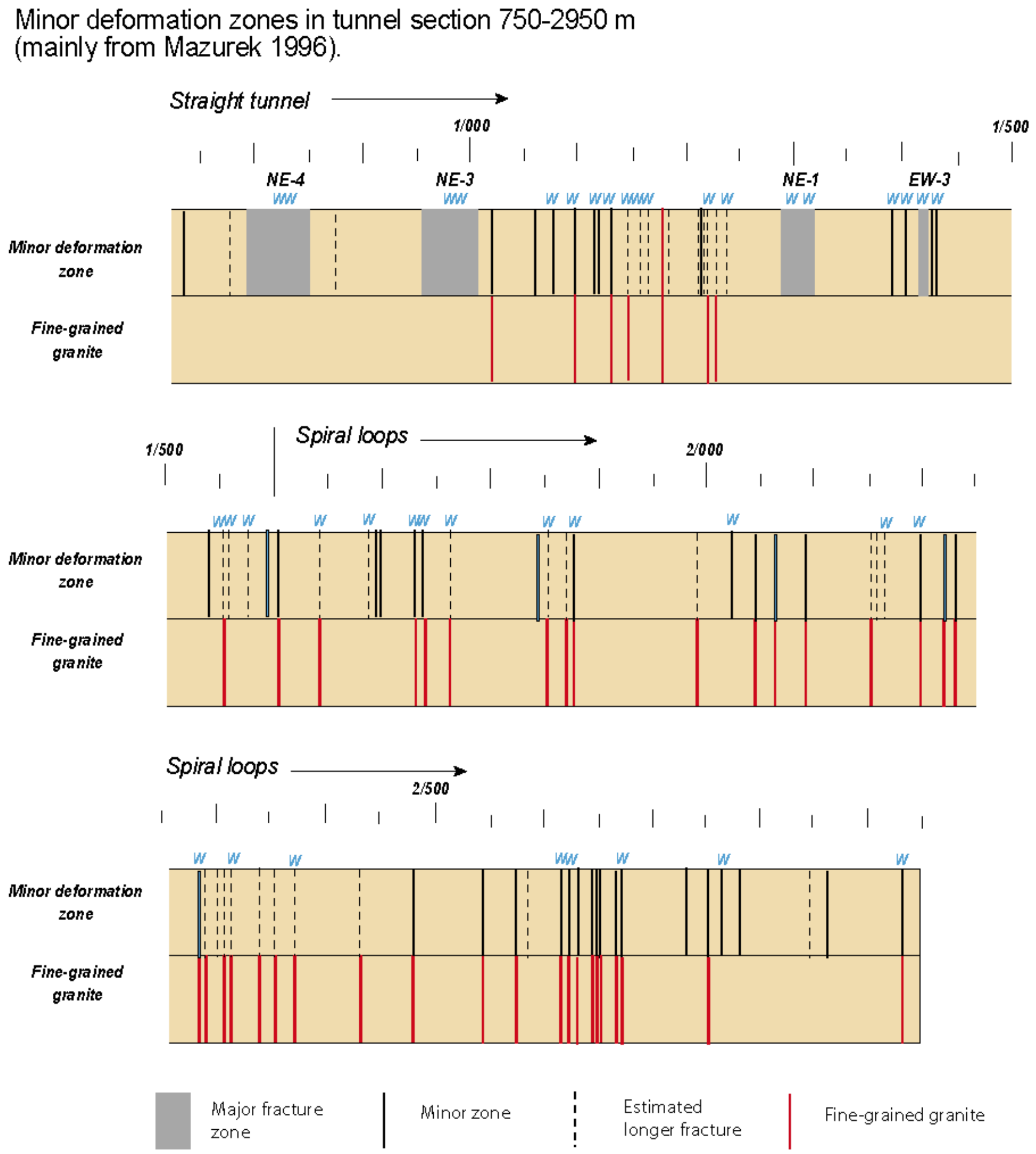


Figure 6-1. Distribution of MDZs in the Äspö HRL.

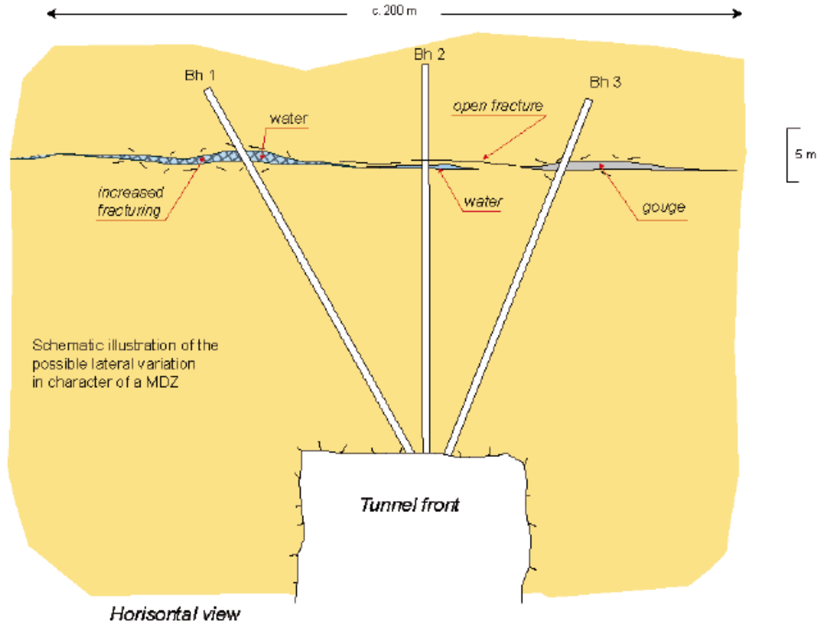


Figure 6-2. *Example illustrating possible lateral variation in character of an MDZ.*

There is also a relationship between the water-bearing MDZs and the stress field. Over the whole depth, the maximum stress axis is oriented in a NW-SE direction. The NW-SE oriented MDZs, which are parallel to this direction could explain the higher conductivity of these structures compared to the more tight NE-SW trending MDZs.

Detailed geological mapping along cleaned trenches, combined with geophysical measurement, are the best methods to indicate MDZs at surface. In boreholes a combination of BIPS, boremap, geophysical logging, radar and hydraulic diff. logs has proved to be most useful (Figure 6-3). However, it is interesting to notice that many radar indications correspond to lithological contacts.

The sub-horizontal cored borehole KBH02 was drilled prior to the tunnel excavation. The main aim of the borehole was to locate and investigate geophysically indicated deformation zones. The borehole is close to and almost parallel with the tunnel for about 600 m. There is a good correlation between major fracture zones detected in KBH02 and those recorded in the tunnel mapping. In addition, the number of MDZs is almost the same in borehole and tunnel but it is very difficult to correlate a particular zone in the borehole with a specific zone in the tunnel (cf Appendix B). Two other examples demonstrating the possibility of identifying MDZs prior to excavation in a TBM tunnel and in a vertical shaft, by use of boreholes, are presented in Appendices C and D.

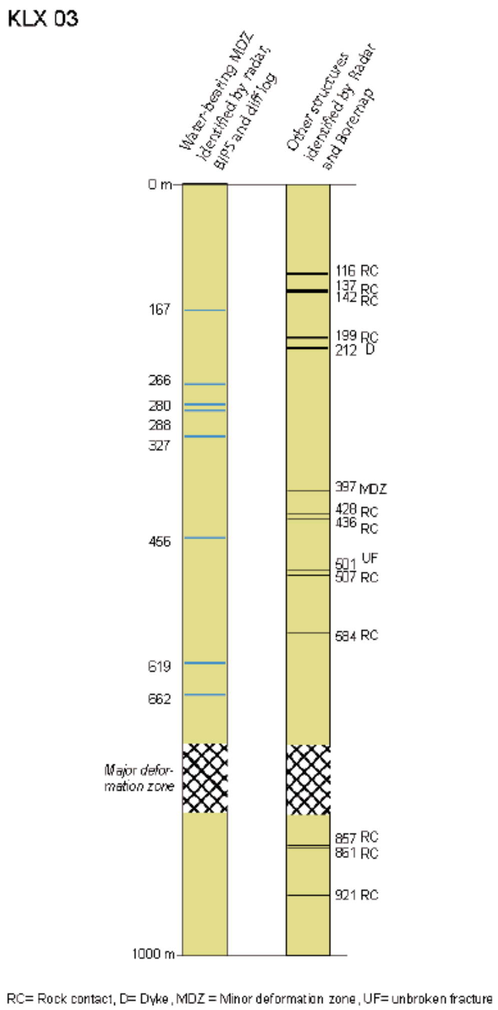


Figure 6-3. *Example of combined radar, BIPS and diff. log investigation in order to identify MDZ in core borehole KLX03 /Carlsten in Cosgrove et al. 2006/.*

7 Conclusions

7.1 Classification and definition of minor structures

10 m seems to be the approximate upper limit of fracture length recorded during small scale fracture mapping on outcrops. A discrete fracture (fault or joint) can of course be larger than 10 m as there is no natural limit between "fractures" and minor deformation zones. The thickness of a discrete fracture is normally in the mm–cm scale. The term MDZ (minor deformation zone) should be used to designate an essentially 2-dimensional structure, which has a lateral extent of < 1,000 m and thickness < 5 m. MDZs commonly show evidence of both brittle and ductile deformation from brittle low-cohesive indicators like increased fracturing, breccia and gouge to ductile cohesive indicators such as strongly foliated or mylonitic rock.

7.2 Identification of conductive MDZs from surface

The feasibility of identifying conductive MDZs and their properties is dependent on the geological structural model (the site), the number of interference tests, the number of pressure observation sections in boreholes and the complexity of the major conductive structures themselves.

Field data, both geological and geophysical, gave the first indications of NNW-NNE-trending swarm of MDZs. Fractures in this swarm are often red-stained or filled with quartz. Hydraulic interference tests in boreholes on southern Äspö revealed their hydraulic importance. During excavation of the tunnel, this kind of MDZ has been identified by mapping and some found by drilling. This type of hydraulically significant zone is complex to describe deterministically by means of geological and geophysical investigations. Possibly they are rather common in what is considered to be "rock blocks between the major fracture zones" but the exact position and orientation of sub-vertical MDZs at depth seem to be almost impossible to determine within reasonable efforts.

7.3 Verification of MDZs in the tunnel

During the excavation of the tunnel at Äspö, three types of investigations have been performed involving documentation of each blast round, an on-line borehole monitoring programme and supplementary borehole investigations.

MDZs predicted to intersect the tunnel were verified mainly by mapping in the tunnel. In some cases short boreholes have been drilled into the zone in order to perform hydraulic tests and to characterize the zone. Character, dip and direction are important for verifying a predicted zone. However, fracture zones are generally irregular,winding and with varying thickness, and the measured dip and direction cannot be expected to be exactly as predicted (Figure 6-2). Except in a few cases, the extent of the fracture zones cannot be verified from the tunnel though hydraulic tests can be helpful in some cases.

Core drilling has occasionally been used to define the positions of expected fracture zones in front of or close to the tunnel. In these cases, position in the borehole, character and hydraulic tests have been used to verify the fracture zone. Using just one cored borehole when the tunnel does not intersect the zone may lead to problems with verification depending on the character of the zone. If the fracture zone does not intersect the tunnel, but only the borehole, only geological character, similarity in hydraulic properties and hydraulic responses in observation boreholes verify the fracture zone. For successful evaluation of the responses it is important to have a large number of observation points in the rock mass, and one or more should intersect the zone.

7.4 Geological character of MDZs

There is no distinguishing feature or specific geological signature of the mapped water-bearing MDZs, but the main strike is roughly NW to WNW with subvertical dip. Sub-horizontal zones seem to be of minor hydraulic importance.

About 50% of the zones contain cohesive fault rock and have reactivated pre-existing shear zones, the other 50% have some incohesive fault rock such as gouge and fault crush.

Dominating fracture fillings are mainly chlorite, calcite and epidote. Clay and Fe-oxyhydroxides occur in minor amounts.

There is a correlation between dikes and veins of fractured fine-grained granite and water-conducting structures.

7.5 How can we estimate the length of a MDZ

With the exception of a few MDZs that have been possible to trace from the surface down to the –450 m above sea level in Äspö, we do not know anything about the length of the mapped structures.

There is no evident correlation between a specific geological signature of an MDZ and hydraulic conductivity. However, water-bearing fractures are often longer than other fractures. /Hermansson 1995/, and /Kickmaier 1995/ found that N-S striking water-bearing fractures can be traced at least 200 m in the tunnel.

As displacements along fractures (MDZs) with a radius > 100 m that cut the canister hole are assumed to damage the canister, it is important to identify these critical structures during construction of a repository. Experience from Äspö shows that it is almost impossible to determine the length of an MDZ by direct observations in the tunnel. The only reasonable method is to regard all MDZs with full perimeter intersections as critical.

The best methods for investigation of structures that may lie parallel to the tunnel and intersect canister holes are core drilling with Boremap, BIPS and Borehole radar. The parameters most closely linked to MDZ length are considered to be MDZ thickness and to some extent kinematic indicators. High conductivity is more likely linked to longer than shorter structures. It is possible to get a good estimate of the frequency and orientation of longer structures using detailed interpretation of topographic and geophysical lineaments during surface pre-construction investigations.

8 References

Andersson P, Byegård J, Dershowitz B, Doe T, Hermanson J, Meir P, Tullborg E-L, Winberg A, 2002. Final report of the TRUE Block Scale projekt 1. Characterization and model development. SKB TR 02-13, Svensk Kärnbränslehantering AB.

Barmen G, Stanfors R, 1988. Ground level geophysical measurements on the island of Äspö. SKB PR 25-88-16, Svensk Kärnbränslehantering AB.

Bäckblom G, 1989. Guide-Lines for use of nomenclature on fractures, fracture zones and other topics. SKB HRL-96-18, Svensk Kärnbränslehantering AB.

Carlsten S, 1989. Results from borehole radar measurements in KAS05, KAS06, KAS07 and KAS08 ar Äspö. Interpretation of fracture zones by including radar measurements from KAS02 and KAS04. SKB PR 25-89-10, Svensk Kärnbränslehantering AB.

Carlsten S, 1990. Borehole radar measurements at Äspö boreholes KAS09, KAS10, KAS11, KAS12, KAS13 and KAS14. SKB PR 25-90-05, Svensk Kärnbränslehantering AB.

Cosgrove J, Stanfors R, Röshoff K, 2006. Geological characteristics of deformation zones and a strategy for their detection in a repository. SKB R-06-39, Svensk Kärnbränslehantering AB.

Ericsson L O, 1988. Fracture mapping study on Äspö island. Findings of directional data. SKB PR 25-88-10, Svensk Kärnbränslehantering AB.

Fridh B, Stråhle A, 1989. Orientation of selected drillcore sections from the boreholes KAS05 and KAS06 Äspö, Sweden. A Televiewer investigation in small diameter boreholes. SKB PR 25-89-08, Svensk Kärnbränslehantering AB.

Hermansson J, 1995. Structural geology of water bearing fractures. SKB PR 25-95-23, Svensk Kärnbränslehantering AB.

Kickmaier W, 1995. Definition and characterization of the N-S fracture system – tunnel sections 1/600 to 2/400 m. Relationships to grouted sections – some remarks. SKB ICR 95-02, Svensk Kärnbränslehantering AB.

Kornfält K-A, Wikman H, 1988. The rocks of the Äspö island. Description to the detailed maps of solid rocks including maps of 3 uncovered trenches. SKB PR 25-88-12, Svensk Kärnbränslehantering AB.

Mazurek M, Bossart P, Eliasson T, 1996. Classification and characterization of water-conducting features at Äspö: Results of investigations on the outcrop scale. SKB ICR-97-01, Svensk Kärnbränslehantering AB.

Munier R, 1995. Studies of geological structures at Äspö – Comprehensive summary of results. SKB PR 25-95-21, Svensk Kärnbränslehantering AB.

Nisca D, Triumf C-A, 1989. Detailed geo-electric mapping of Äspö. SKB PR 25-89-01, Svensk Kärnbränslehantering AB.

Niva B, Gabriel G, 1988. Borehole radar measurements at Äspö and Laxemar. Boreholes KAS02, KAS03, KAS04, KLX01, HAS02, HAS03 and HAV07. SKB PR 25-88-03, Svensk Kärnbränslehantering AB.

Olsson O, 1992. Characterization ahead of the tunnel front by radar and seismic methods – a case history from the Äspö HRL. SKB PR 25-92-01, Svensk Kärnbränslehantering AB.

Olsson O (ed), 1994. Localization of experimental sites and layout of turn 2. Results from core mapping, radar and hydraulic investigations. Compilation of Technical Notes 2. SKB PR 25-94-15, Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, Nilsson L, 1991. Hydraulic test on Äspö, Bockholmen and Laxemar 1990 in KAS09, KAS11–14, HAS18–20 KBH01–02 and KLX01. Evaluation. SKB PR 25-91-01, Svensk Kärnbränslehantering AB.

Rhén I, Stanfors R, Wikberg A, Forsmark T, 1995. Comparative study between the cored test borehole KA 3191F and the first 200 m extension of the TBM tunnel. SKB PR-25-95-09, Svensk Kärnbränslehantering AB.

Rhén I, Gustafson G, Stanfors R, Wikberg A, 1997. Äspö HRL – Geoscientific evaluation 1997/s. Models based on site characterization 1986–1995. SKB TR 97-06, Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, 2001. Äspö Hard Rock Laboratory, Prototype repository, Hydrogeology, Summary report of investigations before the operation phase. SKB IPR 01-65, Svensk Kärnbränslehantering AB.

Rydström H, Gereben L, 1989. Seismic refraction survey on Äspö and Hålö. SKB PR 25-89-18, Svensk Kärnbränslehantering AB.

Sehlstedt S, Triumf C-A, 1988. Interpretation of geophysical logging data from KAS02–04 and HAS08–12 at Äspö and KLX01 at Laxemar. SKB PR 25-88-15, Svensk Kärnbränslehantering AB.

Sehlstedt S, Stråhle A, 1989. Geological core mapping and geophysical borehole logging in the boreholes KAS05–08 at Äspö. SKB PR 25-89-09, Svensk Kärnbränslehantering AB.

Sehlstedt S, Stråhle A, Triumf C-A, 1990. Geological core mapping and geophysical borehole logging in the boreholes KBH02, KAS09, KAS11–14 and HAS18–20 at Äspö. SKB PR 25-90-06, Svensk Kärnbränslehantering AB.

Stille H, Gustafson G, Håkansson U, Olsson P, 1993. Passage of water-bearing fracture zones. Experiences from the grouting of the section 1–1,400 m of the tunnel. SKB PR 25-92-19, Svensk Kärnbränslehantering AB.

Stille H, Jansson T, Olsson P, 1994. Experiences from the grouting of the section 1,340–2,465 m of the tunnel. SKB PR 25-94-13, Svensk Kärnbränslehantering AB.

Stille H, Olsson P, 1996. Summary of rock mechanics experience rom the construction of the Äspö Hard Rock Laboratory. SKB PR HRL 96-07, Svensk Kärnbränslehantering AB.

Stråhle A, 1989. Drillcore investigations in the Simpevarp area. Boreholes KAS02, KAS03, KAS04 and KLX01. SKB PR 25-88-07, Svensk Kärnbränslehantering AB.

Sundin S, 1988. Seismic refraction investigation at Äspö. SKB PR 25-87-15, Svensk Kärnbränslehantering AB.

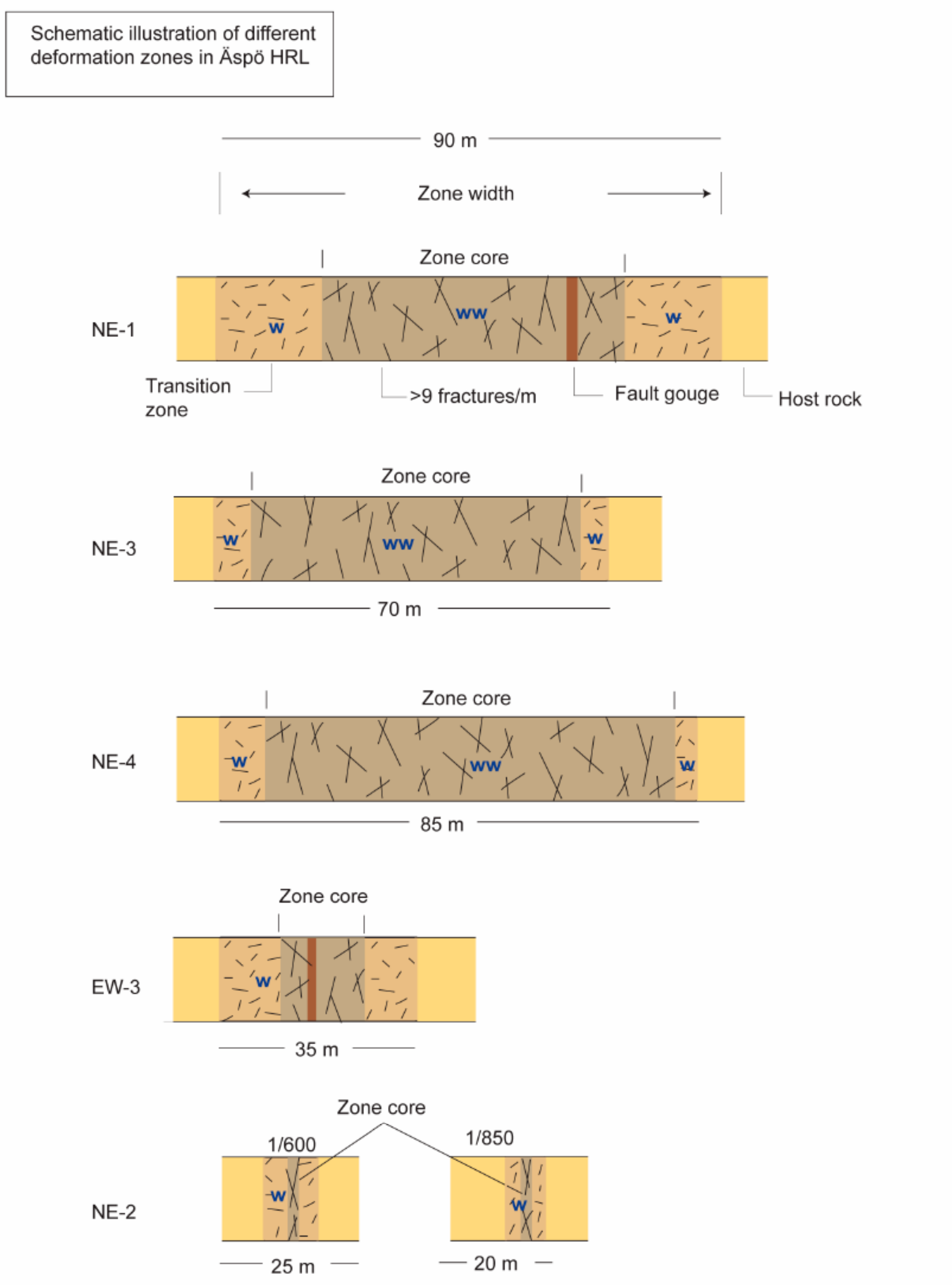
Talbot C, Munier R, 1989. Fault and fracture zones on Äspö. SKB PR 25-89-11, Svensk Kärnbränslehantering AB.

Tirén S, Beckholmen M, 1987. Structural analysis of contoured maps, Äspö and Ävrö, SE Sweden. SKB PR 25-87-22, Svensk Kärnbränslehantering AB.

Winberg A, Andersson P, Hermansson J, Stenberg L, 1996. Results of the Select Project. SKB HRL-96-01, Svensk Kärnbränslehantering AB.

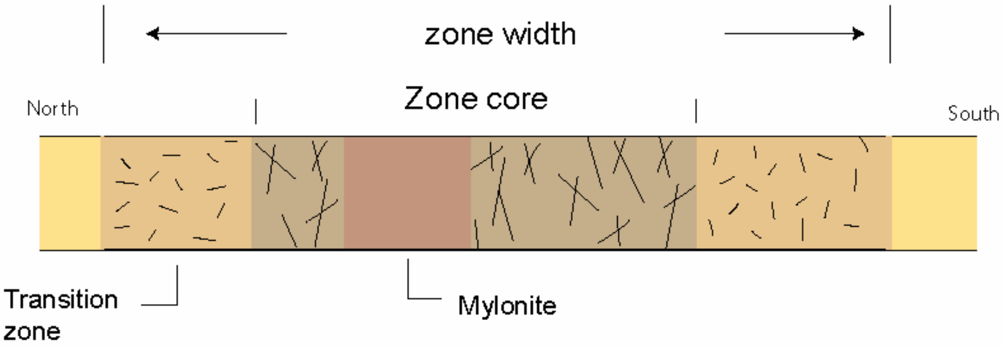
Appendix A

Examples of deformation zones in Äspö HRL



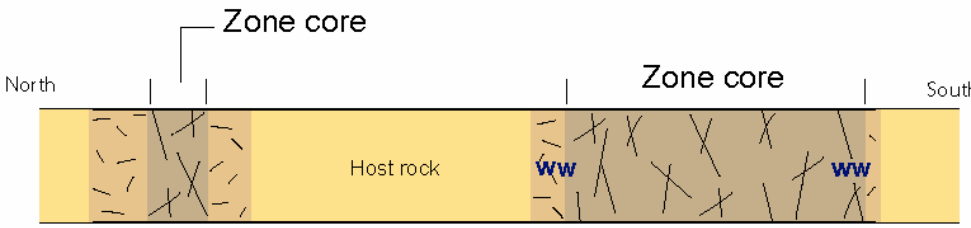
Schematic illustration of the major deformation zone EW-1 mapped on surface and in a subhorisontal core borehole at a depth of 300-350 m.

Surface mapping along trench crossing EW-1



The core is mylonitic, heavy fractured and partly altered. Surrounded by transition zones with moderate increased fracturing.

KA1755A, core mapping (300-350 m depth)



EW-1 at 300-350 m depth is divided into two fractured branches separated by c. 50 m fresh host rock.

Comparison between the Äspö tunnel and the sub-horizontal borehole KBH02

Comparison between the Äspö tunnel and the sub horizontal borehole KBH02

The sub horizontal cored borehole KBH02 was drilled during investigations. prior to tunnel excavation. The main aim of the borehole was to locate and investigate geophysically indicated deformation zones. The borehole is close to and almost parallel with the tunnel for about 900 m (Figure B-1).

A comparison between tunnel mapping data and data obtained from the borehole investigations, especially concerning deformation zones and longer fractures, is presented in Figure B-2 and Table B-1.

Tunnel mapping data is taken mainly from Äspö TMS (Tunnel Mapping System) and /Mazurek et al. 1996/. It's important to note that the borehole mapping of KBH02 was performed without BIPS TV.

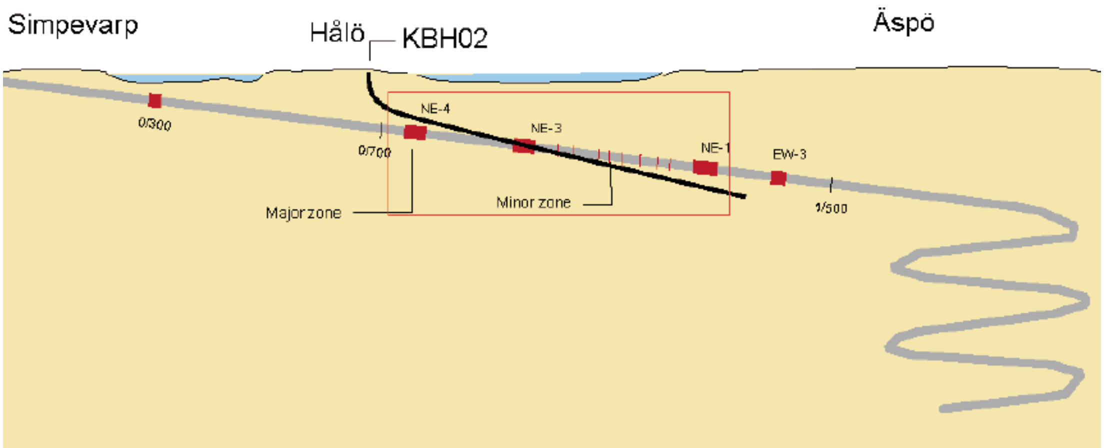


***Figure B-1.** Position of KBH02 in Äspö HRL.*

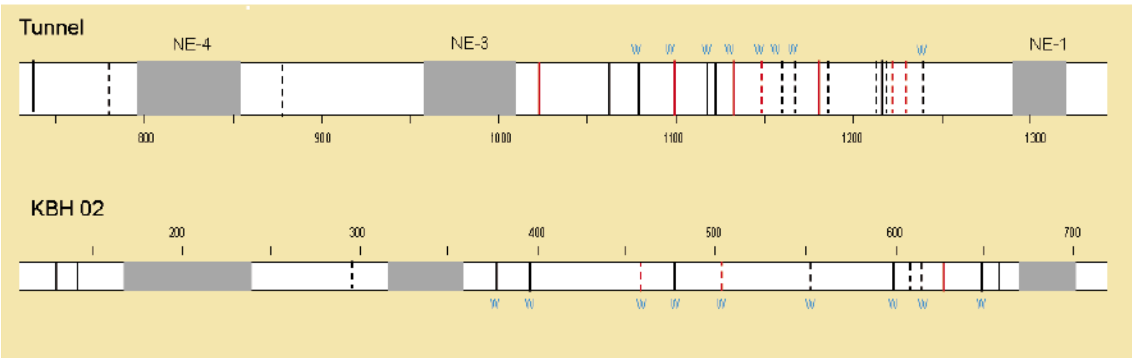


***Figure B-2.** Comparison between the Äspö Tunnel section (750–1,350 m) and KBH02 (100–700 m).*

Table B-1. Comparison between mapping data in tunnel section (650–1,350 m) and core borehole KBH02 (100–700 m). Note: length in KBH02 translated to tunnel length.

Tunnel Length	Zone	Water inflow	KBH02 Length	Zone	Water inflow
735	MZ	–	750	MZ	–
780	LF	–	762	MZ	–
796–858	NE-4	ww	785–860	NE-4	w
875	LF	–	–	–	
–	–		915	LF	–
958–1,009	NE-3	ww	955–1,005	NE-3	ww
1,020	MZ*	–	1,015	MZ	w
1,060	MZ	–	–	–	–
1,080	MZ	w	1,080	LF*	w
1,100	MZ*	w	1,095	MZ	w
1,120	MZ	w	–		
1,125	MZ	–	1,125	LF*	w
1,135	MZ*	w	–	–	
1,148	LF* (r)	w	–	–	
1,156	LF	w	–	–	
1,165	LF (r)	w	–	–	
1,180	MZ*		1,175	LF	w
1,185	LF				
1,210–1,220	MZ+ LF (r)	w	1,220	MZ	w
1,230	LF*		1,230	LF	
1,240	LF	w	1,240	LF	w
–	–		1,250	MZ*	
–	–		1,270	MZ	w
–	–		1,280	MZ	
1,290–1,320	NE-1	ww	1,295–1,330	NE-1	ww

MZ: minor zone,

LF: long fracture,

NE-1, NE-3, NE-4: major zones,

*: associated with fine-grained granite,

(r): radar indicator.

Main results

- There is a good correlation between major fracture zones detected in borehole KBH02 and those recorded in the tunnel mapping data regarding both position and zone width.
- The number of minor zones is almost the same in borehole and tunnel but it is often very difficult to correlate a particular zone in the borehole with a specific zone in the tunnel.
- The lower number of long fractures detected in KBH02 compared to the tunnel can be explained by the difficulty in detecting fractures in a borehole, without radar and BIPS.
- Both in KBH02 and in the tunnel it was noted that most of the structures were water bearing.
- There was no radar measurements in KBH02 but such measurements were taken in the two boreholes (KA1061A and KA1131B) drilled from niches in the tunnel (Figure B-3) /Olsson 1992/.
- There is a likely correlation between three radar reflectors and the core in the boreholes with fracture zones in the tunnel. However to be certain it is necessary to demonstrate that the structures in the tunnel have the same geological signatures as the corresponding fracture zones in the cores.

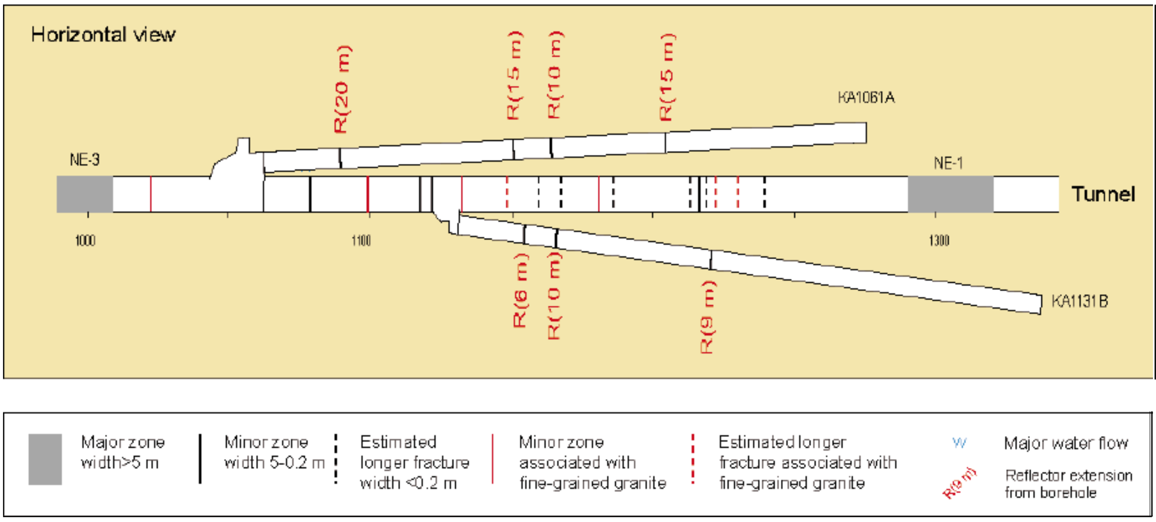


Figure B-3. *Radar reflectors in boreholes drilled from the ramp (KA1061A and KA1131B).*

Appendix C

Comparative study of the cored borehole KA3191F and the first 200 m of the TBM tunnel

Comparative study of the cored borehole KA3191F and the first 200 m of the TBM tunnel

The last 400 m of the ÄHRL were excavated by a Tunnel Boring Machine (TBM) with a diameter of 5 m /Rhén et al. 1995/.

In order to make a good characterization of the TBM rock volume a cored borehole (KA3191F) was drilled in advance of the TBM boring. One aim was to compare data from the cored borehole KA3191F with the documentated data from the TBM-tunnel.

The borehole KA3191F was drilled from the TBM assembly hall along the centre line of the planned TBM tunnel down to the lowest position of the excavation at a depth of 450 m below ground surface in the vicinity of the shafts. The borehole was 210 m long (Figure C-1).

A Comparison of the data from borehole KA3191F and the TBM-tunnel is presented in Figure C-2 and Table C-1.

Main results

- It was possible to make accurate predictions from the borehole data regarding the major rocks and major conductive sections encountered in the tunnel.
- A correlation was also found between some but not all radar reflectors detected in the borehole and geological and hydraulic structures within the tunnel.
- There is normally a good correlation between geophysical logging data and increased fracturing/alteration of the rock in the tunnel.
- There is a direct correlation between the results of flow mapping during drilling and hydraulic tests and the parts of the tunnel that have or have not been grouted.

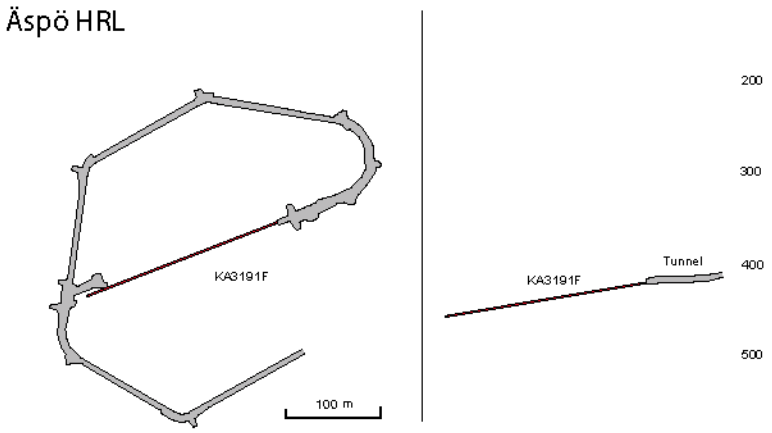


Figure C-1. *Position of KA3191F and the TBM tunnel.*

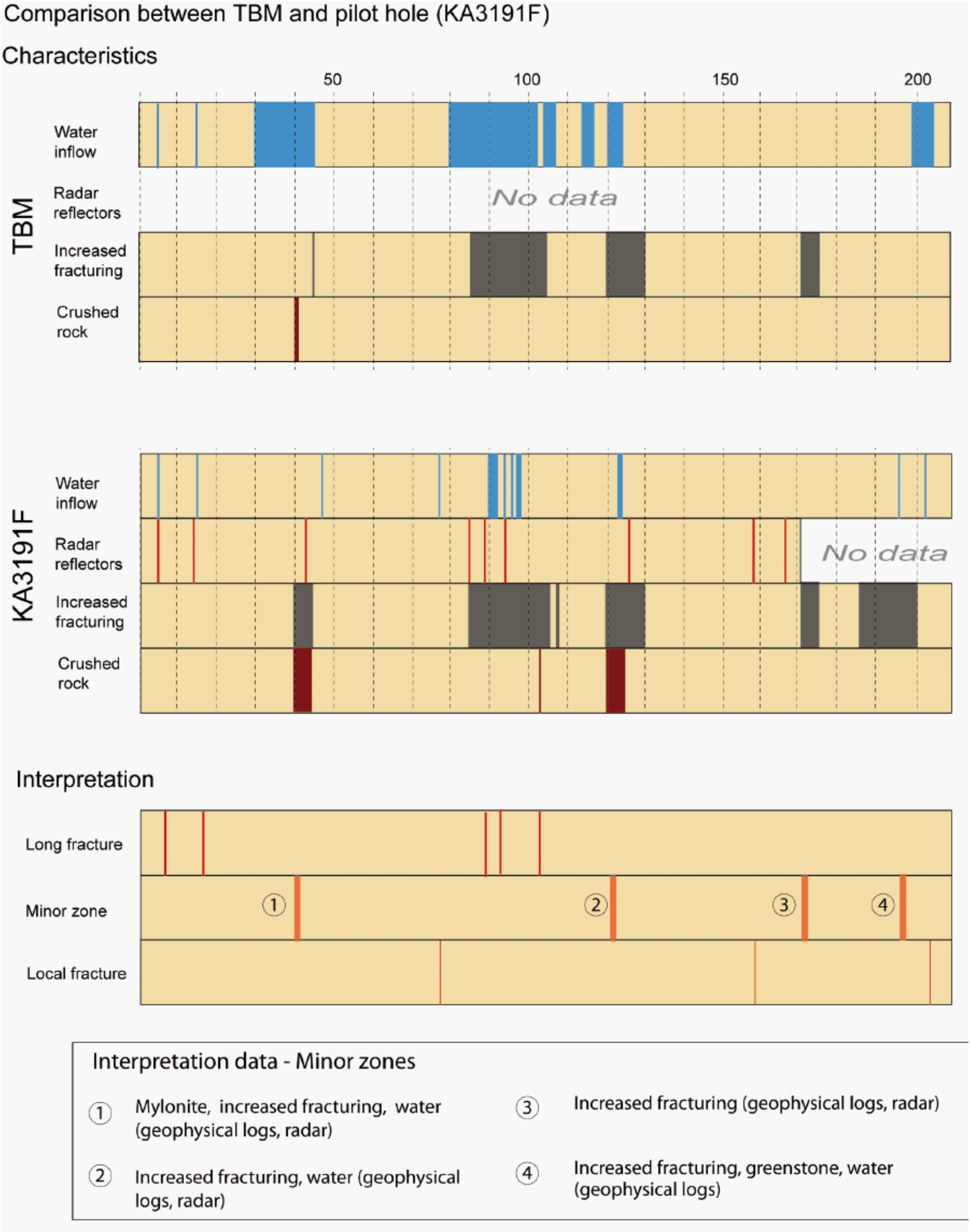


Figure C-2. *Comparison of data from borehole KA3191F and the TBM tunnel.*

Table C-1. Comparison between characteristics mapped in TBM-tunnel and borehole data in KA3191F.

Characteristics	TBM Tunnel investigations	KA3191F Borehole investigations	Borehole radar
Increased fracturing	45 m	40–43 m	42 m
	80–105	85–105	85, 88
	–	108	–
	120–130	120–130	126
	–	–	158
	171–175	171–175	166
	–	188–200	–
Crushed rock	40–41 m	40–43 m	42 m
	–	102	–
	–	120–125	126
Water inflow	5 m	5 m	5 m
	15	15	14
	30–45	48	42
	–	78	
	80–102	90–92	88
		94	94
		96	
		98	
	104–106	–	
	113–116	–	
	120–123	120–123	126
	198–203	195	No data
		202	No data

Appendix D

Comparative study between geological mapping data of the elevator shaft and the cored boreholes KAS05 and KAS02

Comparative study between geological mapping data of the elevator shaft and the cored boreholes KAS05 and KAS02.

During the construction of the two ventilation shafts in the Äspö HRL (diameter 1.5 m) and one elevator shaft (diameter 3.8 m) were excavated using the raise-boring technique. The elevator shaft was mapped from 0–440 m depth. The ventilation shafts were only partly available for mapping /Munier 1995/.

Data from the sub-vertical cored boreholes KAS05 and KAS02 can be compared with geological shaft data (Figure D-1) /Sehlstedt and Stråhle 1989, Stråhle 1989/. KAS05 and KAS02 were drilled at an early phase of the investigations for Äspö HRL. The separation between boreholes and shafts is 40–50 m.

The only prominent structure in the elevator shaft is an approximately 10 m thick mylonite zone at a depth of between 150–170 m that locally strikes N-NNE and dips 75° NW. The mylonite contains a thin fault zone with a measured flow rate in the range of 1–5 l/min. It is noteworthy that only a handful of fractures carry water in the elevator shaft /Munier 1995/.

Main results

- The distribution of rocks in the shaft and the boreholes (Småland granite with fine-grained granite and greenstone) is quite similar.
- The frequency of MDZs and longer fractures mapped in the shaft is in the same order as that estimated in the boreholes. It seems to be very difficult to make a correlation between specific structures in a shaft and boreholes ca 50 m from the shaft.
- The separation between the boreholes and the shaft (between 40–50 m (see Figure D-1) has resulted in an element of uncertainty in tracing a specific structure in the shaft to the adjacent boreholes. However, Figure D-2 shows a probable correlation based on radar data from the boreholes and oriented data from the shaft. Radar can normally be used to trace fractures from the borehole into the surrounding country rock for distances between 10–40 m /Carlsten 1989/.

Conclusions

- In the Äspö HRL there is a good correspondence between minor deformation zone indications on the surface, in the tunnel and in cored boreholes concerning estimated fracture frequency and spacing.
- Considerable uncertainty is associated with attempting to correlate a specific minor structure between parallel boreholes or between a borehole and a parallel tunnel or shaft when separated by more than 10–20 m, unless they are characterized by a good hydraulic or geological signature.
- Hydraulic conductivity can be an important signature of long fractures.
- In the few cases where we have been able to estimate the length of the MDZs at Äspö, it is not possible to define any relationship between length, thickness, hydraulic and geological properties. However, it has been possible to follow some MDZs in the range of 100–500 m using their kinematic signatures or hydraulic conductivity.

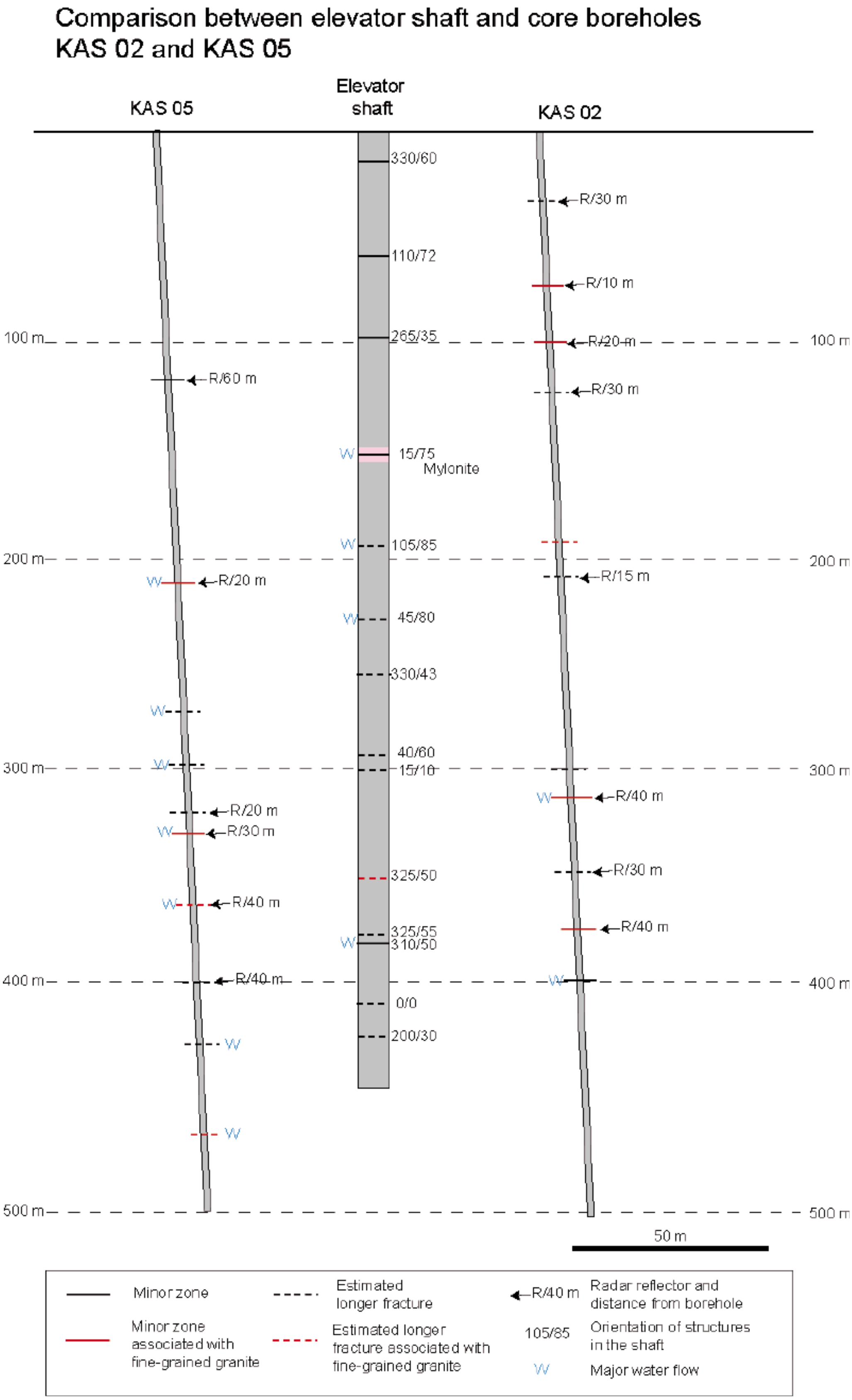
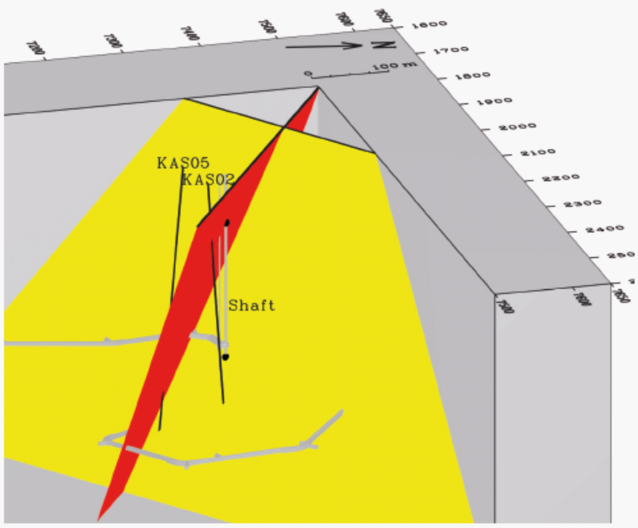


Figure D-1. *Comparison of the boreholes and shaft.*



Shaft Depth (m)	Orientation (strike/dip)	Character	KAS02 Calculated intersection	Calculated angle	Reflector intersection	Reflector angle	KAS05 Calculated intersection	Calculated angle	Reflector intersection	Reflector angle
63 m	110/72	Minor zone	76 m	21°	72 m	20°	292 m	14°	316 m	28°
240 m	045/33	Minor zone	294 m	42°	316 m	35°	340 m	31°	330 m	30°

Figure D-2. *Possible extension of structures based on radar data from the boreholes and orientation data measured in the shaft.*