EMPOWERING UNDERGROUND LABORATORIES NETWORK USAGE

Activity Report of WP3.3 **12|2021**

SITE DESCRIPTION AND DATA OF THE ÄSPÖ HRL

Site services, Characteristics and Data

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1 Aim and Introduction

This report provides an overview of the features, properties and services of the Äspö Hard Rock Laboratory (Äspö HRL) for external users and site managers.
The aim is to support marketing, project planning/execution, business, and innovation development. General site information, including current use and access to the Äspö HRL, is followed by information on research, innovation and cooperation possibilities, and the onsite support, including the database. The bedrock geology, hydrogeology, and hydrochemistry data and properties are described in detail. The information in this report is based on (Laaksoharju et al. 2020). The web site for Äspö HRL is: https://www.skb.com/research-and-technology/laboratories/the-aspo-hard-rock-laboratory/.

2 Overall description of the Äspö HRL

2.1 Location

2.1.1 Geographical settings

Äspö HRL (coordinates: 57° 25′ 59.4″ North / 16° 39′ 35.4″ East) is located in the Simpevarp area in the municipality of Oskarshamn in Sweden (Fig. 1a). The underground part of the laboratory consists of a main access tunnel from the Simpevarp peninsula to the southern part of the island Äspö, where the tunnel continues in a spiral down to a depth of 460 m (Fig. 1b). The island Äspö is located 30 km north of the centre of the town of Oskarshamn. A 3D visualization of the Äspö HRL can be found at https://sketchfab.com/3d-models/aspo-hrl-2e6d094cc3c0415da09da8334586310a.

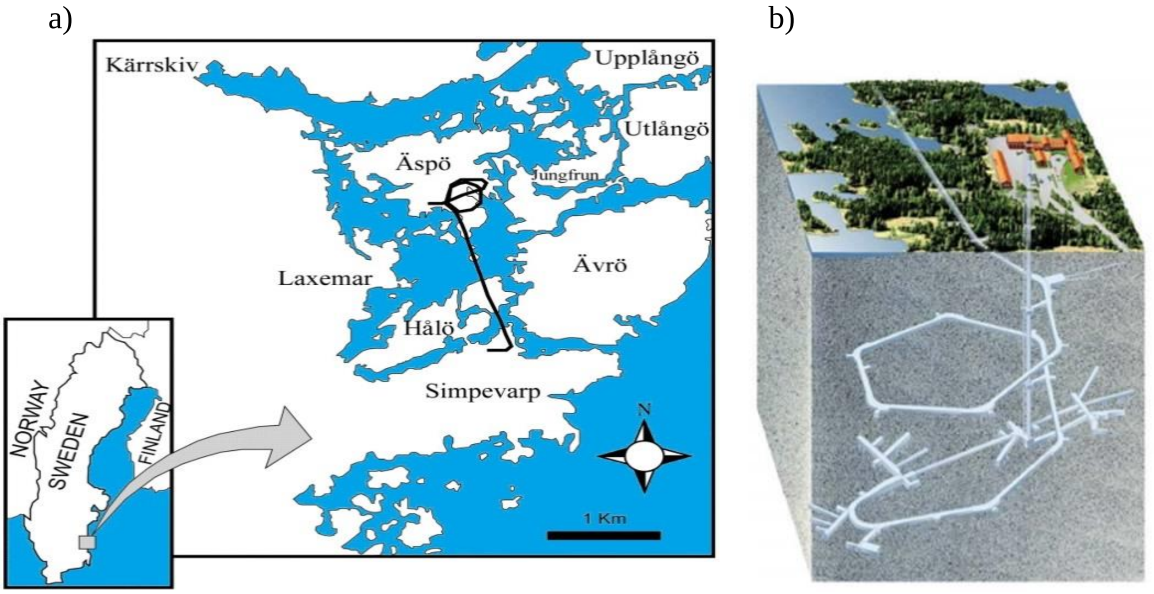


Figure 1: a) Location map of the Äspö HRL and b) the tunnel system viewed from north to south.

2.2 Use and Access

2.2.1 The original purpose and current use

The Äspö HRL is the key research facility for SKB's work on the design and construction of a deep geological repository for the final disposal of Sweden's spent nuclear fuel. A fundamental reason for the 1986 decision to construct an underground laboratory was to create opportunities for research, development, and demonstration in a realistic and undisturbed rock environment down to repository depth. Äspö HRL has been in operation since 1995 and there has been considerable international interest in its research, as well as in its development and demonstration of technologies. The main infrastructure of Äspö HRL is shown in Figure 2.

Figure 2: a) Aerial view of the Äspö HRL (red buildings), b) the underground facility with different test sites, c) the accredited ground water chemistry laboratory at Äspö HRL, d) underground view from one of the galleries.

Specialized knowledge and uses of Äspö HRL include geology, hydrogeology, geochemistry, ground water chemistry, geophysics, rock mechanics, rock engineering, and the physics of clay materials, particularly swelling clays. The underground environment in Äspö HRL is also used as a testbed for the development and testing of the fully automatic transportation and robotic systems needed in the future final repository for spent nuclear fuel.

2.2.2 Available infrastructure

The following infrastructure is available:

- Workshops, stores and crew sheds at Äspö and at the tunnel entrance.
- Offices and meeting rooms.
- High security as the facility has controlled access via access cards. An RFID (radio frequency identification system) system records where personnel and vehicles are underground. The tunnel is also monitored by cameras, which facilitates operational monitoring and evacuation in the event of an emergency. In addition, there is an advanced fire alarm system, good tunnel ventilation, and a control room where all operating and monitoring systems are located. A

large rescue chamber is available for up to 60 people. Mobile rescue chambers are located directly adjacent to the experimental sites. Underground protective equipment is provided. The underground facilities are controlled, and reinforced continuously.

- The hydrogeochemical monitoring programme consists of monthly to biannual sampling campaigns depending on the type of aqueous environment.
- The hydrogeological monitoring programme is a cornerstone of the hydrogeological research and provides support for the experiments undertaken in the Äspö HRL. The monitoring activities started 1987 and are still ongoing. A computerised hydrologic monitoring system (HMS) was introduced in 1992, and the first pressure measurements from tunnel-drilled boreholes were included in the HMS in the same year.
- A research laboratory with equipment for sampling and material analysis of bentonite clay, and geotechnical and geochemical examination methods. Large and high test hall with traverse crane for 32 tonnes, pellet press, and Eirich material mixer.

2.2.3 Current ownership and organisation

The Swedish Nuclear Fuel and Waste Management Co (SKB) owns Äspö HRL, which is operated by the Repository Technology Unit. The unit has employees in Äspö, Stockholm and Forsmark. The main responsibilities of the unit are as follows:

- Develop, demonstrate and streamline repository technology for nuclear waste, including installation methods, transport and handling techniques.
- Operate Äspö HRL as an attractive resource for experiments, demonstration tests, and visitor activities.
- Actively work for a broadened use of Äspö HRL, with the aim of turning the facility over to future research and development stakeholders.

The Äspö HRL has high availability and accessibility and provides an opportunity to test in an operational but undisturbed underground environment. The tunnel depth is 0–460 m. Most of the experiments and full-scale demonstration tests are carried out at the 420 and 450 m levels (Fig. 2b and d). The total tunnel length is about 3 600 m. There are an additional 1 400 m of side tunnels and niches for experiments, with a total of about 5 km for the tunnel system. The access and geometrics of the Äspö HRL are as follows:

- Elevator shaft hoisting up to 2 t or 20 persons. The lift serves three levels, at –220 m, –340 m and –450 m. This provides the opportunity for large-scale tests with good work logistics.
- Mine vehicles for material and personal transportation provide additional transportation via the access ramp.
- The access ramp cross-sectional area is between 30 m^2 and 48 m^2. The width of the galleries varies between 4.3 and 8 m, and the height between 2.3 and 5.5 m.
- The access portal to the underground facility is 4.5 m high and 4.3 m wide. The access ramp behind the portal is higher and wider than the portal itself all the way down to a depth of 460 m. This means that the underground entrance allows transportation of large machines and equipment.

2.2.4 Commuting

The distance between Stockholm and the island Äspö is 340 km, and the Äspö HRL can be reached by car from Stockholm within 4 hours. The nearest regional airport is located in Kalmar, an hour's flight from Stockholm's Arlanda airport. The travel time by car between Kalmar airport and Äspö is 75 minutes (100 km). Kalmar can also be reached by train from Copenhagen airport in Denmark within 4 hours. The region has a well-functioning and comfortable infrastructure including communications, hotels and restaurants.

2.3 Research, innovation and cooperation possibilities

2.3.1 Innovation and research

For innovation and research we provide access to a unique data and operational underground facility with typical Scandinavian bedrock conditions (crystalline, fractured and water-bearing bedrock crossed by larger and smaller weakness zones). The conditions are very well documented in reports, scientific articles and doctoral theses.

The following are examples of some areas of research and innovation:

- Underground tests of new machines, materials, equipment and systems
- Tunnel construction methods and techniques
    - Drill and blast
    - Full-face tunnel boring machine (TBM)
    - Mobile miners
- Access to existing boreholes for sampling

- Injection methods and bolting in rock
- Tunnel closure and backfilling of tunnels
- Experiments with concrete, for example, spray concrete
- Safety concepts such as an evacuation study
- Underground tests of autonomous vehicles and drones
- Photogrammetry and 3D visualization of different spaces
- Geoscientific research
- Microbial research
- Geo-energy and geothermal research
- Astroparticle physics which needs a shielded environment
- Material impact in underground environment

2.3.2 National and international cooperation

The renowned Äspö HRL has a very good reputation and much experience with collaborative projects. Many current activities are carried out in collaboration with other organizations, colleges and universities and through the EU's framework programme for research and technology. Customers thus have the opportunity to utilise a large network of existing international partners.

The Äspö Task Force has undertaken significant modelling tasks since 1992 (Tasks 1-8). These have involved specialists from several countries studying groundwater flow and solute transport processes in deep bedrock formations. These efforts were made to assess the suitability of these rock formations to host geological repositories for spent nuclear fuel. Two forums were established to model groundwater flow and technological barriers.

2.4 Support at the site and available database

2.4.1 Project handling, competencies and quality control

The Äspö HRL can take total responsibility for a research project or assist in some parts of the project. The customer can choose which combination is most suitable. For example, it is possible to

- Hire the Äspö HRL as an area for experiments and tests.
- Hire equipment.
- Hire staff/skills.

At the site there is deep knowledge of various properties of the bedrock, including its geology, hydrogeology and hydrogeochemistry. This knowledge can be drawn on to recommend suitable experimental locations, optimal conditions for experiments, and experienced personnel from Äspö HRL. Customers can access the following:

- Experimental support and guidance.
- Results and lessons learned from SKB's previous studies and research.
- Long experience of testing activities throughout the innovation and technology development chain.
- Quality-controlled work processes that follow certified management systems according to SS-ISO9001:2015, ISO14001 and ISO45001:2018.

2.4.2 Database

Data from SKB's studies and research activities are stored in SKB's site characterization database (SICADA). The data in the database are available for researchers using the Äspö HRL site for ongoing or planned research activities. Relevant geoscientific data from Äspö HRL are available from 1986 onwards.

The area adjacent to Äspö HRL in the Simpervarp-Laxemar area (Fig. 1a) on the mainland was also extensively studied in a 2002–2008 site investigation for the location of the final repository for spent nuclear fuel. The landscape in this area and the rock down to 1000 m have been very thoroughly investigated, modelled and documented.

3 Site description data and data properties

3.1 Bedrock geological data and properties

3.1.1 Description of data

3.1.1.1 Surface data

The following geological and geophysical surface information is available:

- Various bedrock maps at a scale of 1:2 000 and 1:10 000, with descriptions of the Äspö island (see Fig. 3).
- Detailed geological mapping of an excavation trench that stretches across the Äspö island.
- Detailed structural mapping with kinematic interpretations for the Äspö island.
- Data from ground magnetic, resistivity and seismic surveys of the Äspö island and its surroundings, along with lineament interpretations.

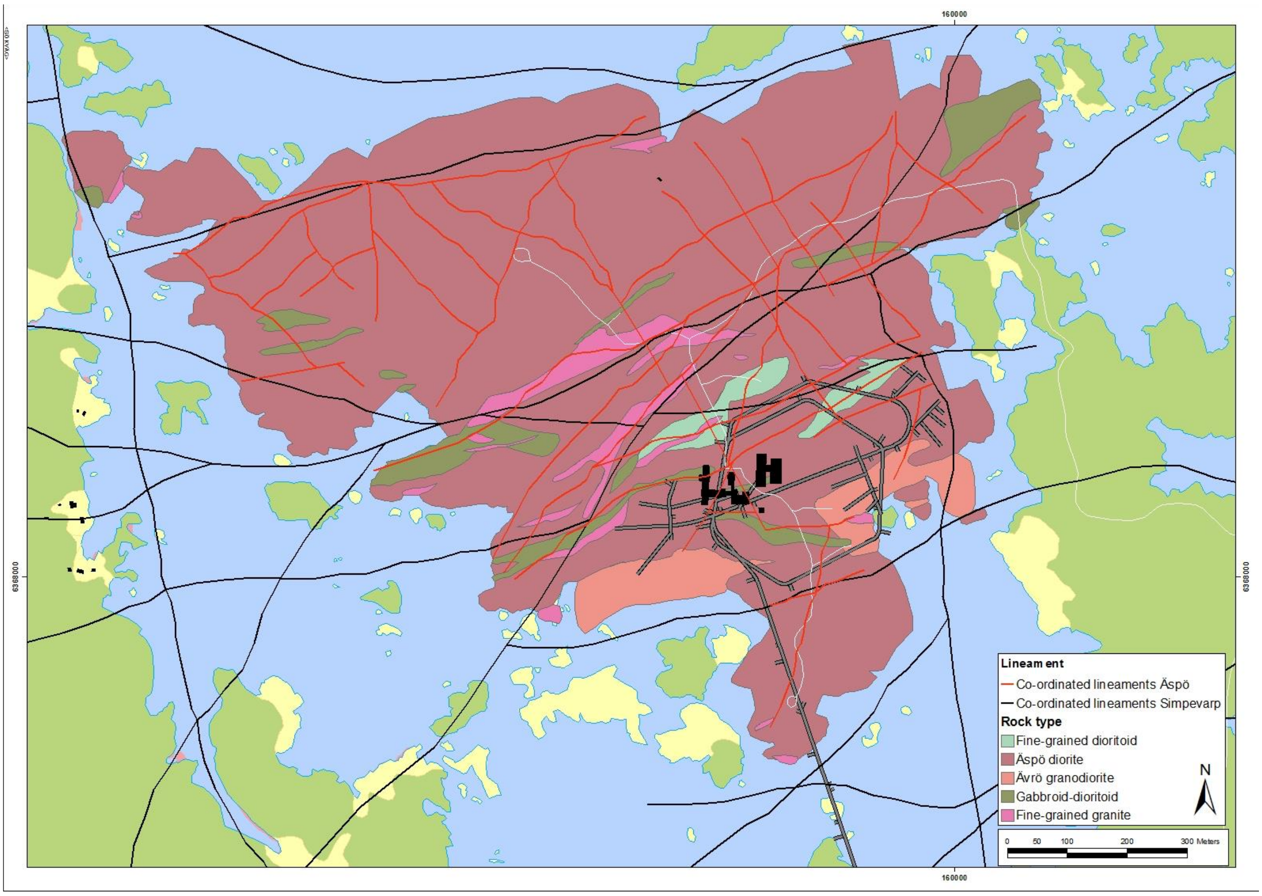


Figure 3: Geological map of the Äspö island compiled on the basis of work by Kornfält and Wikman (1988). Linked lineaments for the Äspö island (Mattsson and Wahlgren 2010, P-10-49) and the regional area (Johansson 2006, R-06-53) are shown as red and black lines, respectively.

3.1.1.2 Borehole data

Cored boreholes with a total length of more than 20 000 m were drilled. Geological mapping is available for 16 200 m of these boreholes. Borehole images for structural orientation, drill core photography and geophysical data are available for approximately half of the mapped boreholes.

3.1.1.3 Tunnel data

Geological tunnel mapping (Fig. 4 and 5) is available for approximately 5 km of underground openings. Most of the mapping is available as digitised 2D drawings and includes rock types, rock quality, fractures, deformation zones and water. About 312 m of the tunnel system have been mapped using RoCS (Rock Characterization System), where the spatial extent of various geological objects is digitised on photogrammetric 3D models of the tunnel geometries.

TASA 1/139–1/158	Z1
Orientation (right-hand rule):	030°/70°
Estimated thickness at intersection:	18.2 m

GEOLOGY

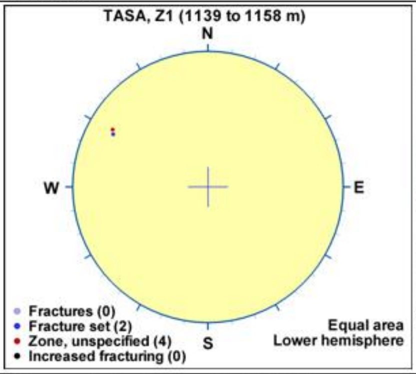
Deformation style:	Proper deformation zone. Blocky.
Alteration:	Weak
Mineralogy:	no information
Water:	0.2–1 l/min (TMS), 12 l/min (PR 25-95-20)
Kinematic indicators:	One master fault, some splays. Anticlockwise (?) type (PR 25-95-03).
Displacement:	Stepping ca 1m (PR 25-95-03).
Undulation:	Undulating to curved (PR 25-95-03)
Confidence in existence/orientation:	Medium/high

TMS-data:
Stepped, fairly simple fracture.

Grouting and reinforcement:
Grouting nr. 53–55 (PR 25-95-20).

Borehole intersections:
SA1128A and B, SA1145A and B, SA1150F, KA1061A, KA1131B (PR 25-95-20).

Current exposure (2017-02-07):
Mostly covered by shotcrete, but exposed in a niche (NASA1138B) at right side with abundant bacterial precipitation.



Z1 1/158.1

Water-conducting features (PR 25-95-03):

Length	Thickness	Orientation	Description
1/158	<0.4m	305°/90°	Stepped, fairly simple fracture. *Fracturing:* one master fault, some splays, steep circa 1m, A-type (uncertain). *Geometry:* smooth, undulating to curved, stepped. *Water:* flow to dropping.

Figure 4. Example of a property table for a tunnel deformation zone.

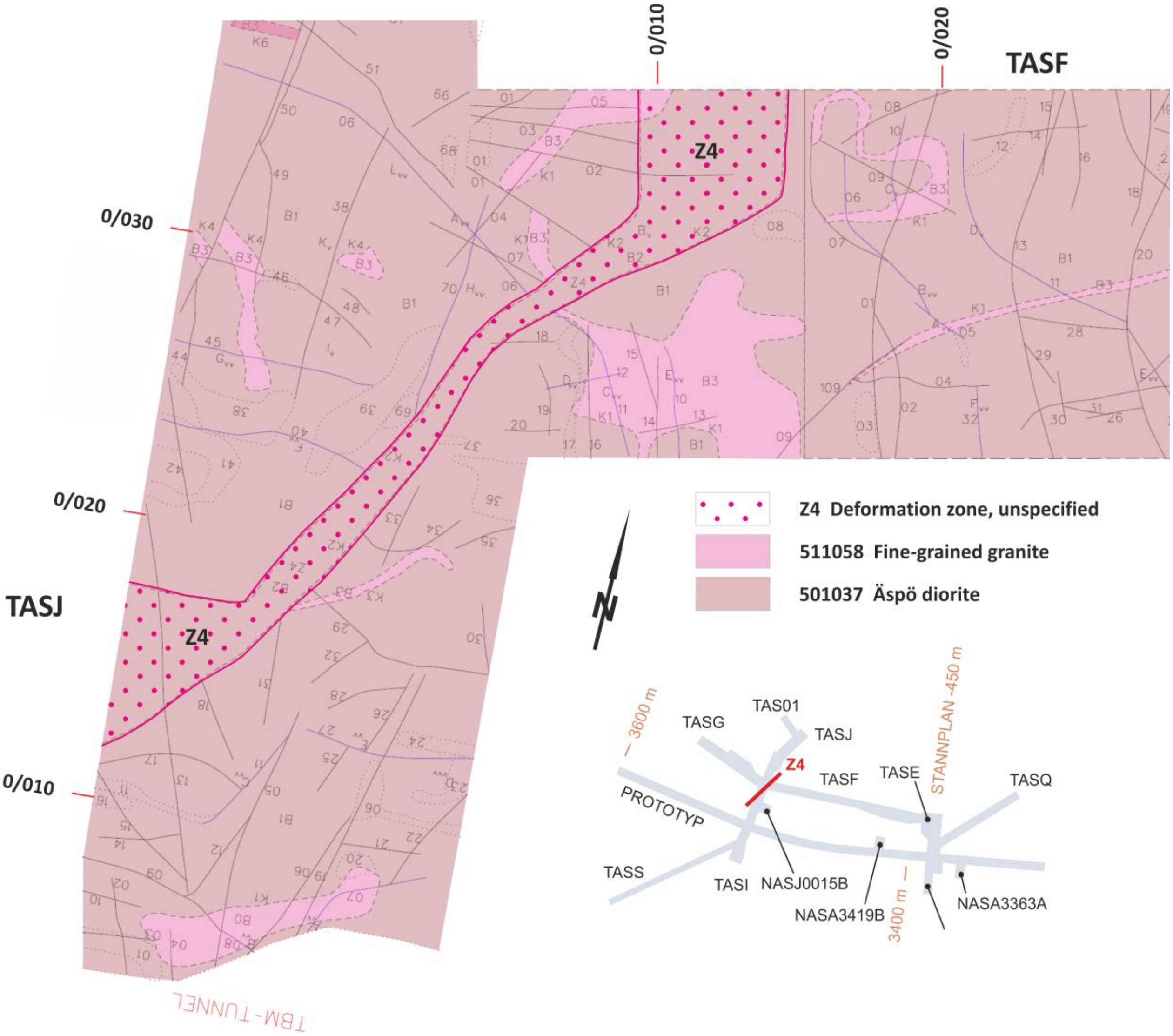


Figure 5: Example of the results obtained by following the SKB geological tunnel mapping procedure TMS (Tunnel Mapping System, SKB IPR-02-49*).*

3.1.1.4 Petrography, geochemistry, rock mechanics, petrophysics and thermal properties

Petrography and geochemistry are available for whole-rock samples, fracture filling materials and wall rock alteration. These include modal and textural analyses of thin sections, analyses by SEM-EDS and XRD, along with stable and radiometric isotope (C, O, Sr and U-series) analyses.

Stress measurements were performed both with the hydraulic fracturing technique and the overcoring method. These are available from a number of places in the Äspö area. Mechanical properties from laboratory testing of both intact rock samples and fractures are available for the main rock types in the Äspö HRL and include uniaxial/triaxial compressive strength, uniaxial tensile strength, Young's moduli, Poisson's ratio, cohesion, fracture stiffness and fracture toughness (mode I and II), and residual friction angle.

Petrophysical analyses for magnetic susceptibility, wet and dry density, and porosity are available. Thermal analyses for thermal conductivity, thermal expansion, and heat capacity are also available.

3.1.1.5 Data from special studies

Data is available from the following special studies:

- Geological characterization of fault rock zones.
- Excavation spalling, damage (EDZ) and disturbance in crystalline rock.
- Classification and characterization of water-conducting structures.
- Tunnel convergence measurements.

3.1.2 Description of properties

3.1.2.1 Geological setting and tectonics

The Äspö area is part of the Precambrian basement in SE Sweden that is dominated by 1.8 G years old Småland granite intrusions. The deformation zones in the Laxemar-Simpevarp-Äspö area are characterised by brittle deformation, and the majority of these zones contain ductile precursors. Two shear belts that strike NE−SW mark the boundary between the Simpevarp and Laxemar subareas. These belts constitute two branches of what has traditionally been called the Äspö shear zone, or EW-1. At the regional scale, most prominent ductile shear zones are sub-vertical and strike in N−S, NE−SW and E−W. A study of their kinematics has revealed that the brittle history in Laxemar-Simpevarp-Äspö is a result of multiple reactivation of faults and fractures caused by far-field effects of orogenic events that have affected the bedrock over at least the last 1.5 Ga of geological evolution.

3.1.2.2 Major rock type(s)

The bedrock in the Laxemar-Simpevarp-Äspö area is dominated by intrusive rocks with a quartz monzodioritic, granodioritic or granitic composition with a variable content of quartz. The age of these quartz monzodiorites, granodiorites and granites is in the order of 1.8 G years. There is evidence of magma-mingling and magma-mixing processes. The two dominant rock types on the Äspö island are Äspö diorite (quartz monzodiorite to granodiorite, porphyritic) and Ävrö granodiorite (granite to quartz monzodiorite, generally porphyritic). Important subordinate rock types are dykes, veins, patches and minor bodies of fine-grained granite, pegmatite and composite intrusions. The latter are composed of a mixture of fine-grained diorite-gabbro and fine-grained granite. All rock types are affected by foliation, most notably the dyke-like bodies of fine-grained granite and fine-grained diorite-gabbro. The foliation in these rocks formed in the solid state and is more or less strongly developed. Particularly in the southern part of Laxemar, these dyke-like bodies locally correspond to ductile shear zones.

3.1.2.3 Mechanical properties and conditions

The uniaxial compressive strength (UCS) of the dominant quartz monzodiorites and granodiorites is in the range of 220–230 MPa. The UCS has locally been measured to around 300 Mpa in very fine-grained portions of the diorites. The dykes of pegmatite and fine-grained granite normally have a UCS of 170–200 MPa. The indirect tensile strength is in the range of 12–14 MPa. The dominant joint sets have different types of mineral precipitations, and consequently a range of cohesion and friction angle values. The in-situ stress field is characterised by an excess of horizontal stresses. The value of σ_H is in the range of 22–28 MPa at 420–460 m depth, while σ_h and σ_v are both in the range 11–14 MPa at that depth.

3.1.2.4 Thermal properties and conditions

The large-scale thermal conductivity of the rock mass is well understood from in-situ heating experiments and is 2.62 $W\cdot m^{-1}\cdot K^{-1}$.

3.1.2.5 Radionuclide data

Radionuclides are of importance for both occupational safety and for users looking for low natural background radiation environments. In the data base SICADA there are available radionuclide data of the major rock types and in groundwater. Low values from regularly radon gas measurements in the bedrock are obtained.

3.2 Hydrological data and properties

3.2.1 Description of data

The hydrogeological characterization at Äspö and surrounding areas was performed through boreholes drilled from the ground surface and from tunnels over a period of more than 25 years. It includes extensive monitoring of groundwater level and pressure, tunnel flow, and electrical conductivity.

The borehole data contain time series of groundwater level and pressure, as well as steady state and transient hydraulic tests at different scales providing transmissivity, storativity, flow regime, and borehole skin. Borehole flow logging also provides volumetric fracture inflow and transmissivity. Test data from dilution, sorption, and tracer in-situ and laboratory tests are included.

The tunnel data include time series volumetric inflow and electrical conductivity for different parts of the Äspö HRL tunnel system and qualitative inflow assessment of leakage on the tunnel wall. Data on the temperature, humidity, and pressure of the tunnel air is also available.

The surface data include monitoring of the Baltic sea water level as well as the discharge, temperature, and electrical conductivity of river and lake water. Data on meteorological variables available from a station at Äspö include precipitation, barometric pressure, air temperature, relative humidity, wind speed and direction, global radiation, and calculated evapotranspiration.

The following focused studies/experiments have been conducted:

- Solute transport in a single fracture
- Solute transport in a fracture network
- Solute diffusion processes
- Excavation damage zone characterization
- Two phase flow
- Stress dependent transmissivity
- Tunnel grouting effect on inflow
- Modelling based on Äspö data through the Modelling Task Force (https://www.skb.se/taskforce/)

Data in the SKB database SICADA are classified according to the type of science, type of object, type of measurement method, and the data collected in different campaigns. Table 1 gives an indication of the amount of data stored in the database SICADA for the science type Hydrology, which includes hydrogeology data.

Table 1: The amount of hydrogeology observations stored in the SKB database SICADA.

Type of measured object	Measurement method	Number of measurement campaigns	Number of objects measured
Borehole	pressure monitoring	28 229	1172
Borehole	build up and fall off tests	1205	561

Borehole	flow logging	896	462
Borehole	flow measurements	6568	1289
Borehole	injection tests	2615	674
Borehole	interference test	2356	379
Borehole	pulse & slug tests	303	131
Borehole	withdrawal tests	645	239
Ground surface	water retention and porosity of soil	105	37
Surface water	lake & sea monitoring	607	143
Surface water	river monitoring	1382	100
Tunnel	air monitoring	365	21
Tunnel	Thompson weir, inflow	6539	200
Tunnel	Sump and pipe discharge	90	13
Total		**51 905**	**5421**

3.2.2 Description of properties

The hydraulic characteristics of the bedrock in hydraulic rock domains are strongly coupled with the structural geology. The rock is sparsely fractured and heterogeneous with a clear anisotropy in K, ranging on average in different direction between $2*10^{-9}$ and $3*10^{-7}$ m/s. Matrix rock at Äspö has background effective hydraulic conductivity of approximately $1*10^{-12}$ [m/s]. The specific storage values for the rock mass are inferred from a linear regression on data with a lower bound of approximately $1*10^{-9}$ up to $7*10^{-7}$ [m^{-1}]. There is little support for any scale dependency in this relationship between the specific storage and the hydraulic conductivity. No unambiguous depth dependency for K has been established at Äspö.

3.3 Hydrogeochemical data and properties

3.3.1 Description of data

Hydrochemical monitoring has been performed since its inception more than two decades ago. The parameters of the sampling programme include main components (e.g. pH, EC, alkalinity, anions, cations, nitrogen compounds, DOC, HS^-) and several isotopes (e.g. ^{18}O, ^{3}H, ^{34}S, ^{87}Sr, ^{14}C).

In addition, groundwater has been sampled in different boreholes (drilled from the surface or from a tunnel). Water samples have also been collected regularly in shallow drill holes (soil tubes) and from streams, the Baltic Sea, and precipitation.

The hydrochemistry data in the SICADA database are classified according to sampling method (activity type title) and type of sampling site. Every chemistry sample has a unique SKB sampling number. Table 2 below gives an indication of the number of chemistry samples and sampling sites stored in the database.

Table 2: The number of hydrogeochemical observations stored in the SKB database SICADA.

Activity type title	Example	Number of chemistry samples	Number of sampling sites
Surface water sampling	Streams and Baltic Sea (analysis)	2068	104
Surface water measurements	Streams and Baltic Sea (field measurements)	1507	61
Precipitation sampling	Precipitation collectors	675	2
Near-surface groundwater analysis	Soil tubes (analysis)	787	66
Near-surface measurements	Soil tubes (field measurements)	794	56
Hydrochemical monitoring in tunnel boreholes	Water samples from tunnel boreholes	1252	82
Miscellaneous groundwater sampling methods	Different sampling methods	2516	355
Groundwater sampling	Water samples from surface boreholes	1918	156
Water sampling - DGT	Diffusive gradients in thin-films	43	16
Sampling dissolved gas	Gas data from boreholes	147	34

3.3.2 Description of properties

The fractures in the bedrock are more or less covered with secondary minerals (including clay minerals, calcite, and pyrite) which were formed as far back as the Proterozoic and are still forming today. The waters in the fractures have a wide range of compositions, ages, and origins, including old saline water, glacial meltwater, and recently infiltrated marine and meteoric waters. The microbiology of the fracture groundwaters is predominantly bacteria from uncultured, candidate phyla that have a small cell size as a likely adaptation to the low energy environment. The modern water microbial communities are dependent on organic carbon recharge via surface water infiltration for cell growth, while the deeper, old saline waters are dependent on the 'geo-gases' of hydrogen and carbon dioxide for energy and carbon.

4 Summary

As a summary of the major site properties the the Äspö96 model is used (Rhén (ed.) et al., 1997). The model is still valid today for the main geological, hydrogeological and hydrogeochemical features of the site.

The geological model shows domains of Äspö diorite and Smålands (Ävrö) granite with inclusions of fine-grained granites, greenstone, and mylonite. The structural model shows major fracture zones with a width exceeding 5 m and fracture swarms (Fig. 6a).

The hydrogeological model (Fig. 6b) shows the hydraulic conductivity of the major fracture zones and a typical range of hydraulic conductivity for the rock mass between the fracture zones. The widths of zones are only indicative.

The hydrogeochemical model shows the distribution of saline water in the Äspö area based on 3D interpolation and observations in borehole sections (Fig. 6c).

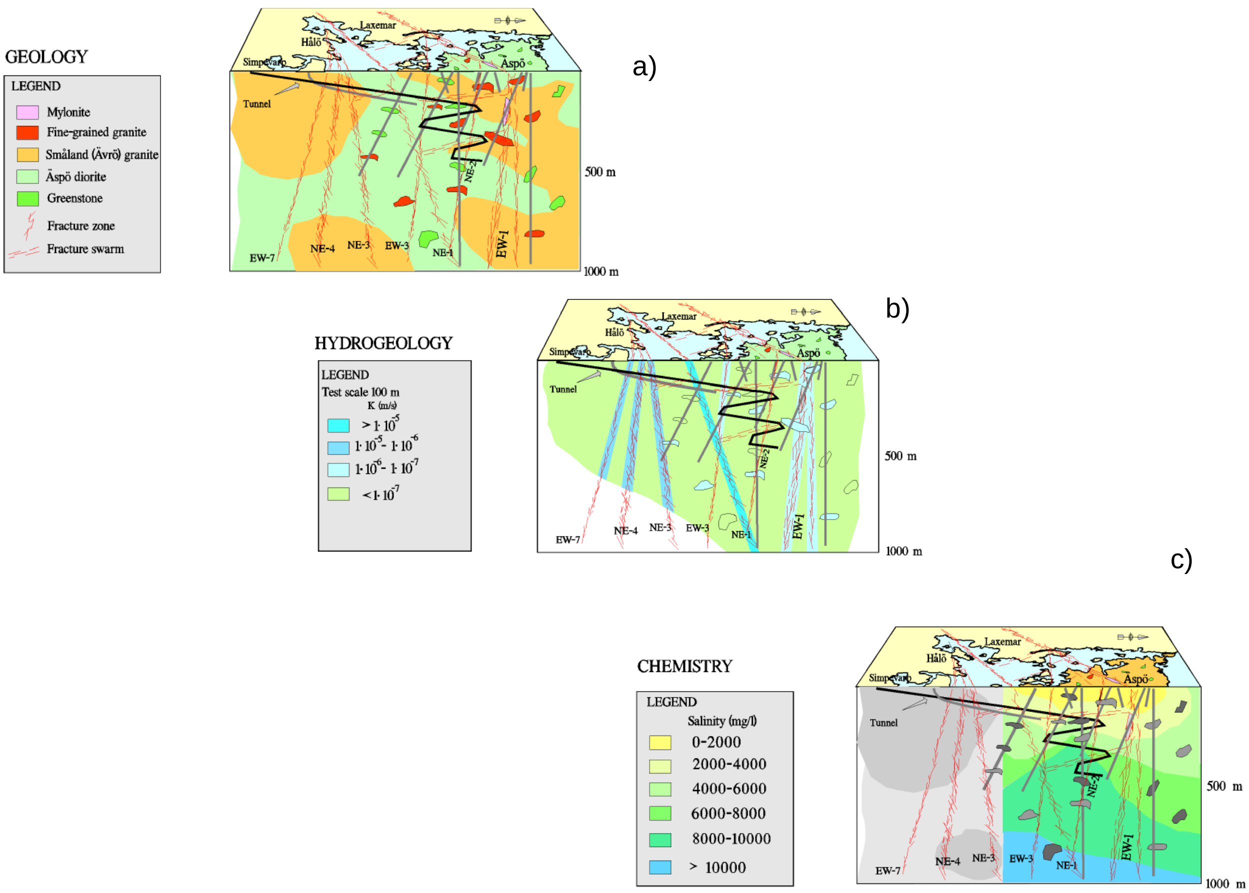


Figure 6: The conceptual site model for a) geology, b) hydrogeology, and c) hydrogeochemisty along the tunnel of Äspö HRL (Rhén (ed.) et al., 1997, SKB TR-97-03).

5 References

The references used in this report are listed below. The SKB reports can be downloaded from: https://www.skb.com/publications/

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