Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Author: Joel Geier

Research

2012:49

Hydrogeological characteristics of sites for low- and intermediate-level waste disposal

Report number: 2012:49 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) is responsible for the review of license applications for final repositories for low- and intermediate-level radioactive waste (LILW). The Swedish Nuclear Fuel and Waste Management Co. plans to apply for an extension of the SFR facility in Forsmark to be able to dispose of decommissioning LILW. As a preparation for this license application review SSM has commissioned a project to study the hydrogeological characteristics of some alternative sites for such a facility. An inland location in the Forsmark area and two sites in the Laxemar-Simpevarp area have been selected as potential alternative sites that are studied in this project.

Objectives

The objective of the study is to improve the knowledge on the controls on groundwater flow at selected potential alternative sites for a final repository for LILW. In particular, the aim is to compare these sites in terms of likely ranges of flow rates through depths of interest for a LILW facility, in terms of magnitude, predictability and uncertainties. Furthermore, the aim is to gather knowledge on the likely discharge areas and corresponding transport distances for groundwater passing through potential LILW facility locations, and how sensitive these are to changes in surface climate and relative sea level.

Results

The Forsmark area with its selected two sites and the Laxemar-Simpevarp area with its two sites are broadly similar in terms of lithology, rock ages, and tectonic histories. The two areas differ in terms of degree of deformation, and tectonic fabric. Some lithologic and tectonic differences are noticeable between the two sites in the Forsmark area and between the two sites in the Laxemar-Simpevarp area.

These differences can be expected to influence hydrologic properties including the magnitude and anisotropy of effective hydraulic conductivity on various scales. However, prediction of the consequences is dependent on complex fracture-network models, and these have not been presented at the same level of development or level of detail for all sites. In this study a simple evaluation of Darcy flux and transport resistance has been made for the sites.

This evaluation indicates that the inland Forsmark-lens site has highest predicted fluxes and also the lowest minimum transport resistances, due to the very high horizontal hydraulic conductivity in the shallow bedrock. The simple evaluation also indicates that the Laxemar and Simpevarp sites have a lower minimum value of transport resistance than the Forsmark-SFR site; however, estimates are within roughly an order of magnitude.

Project information

Contact person SSM: Georg Lindgren
Reference: SSM2011-3291

Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Author: Joel Geier
Clearwater Hardrock Consulting, Corvallis, U.S.A.

2012:49

Hydrogeological characteristics of sites for low- and intermediate-level waste disposal

Date: February 2012
Report number: 2012:49 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Abstract

Hydrogeological circumstances are compared for four example locations in Sweden, focusing on factors that could be relevant for a disposal facility for short-lived, low-and intermediate-level radioactive waste (LILW). The four sites are:

- SFR site at Forsmark (the proposed site for SFR expansion),
- Forsmark tectonic lens (current candidate site for a spent-fuel repository),
- Laxemar (former candidate site for a spent-fuel repository), and
- Simpevarp (former candidate site for a spent-fuel repository).

All four sites are coastal sites with low to moderate relief, and relatively thin, discontinuous Quaternary deposits overlying granitic bedrock of low permeability which limits infiltration to the deep groundwater system. The two sites in the Forsmark area have relatively low relief and are undergoing relatively land rise. This implies a more dynamically evolving hydrologic situation, with greater influence of both modern and relict marine waters, in comparison with the Laxemar-Simpevarp area.

Although broadly similar in terms in terms of lithology, rock ages, and tectonic history, bedrock in the Forsmark area differs from the Laxemar-Simpevarp area in terms of degree of deformation, and tectonic fabric. Lithologic and tectonic differences also are seen between each pair of sites in each of these areas. These differences influence patterns of deformation zones and smaller-scale fractures, and can be expected to influence hydrologic properties including the magnitude and anisotropy of effective hydraulic conductivity on various scales.

A simple evaluation of Darcy flux and transport resistance yields a conclusion that the Forsmark-lens site has the highest predicted fluxes and also the lowest minimum transport resistances, due to the very high horizontal hydraulic conductivity in the shallow bedrock. This indicates that the Forsmark-lens site would be the least optimal for a LILW disposal facility in the shallow bedrock, due to the high hydraulic conductivity of the shallow bedrock (in contrast to the deep bedrock). The Laxemar and Simpevarp sites compare favourably to the Forsmark-SFR site in terms of the minimum value of transport resistance, although estimates are within roughly an order of magnitude.

Content

1. Introduction

Background

Short-lived, low-and intermediate-level radioactive waste (LILW) from Swedish nuclear facilities is currently being sent to the SFR facility along the northern coast of Uppland, near the Forsmark nuclear power facility. The Swedish Nuclear Fuel and Waste Management Co. (SKB) has estimated that in addition to the space available in the current SFR, an additional 140,000 cubic meters of space will be needed to dispose of the volume of LILW that is expected to be generated in future decades, including operational waste and decommissioning waste from existing nuclear power plants.

One option under investigation is an expansion of the existing SFR, by adding a connected set of waste-disposal tunnels a short distance to the southeast of the facility (SKB, 2008b). As background for evaluating this choice of options for meeting the need for an expanded LILW disposal facility, it is of interest to compare with other sites that could be considered.

This research project compares hydrogeological circumstances among four example locations in Sweden for which comparable amounts of geoscientific information are available:

- SFR site at Forsmark (the proposed site for SFR expansion),
- Forsmark tectonic lens (current candidate site for a spent-fuel repository),
- Laxemar (former candidate site for a spent-fuel repository), and
- Simpevarp (former candidate site for a spent-fuel repository, and location of CLAB facility).

All four of these sites have been the focus of detailed site investigations and groundwater modelling studies by the Swedish Nuclear Fuel and Waste Management Co. (SKB). The first two are located near the Forsmark nuclear reactor site in the Östhammar municipality, while the last two are located near the Oskarshamn nuclear reactor site in Oskarshamn municipality. For the sake of brevity, the two sites in the Forsmark area are referred to herein collectively as the “Forsmark sites” and individually as “Forsmark-SFR” and “Forsmark-lens.” The Laxemar and Simpevarp sites are referred to collectively as the “Oskarshamn sites.”

Figure 1.1 Location of Forsmark and Laxemar-Simpevarp sites in Sweden (from SKB R-08-95, Figure 1-1).

Scope

The principal research questions addressed in this report are:

- What are the fundamental controls on groundwater flow at these sites (including geologic features influencing groundwater flow, topographic differences, surface climate, palaeohydrological impacts, and existing subsurface facilities)?
- How do the sites compare in terms of likely ranges of flow rates through depths of interest for a LILW facility, in terms of magnitude, predictability and uncertainties?
- What are the likely discharge areas and corresponding transport distances for groundwater passing through potential LILW facility locations, and how sensitive are these to changes in surface climate and relative sea level?

All four of these sites have been the subject of hydrological and hydrogeological modelling using sophisticated computer models. Results from these modelling studies, in combination with a simple evaluation based on fundamental hydrogeologic principles, are used as the basis for analysis, rather than entirely new, complicated site models.

Approach

The research questions outlined above are addressed by the following steps:

- Literature survey to identify the most relevant site documents;
- Compilation of hydrological information from these sources;
- Simple evaluation of groundwater flow for each site
- Evaluation of findings

The details of the literature survey have been documented in an earlier memorandum, and are not repeated in full detail here. The main results are documented by the list of references for this report (Chapter 8).

2. Site investigations

The Simpevarp, Laxemar, and Forsmark-lens sites have been investigated extensively as part of the Swedish spent-fuel repository programme. In general, the regional-scale results of investigations for the Forsmark-lens site are also relevant for the Forsmark-SFR site, which is within the regional-scale modelling area for the former.

Preliminary feasibility studies at these locations are given by (SKB, 2000a) and (SKB, 2000b). Simplified overviews of the subsequent investigations from 2002 through 2007 at Forsmark and Oskarshamn are given by (SKB, 2008c) and (SKB, 2008d).

Technically comprehensive descriptions of the investigations and their outcomes are given for Forsmark as (SKB, 2008e), for Laxemar as (SKB, 2009A), and for Simpevarp as (SKB, 2005a). In the case of Simpevarp, site investigations were terminated after a preliminary version of the site-descriptive model. The investigations for Forsmark and Laxemar were carried out fully to the point of producing site-descriptive models that could support a license application for a spent-fuel repository.

Ultimately, in March, 2011 a spent-fuel repository license application was submitted only for Forsmark, with the safety assessment SR-Site (SKB, 2011) as supporting documentation. However the investigations for Forsmark and Laxemar followed the same formal methodology, were carried out to very similar levels of detail, and documented in a consistent fashion.

Site investigations specifically for the Forsmark-SFR site are described in (SKB, 2008b), plus numerous subsequent reports on specific parts of the ongoing site investigation for expansion. The focus of these investigations have generally been at shallower depths , so far as bedrock hydrogeology is concerned, but similar in terms of surficial hydrological characterisation.

Depth and area of site descriptive models

The site-descriptive models for the Laxemar, Simpevarp, and Forsmark-lens sites extend to 2.1 km depth below sea level, although drill-hole investigations are generally limited to depths of 1 km. The local site-descriptive model for the Forsmark-SFR site extends to 300 m below sea level, although a regional-scale model (which overlaps with the regional-scale model for the Forsmark-lens site) is developed to 1 km depth.

The regional model area investigated for both Laxemar and Simpevarp covered an area of 273 km^2. Local model areas were 16 km^2 for Laxemar (SKB TR-09-01), and 24 km^2 for Simpevarp (SKB R-5-08). The local model area for Forsmark-lens covers about 12 km^2, with more intensive characterisation of a smaller target area of roughly half that size. The local- and regional-scale structural models for the SFR have been developed for a comparatively small area (0.6 km^2 and 2.6 km^2, respectively). However, geoscientific understanding of the Forsmark-SFR area is augmented by information from the overlapping Forsmark regional model.

Quaternary cover and bedrock exposure

Bedrock exposure is comparatively good in the Laxemar-Simpevarp area, where Quaternary overburden covers the bedrock in only about 58% of the area (SKB TR-09-01). Bedrock exposure is comparatively limited in the Forsmark-lens area, where Quaternary deposits cover about 90% of the ground surface. For the Forsmark-SFR site, most of the local model area is covered by water, except for bedrock exposures on several small islands, plus and artificially constructed causeway. Thus Laxemar and Simpevarp provide the best exposures for studying bedrock characteristics, followed by the Forsmark-lens site.

Geologic mapping data from underground in the existing SFR facility partly compensates for the comparative lack of surface exposure at the Forsmark-SFR site. Underground exposures are also available from the Äspö Hard Rock Laboratory which is within the Laxemar-Simpevarp regional model area, plus information from shallower depths obtained during construction of the Central Interim Storage Facility (CLAB) on the Simpevarp peninsula.

In addition to covering a larger area, Quaternary deposits also tend to be deeper in the Forsmark area. Along with artificially placed fill which forms the causeway to the SFR, Quaternary deposits are expected to be more important for present and future shallow groundwater flow in the Forsmark area than in the Laxemar-Simpevarp area.

Surface-based geophysics and lineament studies

An extensive suite of surface-based geophysics and remote-sensing methods have been used in both the Laxemar-Simpevarp areas and in the Forsmark area, to support descriptions of the bedrock geology and to identify potential deformation zones, as summarized in Table 2.1.

LIDAR mapping was used for identification of minor deformation zones down to a length scale of 100 m at the Laxemar site, but was judged to be unsuitable for Forsmark due to extensive Quaternary cover limited the identification of lineaments. At Forsmark-lens, a high-resolution ground magnetic survey was key for identifying potential steeply-dipping deformation zones down to a length scale of 100 m.

For Forsmark, access to high-precision bathymetric data improved detection of lineaments in the seabed. However, even with these data, the interpreted lineaments are noticeably more sparse offshore than onshore.

Seismic reflection and seismic refraction surveys have been used to identify potential sub-horizontal to gently-dipping deformation zones at depth, in both the Laxemar-Simpevarp area and the Forsmark area.

Underground facilities in vicinity

Several of the sites contain or closely border underground facilities which might act as sinks for groundwater. The existing SFR in the Forsmark-SFR site adjoins the Forsmark-lens site but is situated across a major regional deformation zone (the Singö Zone), which is interpreted as a hydrogeologic barrier, and thus limits the hydrologic impact within the site. Groundwater pressures were measured in boreholes during construction of the underground caverns, and groundwater chemistry was analysed for samples taken from conductive zones near the facility. During construction and operation since April 1988, monitoring of groundwater pressures and leakage to tunnels and underground rooms has been carried out, along with continued hydrogeochemical sampling (SKB, 2002, SKB R-02-14).

The CLAB facility is located in the western part of the Simpevarp area. This is near the east edge of the Laxemar area. The Äspö Shear Zone, a major regional structure, lies between Laxemar and the CLAB , and may limit hydraulic communication between these areas.

3. Surface conditions

Regional setting

The Laxemar-Simpevarp area is located along the Baltic coast of southeastern Sweden, with the Småland highlands rising to elevations of 300 m over a distance of about 60 km inland. Thus the topographic gradient on the regional scale is on the order of 0.005, from east to west.

The Laxemar-Simpevarp area is in the middle part of an approximately 20 km long section of generally eastward-projecting coastline (neglecting local inlets). This headland area is bounded to the north and south by coastal embayments of 5-10 km where the two nearest regional-scale rivers (Marströmmen and Virån) reach the sea. The drainages of these two rivers join about 10 km inland of Laxemar, which means that this headland area essentially constitutes its own regional-scale catchment, and is drained by local streams generally less than 10 km in length. The highest points on the inland edge of this area are around 100 m.a.s.l., so maximum topographic gradients on the local scale are on the order of 0.01, from east and west.

The Forsmark area is also located on the Baltic coast, along a NW-trending stretch of coastline along the Gulf of Bothnia. The island of Gräsö, separated from the mainland by just a shallow, narrow strait, extends northward about 10 km east of the Forsmark-lens and -SFR sites, partly shielding a coastal bay, Öregrundsgrepen, from storm surges and larger-scale marine circulation.

For the Forsmark sites, the nearest area with elevation above 100 m is about 80 km to the WSW. Thus regional topographic gradients are generally less than 0.00125, about a factor of four lower than in the Laxemar-Simpevarp area. On a local scale the topography in the Forsmark area is also relatively subdued. The steepest local-scale gradient results from a minor (20 m.a.s.l) ridge about 4 km SW of the NW-trending sea coast, yielding a topographic gradient of 0.005.

As for the Laxemar-Simpevarp area, the Forsmark-lens site is within an area that is bounded a short distance inland (4 to 5 km) by surface water divides for one of the two rivers that flows into Öregrundsgrepen via Kallrigafjärden to the SE (Forsmarksån), and a smaller stream that flows into Öregrundsgrepen to the NW. Within this area, surface flow is either directly to the sea, or indirectly via an assortment of shallow lakes and mires.

Precipitation and evapotranspiration

Long-term average annual precipitation in the Laxemar-Simpevarp area is approximately 600 mm/yr according to (SKB, 2008c; Werner, 2009), which is close to the 608 mm/yr precipitation averaged over a three-year monitoring period from October 1, 2004 to October 1, 2007 (SKB TR-09-01; Bosson *et al.*, 2008). A local gradient in precipitation (increasing in the inland direction) is indicated by a 7% difference between a station at Äspö on the coast, versus a station 10 km inland (Werner, 2009).

The annual average potential evapotranspiration for terrestrial areas is calculated from climate data as 530 mm/yr (inland) to 540 mm/yr (near the coast.. Water-balance calculations for the Laxemar-Simpevarp area indicate an actual annual evapotranspiration of 435 mm/yr (Werner, 2009).

Long-term average annual precipitation in the Forsmark area is approximately 560 mm/yr according to (Johansson, 2008), which is slightly higher than the 546 mm/yr precipitation averaged over a three-year monitoring period from April 15, 2004 to April 14, 2007. A relatively strong gradient in precipitation (increasing from east to west or inland) is indicated by a 29% difference between a station on the island of Örskär (15 km NE of the area) vs. Lövsta which is 15 km inland (Johansson and Öhmann, 2008, SKB R-08-10).

The annual average potential evapotranspiration for terrestrial areas of the Forsmark site is calculated from climate data as about 509 mm/yr. Water-balance calculations indicate an actual annual evapotranspiration of 410 – 420 mm/yr (Johansson, 2008).

Thus, in the current climate, the Laxemar-Simpevarp area receives about 7% more annual average precipitation than the Forsmark area. The difference between sites is within the range of local variation in inland vs. coastal stations, for both areas. Both potential and actual annual evapotranspiration are lower at Forsmark, by a similar degree.

At both sites, precipitation in the cold winter months is typically as snow, which accumulates rather than becoming immediately available for run-off or infiltration. Snow melt at intervals during the winter months, but primarily during spring, yields a large contribution to run-off/infiltration/recharge, resulting in a strong temporal variation in this source term over the course of a year (Werner, 2009).

In both areas, recharge to the deeper bedrock appears to be limited by hydraulic conductivity rather than precipitation.

Surface waters and their expected evolution

Lakes, mires, streams, and other surface waters

Freshwater hydrologic features at the Laxemar, Simpevarp, and Forsmark-lens site consist of streams, fens, and natural lakes. The Forsmark-SFR site is under the Baltic, with no significant freshwater features on the neighbouring islets, causeways, and jetties.

The natural lakes at Forsmark (Bolundsfjärden, Fiskarfjärden, Eckarfjärden, Gunnarsboträsket, Gällsboträsket, Puttan, Lillfjärden, Vambörsfjärden, and Stocksjön approximately in decreasing order of size) are all small and shallow, and are generally underlain by clays and gyttja which are indicated to impede hydraulic communication between lakes and groundwater in the deeper rock. Several of these lakes periodically receive brackish water during storm surges on the Baltic.

Wetlands cover up to 25% of the area of some catchments (Grolander, 2009). There are no major, year-round streams, but a variety of small creeks and ditches provide seasonal drainage.

A major artificial feature at the NW end of the Forsmark-lens site is the cooling-water intake canal connecting to the Baltic, which is used to draw water for the nuclear reactors. This canal zigzags inland from the coast over a length of 2.5 km, to where it intercepts a stream that flows out from one of the local lakes, Gunnarsboträsket.

The canal was excavated during the 1970s by blasting a steep-walled channel about 8-10 m deep in the bedrock. The excavation revealed a set of extensive, sub-horizontal fractures which are now understood as part of a very highly transmissive, “shallow bedrock aquifer.” For the past four decades, brackish water from the Baltic has presumably been brought into enhanced communication with the “shallow bedrock aquifer” along the length of this canal.

The Laxemar-Simpevarp area includes six small lakes and ponds: Jämsen, Frisksjön, Söråmagasinet, Plittorpsgöl, Fjällgöl and Grangöl. These lakes are shallow with average depths of 1-4 m and maximum depths of 11 m or less (SKB, TR-09-01). Wetlands cover only about 3% of the area.

According to (SKB, 2009) all of these lakes and ponds are well above sea level and hence currently do not receive brackish water input from the Baltic. An exception to this statement might be Söråmagasinet, part of the strait between the Simpevarp peninsula and Hålö which has been separated from the seaward part by a short causeway which is mapped as fill.

A larger lake, Götemar, lies about 7 km north of the local model area for Laxemar, and straddles the northern boundary of the regional model area. Lake Götemar is in a separate catchment as defined by topography, and has generally been excluded from hydrologic models of this area for that reason. However, Kärrviksån (the main stream in the northern part of the Laxemar area) has one tributary that starts from a spring just 300 m south of the lake, in a narrow valley which is a few meters below the elevation of the lake surface. Thus it seems likely that the Kärrviksån catchment receives some input via shallow groundwater seepage from the Götemar catchment.

The other perennial stream in the area is Laxemarån, in the south part of the Laxemar area. A smaller stream draining the east-central part of Laxemar, Ekerumsån, can flow year-round in wet years but is dry during dry summers. Other small streams in the area are generally dry for about half of the year (SKB, 2009). Most of the streams have been affected to some degree by agricultural drainage measures.

Setting with respect to Baltic

The Baltic acts as a time-dependent boundary condition for regional groundwater flow, with a coastline that changes over time due to global sea level changes in combination with land rise due to isostatic rebound of the Scandinavian lithosphere following the past continental glaciation. The Baltic is a brackish sea, and hence has a density slightly higher than fresh water (1,004 kg/m^3 at Forsmark). The difference in density between the Baltic and groundwater of meteoric origin is an important constraint on groundwater flow and discharge patterns along Sweden's eastern coast.

The Forsmark lens area is presently a coastal site with Öregrundsgrepen (an arm of the Gulf of Bothnia) bordering the site to the NE, and with a rate of uplift relative to sea level of about 6 mm/yr. The site is already part of the mainland. However, the site includes a string of lakes and low wet areas running from NW to SE, that are still less than a meter above sea level. Some of these lakes show evidence of seawater inflows during periods of very high sea levels (*e.g.* storm surges). Thus the surficial boundary conditions are still strongly influenced by the Baltic. Regional groundwater flows from higher--elevation areas inland (as high as 20 m.a.s.l. within 2 km) could discharge within the site as a consequence of this coastal setting.

The Forsmark SFR area is mainly under Öregrundsgrepen, approximately half a kilometre offshore of the present-day coastline. The sea is generally shallow (less than 15 m deep) in the immediate area. Several emergent rocks and islets (Lilla and Stora Asphällen, Asphällskulten, and Grisselgrundet) are connected by an artificial causeway which is built over a natural undersea ridge.

The coastline at Forsmark is expected to continue to recede seaward with continuing land rise due to post-glacial isostatic rebound. The rate of land rise relative to sea level is approximately 6 mm/yr (60 cm per 100 years); this rate is expected to decrease gradually but is expected to remain substantial for many thousands of years (Brydsten, 1999). Due to the shallow bathymetry of Öregrundsgrepen, this is expected to produce a pronounced progression of the shoreline.

As shown in Figures 3.1 through 3.3 (from Brydsten, 1999), changes are expected to include closure of the narrow strait that separates Grässö from the mainland, narrowing of Öregrundsgrepen, and eventual transition of the eastern part of Öregrundsgrepen to a chain of freshwater lakes. These lakes are predicted to have high volumetric turnover, due to flow from the two regional rivers that currently flow into Kallrigafjärden (Forsmarksån and Olandsån), continuing on via a new river that discharges to a distant Baltic.

Other lakes forming in shallow bathymetric basins in the western part of Öregrundsgrepen – including one just NW of the SFR – will be fed by only local streams and hence have lower turnover. The sea bottom directly above the current SFR facility predicted begin to emerge from the sea and to drain around 2400 AD, and to be “completely dry” (presumably sub-aerial) by 3500 AD (Brydsten, 1999).

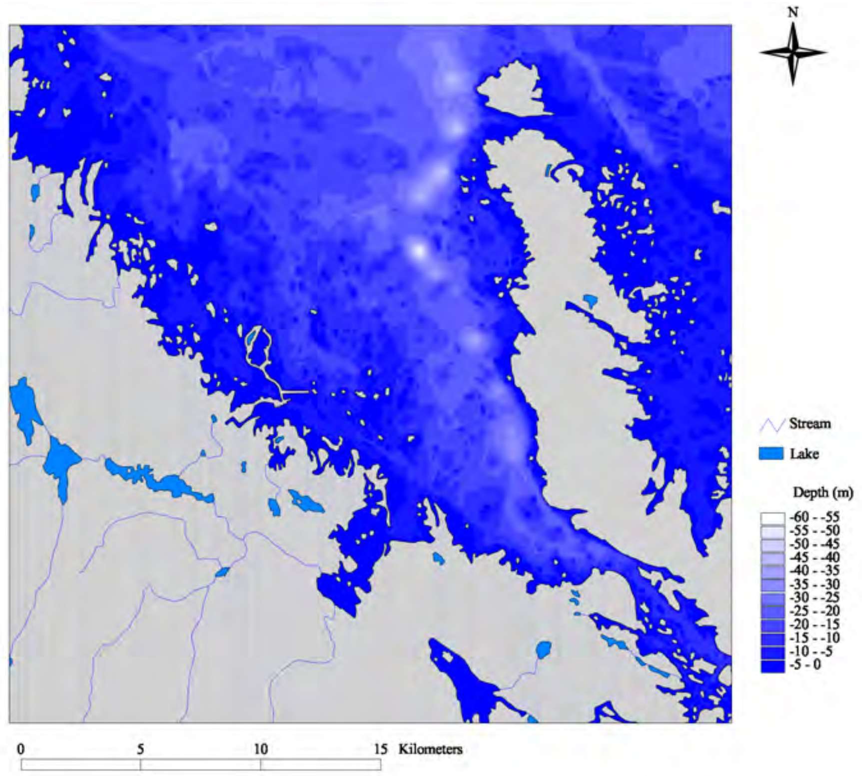

Figure 3.1 Öregrundsgrepen with the water depth conditions that prevail as of 2000 AD. Figure from Brydsten (1999).

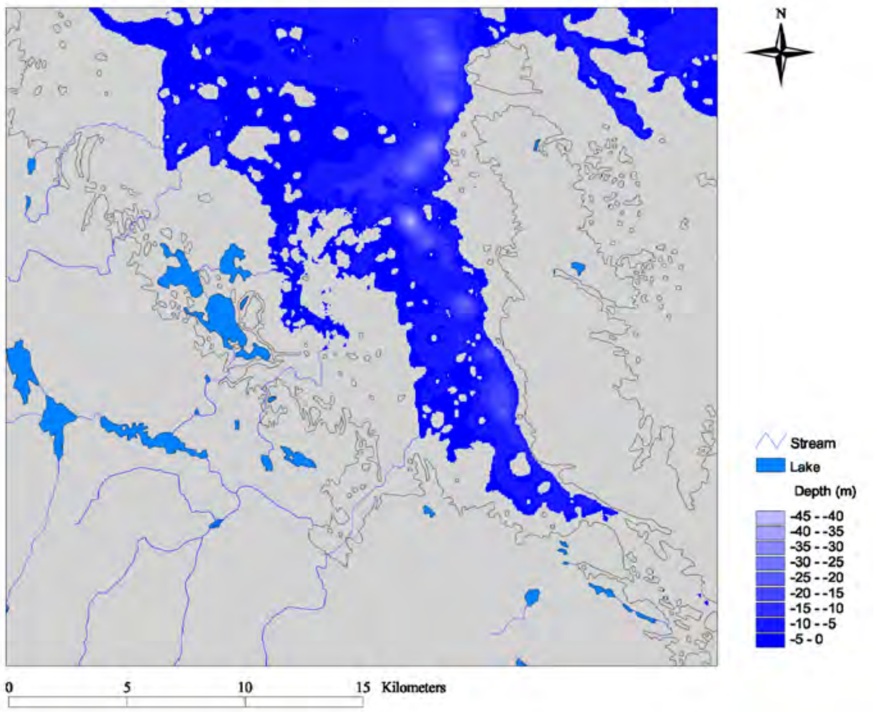

Figure 3.2 Öregrundsgrepen with the water depth conditions that are predicted to prevail in 4500 AD. The current shoreline is marked (black lines) for reference. The larger rivers, their new extensions, and new larger lakes are also shown. Figure from Brydsten (1999).

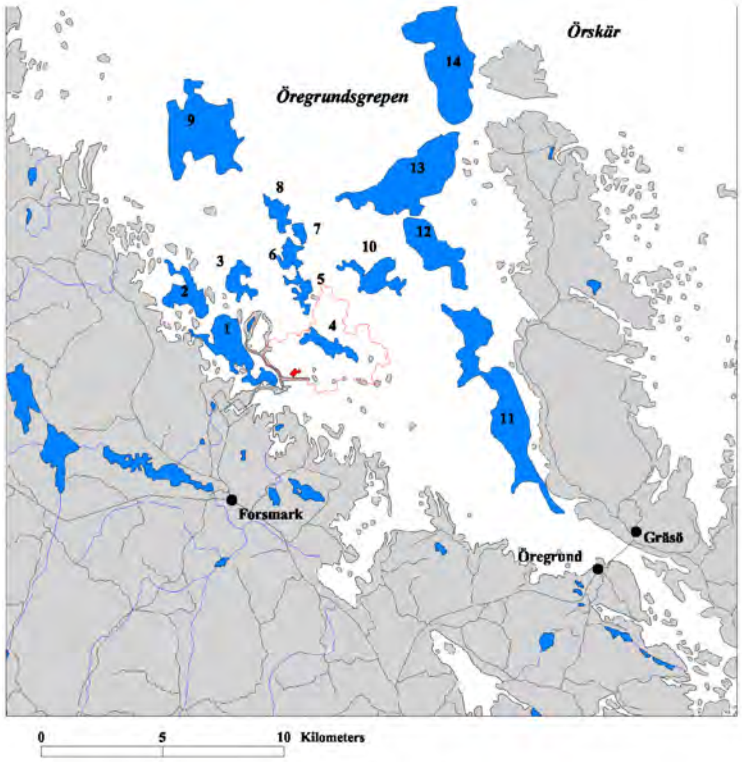

Figure 3.3 Future lakes in Öregrundsgrepen after retreat of the Baltic from the area. SFR-1 is marked in red, along with the region used for local-scale hydrogeological modelling for SFR-1. Figure from Brydsten (1999).

The Simpevarp investigation area consists of a small peninsula extending eastward into the Baltic, connecting to the mainland by a narrow strip of land plus two islands (Ävrö and Hålö) which are separated from the peninsula by narrow straits. The Simpevarp area thus is nearly surrounded by water at sea level, limiting the likelihood of regional groundwater flow being a strong influence on the site. Thus present-day groundwater flow is expected to be driven mainly by the moderate local topographic relief on the peninsula and these two islands (nearly all below 10 m).

Laxemar is situated to the W and NW of Simpevarp, further inland on the same system of narrow straits between the peninsula and nearby islands. The general topographic gradient is (decreasing) toward the brackish strait between the east side of the Laxemar area and the island of Äspö.

The rate of land rise relative to sea level in the Laxemar-Simpevarp area is currently just 1 mm/yr (10 cm per 100 years). The brackish straits on the north side of the Simpevarp peninsula area, to the west of Ävrö, and around the island of Äspö, are generally less than 10 m deep so will fill in gradually over the next 10,000 years, leaving the current land areas as hills and hillocks of high ground, bounded by wetlands and stream courses.

The Baltic deepens rapidly to the SE of Ävrö, reaching depths of over 10 m within about 250 m of the current shoreline. Hence only minor progression of the SE shoreline is expected during the interglacial period. The embayment to the south of Simpevarp is shallower so the shoreline will shift seaward in this area at a somewhat faster rate. However, in comparison with the Forsmark area, the position of the coastline relative to the Laxemar and Simpevarp areas is expected to be relatively stable for the remainder of the current interglacial period. The slower rate of shoreline progression at Oskarshamn also means that the position of the interface between meteoric and brackish groundwaters has changed much less rapidly over recent centuries, compared to Forsmark.

Possible consequences of anthropogenic climate change

These expectations for shoreline progression in the Forsmark and Oskarshamn areas are based on continuation of recent rates of land rise relative to sea level. However, as discussed by (SKB, 2006b) following the results of (IPCC, 2001, later updated in IPCC, 2007), anthropogenic greenhouse-gas emissions may result in short-term warming (over a time scale of centuries) and an extended interglacial warm period, resulting in short-term global sea level rises possibly as high as 7 to 14 m These rises in sea level should be offset by continuing isostatic rebound in the the Forsmark area, within the next two thousand years, and over a longer time period in the Laxemar area.

The consequences of short-term climate change on sea level have been evaluated for the operational phase of radioactive-waste repositories at Forsmark and Oskarshamn by Brydsten et al. (2009). For the year 2100 AD, extreme sea levels (including effects of transient storm surges along with climate-change effects) are expected to be 3.16 m or less at Forsmark, and 3.41 m or less at Laxemar-Simpevarp. The most extreme scenarios considered by

Brydsten (2009) would result in incursions of Baltic water up to 2 km inland of the present coastline at Forsmark, with near-submergence of the islands on which the SFR surface facilities are currently located, and also some parts of the planned surface facilities for the deep repository at Forsmark-lens. For the Simpevarp and Laxemar areas, incursion by Baltic waters would be much more limited due to the generally steeper shorelines.

Presumably (although not addressed by Brydsten *et al.*, 2009), continued melting of Greenland and Antarctic glaciers beyond 2100 AD as predicted by the scenarios described by IPCC (2001; 2007) would lead to further increases in mean sea levels which would only be partly offset by continued isostatic land rise, leading to further inundation in the post-closure period. According to the persistent warm climate scenario developed by (SKB, 2006b), the higher global sea levels could continue for several thousand years.

Locally, this would mean that inundated areas at Forsmark would remain in that condition until the global sea level rise is offset by continuing isostatic land rise. The sequence of shoreline progression, narrowing of Öregrundsgrepen, and transition to a chain of freshwater lakes, would presumably be delayed for some thousands of years into the future. During the period of inundation, it seems likely that some of the recently formed lake-bed sediments and older glacial till in the Forsmark-lens area could be reworked by wave action, affecting local topography (although likely not bedrock-determined topography). Brackish waters could also re-infiltrate into sediments and shallow bedrock in areas that had previously been infiltrated by lower-density meteoric waters. Thus in hydrologic terms, the consequences of global sea level rise due to anthropogenic warming would not be simply a “rewinding of the clock” to the state that existed several thousand years ago, but a more complex hydrogeochemical state with somewhat altered local topography and sediment distributions.

Local topography and Quaternary deposits/regolith

All of these sites, particularly the Forsmark area sites, have fairly low relief, due to a history of peneplanation and later continental glaciation. The regolith forms a discontinuous uppermost layer at all of the sites. Its properties can potentially potential affect the spatial and temporal variability of recharge to the bedrock surface following precipitation events, as well as discharge from the bedrock.

Forsmark area

The topography at Forsmark is gently undulating on the local scale with elevations generally under 20 m.a.s.l. Bathymetry offshore in the Forsmark-SFR are is also subdued, with sea depths generally less than 15 m, although basins as deep as 60 m occur in the regional area closer to Grässö.

The Forsmark-lens area is mostly overlain by Quaternary deposits, mainly glacial till, which covers 75% of the area, typically less than 5 m deep but up to 15 m deep in places. Typically the deepest layers of till are found in bedrock surface depressions. Over most of the area the till is sandy, but clayey till dominate in the SE part of the site. Forsmark also contains organic gyttja deposits, particularly in the bottoms of lakes and fens, which reduce the vertical permeability of near-surface sediments. About 5% of the area is exposed bedrock, *i.e.* lacking Quaternary deposits.

The Forsmark-SFR site lacks data on Quaternary deposits for some areas (cf. Figure 4-10 in Lindborg, 2010, SKB TR-10-05 and Figure 5-26 in Hedenström and Sohlenius, 2008, SKB R-08-04). For the areas that have been characterised, till is the primary cover, followed by glacial clay (often topped with a thin layer of post-glacial sand or gravel). Areas of post-glacial fine sand are found to the N of the SFR. The offshore islets/skerries that rise above the sea typically have good bedrock exposure and little Quaternary cover, except where covered by artificial fill (*e.g.* for building site, causeways, and jetties in the SFR and biotest areas). The hydraulic conductivity of the glacial till has been estimated by Sigurdson (1987) to be within a range of $1x10^{-5}$ m/s through $1x10^{-8}$ m/s. (SKB R-01-02).

Laxemar-Simpevarp area

The Laxemar-Simpevarp area is entirely below 50 m.a.s.l., with distinct valleys bordering elevated bedrock areas. Hummocky moraine is found in the SW and central part of the area, which results in locally undulating topography. A few eskers are found on the regional scale, one of which wends through the SW corner of the regional-scale model area.

The Quaternary deposits at Laxemar are dominated by sandy-gravelly till which overlies the bedrock in most of the area (Werner 2009; Grolander, 2009). Elevated areas are dominated by exposed bedrock or shallow till, while valleys have deeper deposits typically 5-10 m deep, consisting of post-glacial as well as glacial deposits. In most areas the till is overlain by glacial clay with low permeability, which affects groundwater discharge patterns in valleys, constraining discharge to areas where glacial and post-glacial deposits are lacking (Grolander, 2009).

4. Bedrock characteristics

The main documents describing the bedrock geology of these sites are the site-descriptive models by Wahlgren *et al.* (2008) for Laxemar (with regional-scale coverage of Simpevarp), and Stephens *et al.* (2007) for Forsmark-lens (with regional-scale coverage of the Forsmark-SFR site). Bedrock hydrogeological site descriptions are presented by Rhén and Hartley (2008) for Laxemar, Follin (2008) for Forsmark-lens, and Axelsson *et al.* (2002) for Forsmark-SFR. An updated analysis of bedrock hydrogeology for Forsmark-SFR has recently been presented by Öhman & Follin (2010). This document, despite being published in SKB's P-report sequence, presents a significantly more advanced level of analysis than previous documents, and therefore is treated as a major reference for this report.

Bedrock origins, lithology and ductile deformation

The bedrock in the vicinity of all four sites is mainly granitic rock, formed in the Paleoproterozoic era. Rocks in the Forsmark area show strong foliation as a result of polyphase ductile deformation during the Fennian and Svecobaltic orogenies at 1860-1800 Ma. Ductile shear zones formed during these events had a strong effect on later brittle deformation. Rocks in the Laxemar-Simpevarp area were less strongly affected by these events, and generally show only a weak foliation; however ductile shear zones developed which have since influenced brittle deformation.

The Laxemar-Simpevarp area was also affected by igneous activity in the Mesoproterozoic era, around 1450 Ma. This produced the Götemar granite (around Lake Götemar to the north of the Laxemar model area), the Uthammar granite a few km to the south of Laxemar, and the granite island of Blå Jungfrun about 20 km SSE of Simpevarp.

Rocks of Mesoproterozoic or younger ages have not been found at Forsmark or in the immediate vicinity. Remnants of Jotnian sandstones are still found locally in the sea well to the NE of Forsmark, in the deepest depressions in the older bedrock surface (Tirén and Beckholmen, 2009).

The bedrock within the Forsmark-lens area is dominantly a medium-grained (meta)granite which has been affected by penetrative ductile deformation at mid-crustal depths and under high-temperature metamorphic conditions 1.87 to 1.86 Ga. Amphibolite and fine- to medium-grained granitoid were intruded syntectonically as dykes and minor bodies. Locally, at least the amphibolites gave rise to conspicuous alteration (albitization) in the older granitic rocks. Ductile deformation with folding continued to affect the younger intrusive rocks, including amphibolite, under lower metamorphic conditions, prior to 1.85 Ga. Subsequently, until at least 1.8 Ga, the ductile strain continued to affect the bedrock, predominantly along the margins of the tectonic lens along discrete zones (Söderbäck 2008). Borehole data indicate that the tectonic lens is a major geological structure that can be traced from the surface down to at least 1,000 m depth.

In the Forsmark-SFR area, the main rock type according to (Stephens *et al.*, 2007) is a felsic to intermediate volcanic rock, metamorphic, and in part albitised. According to (SKB, 2008 /SKB R-08-67/) the rock volume within which the SFR is placed is strongly metamorphised and inhomogeneous, with fine-grained felsic rock types which have been evaluated as vulcanites and pegmatitic granite. Secondary rock types include metagranitoids, and dykes with amphibolite, pegmatite, and granite. Similar rocks are expected in the area to the SE which has been proposed for SFR expansion. However (SKB, 2008 /SKB R-08-67/) note that the mapping of seabed areas has been less intensive than on land, so some differences might be encountered.

The predominant bedrock at in the Laxemar-Simpevarp area is a medium-grained, finely porphyritic rock that varies in composition between quartz monzodiorite, granodiorite, and granite. This rock is broadly referred to as Ävrö granite, despite the variable composition. A rock of more basic composition, medium-grained quartz monzodiorite, is dominant in the southern part of the Laxemar local model area (Wahlgren *et al.*, 2008). Important subordinate rock types in the area include a fine-grained granite (or aplite), a fine-grained diorite-gabbro, and pegmatites. Dolerite dykes associated with later extensional tectonics around 900 Ma are also found, particularly in the western part of the Laxemar area.

Large-scale brittle deformation zones

Large-scale brittle deformation zones – including ductile deformation zones which have been reactivated in brittle deformation modes – are interpreted as being the most important water-conducting features in the bedrock for depths greater than 100-150 m, at all of these sites. Identification and characterisation of brittle deformation zones has therefore been a central focus of the geological investigations.

Structural configuration

The Forsmark-lens site is situated in a shear lens between two NW- to WNW-striking, anastamosing regional deformation zones, the Singö deformation zone on the NE side, and the Eckarfjärden deformation zone on the SW side. The target volume for the repository is in the footwall of a stack of gently SE-dipping fault zones. The target volume is bounded by the limbs and hinge of a steeply dipping synform, which helps to give confidence in downward projections of the lithology. The bounding regional-scale structures are also presumed to bound the extent of brittle deformation zones within the shear lens. The interpreted configuration of brittle deformation zones is illustrated in Figure 4.1.

At Forsmark, the deformation zones which are interpreted as being most significant for site-scale flow (other than the regional shear zones that bound the shear lens that contains the candidate site) are a stack of gently dipping brittle deformation zones that dip SE or SSE. These gently dipping zones show only brittle deformation. Most exhibit evidence of reverse dip slip and subordinate strike-slip displacements, implying origins in a compressive tectonic environment as thrust faults, but they also are interpreted as having been reactivated multiple times. Hydrologically these zones indicate strong, laterally extensive connections across the site. This has been confirmed by responses in observation wells during in pumping tests.

The local-scale hydrostructural model for Forsmark includes several dozen vertical or sub-vertical hydrogeological zones. These vertical/sub vertical hydrogeological zones at Forsmark result in an interconnected network of zones, particularly in the vertical direction, and provide routes of relatively high hydraulic conductivity (relative to the rock mass) via which groundwater can be driven to depth (*e.g.* due to local topographic heads), laterally, and then upward.

At Forsmark, the vertical/sub-vertical zones tend to be relatively narrow features rather than broad zones, and in places may be represented by just a few discrete fractures.

The Forsmark-SFR site lies to the NE of the Singö zone, and thus is in a different structural domain (though the surface facilities for the SFR are within the shear lens, and the access ramp passes through the Singö zone). One gently dipping zone (H2 in Figure 4.2) is similar in orientation to the stack of gently-dipping deformations zones in the Forsmark-lens.

A deformation zone regarded as a major splay of the Singö zone, ZFMNW0805 in the nomenclature of (Stephens *et al.*, 2007 /SKB R-07-45/), lies to the NE of the existing SFR tunnels. Thus the site lies within a wedge that is bounded on two sides by the Singö zone and a major splay of the Singö zone, opening toward the NW. Several additional deformation zones are interpreted as lying within this volume (Figure 4.2). The priority considered for SFR expansion is to the SE of the existing disposal tunnels, and thus moving toward the narrower part of this wedge.

Within the regional-scale geological site-descriptive model for the Forsmark-lens (Figure 4.1), which contains the Forsmark-SFR site, there is a noticeable deficit in the intensity of deformation zones in the portion of the model that is currently covered by the sea. This might be partly an artefact of the more limited data from the seabed areas. The structural wedge that contains the SFR site, in particular, has an anomalously low frequency of recognized deformation zones. However, the narrower part of this wedge to the SE of the SFR site is in a low-magnetic region (Figure 4.3), which is suggestive of more fractured rock, possibly including smaller-scale deformation zones that have not been recognized in the regional model for Forsmark.

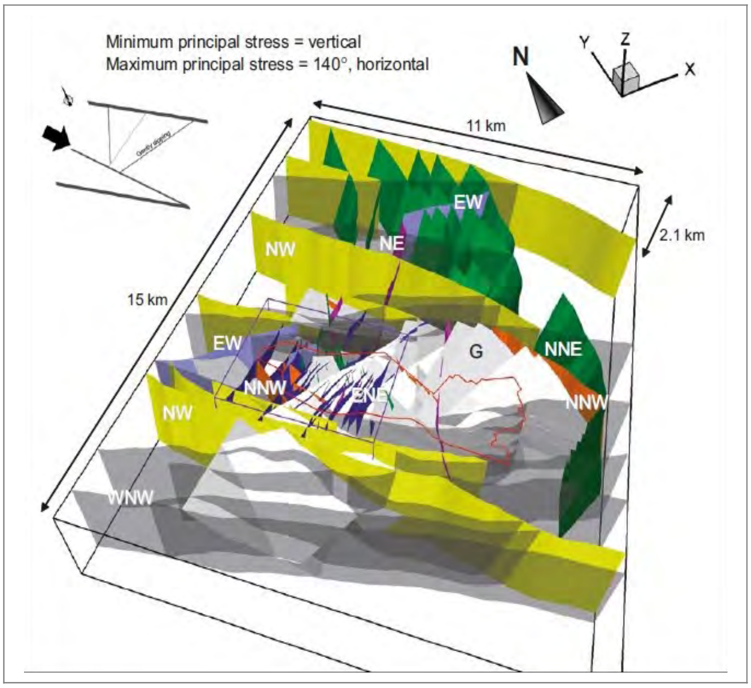

Figure 4.1 3-D visualisation of the 131 deformation zones modelled deterministically for the Forsmark site descriptive model, stage 2.2 (Stephens *et al.*, 2007) focused on the Forsmark-lens site. The steeply dipping zones (107) are shaded in different colours and labelled with regard to their principal direction of strike. The gently dipping zones (24) are shaded in pale grey and denoted by a G. The border of the candidate area is shown in red and the regional and local model domains in black and purple, respectively (Fig 3-4 from Follin, 2008, SKB R-08-95).

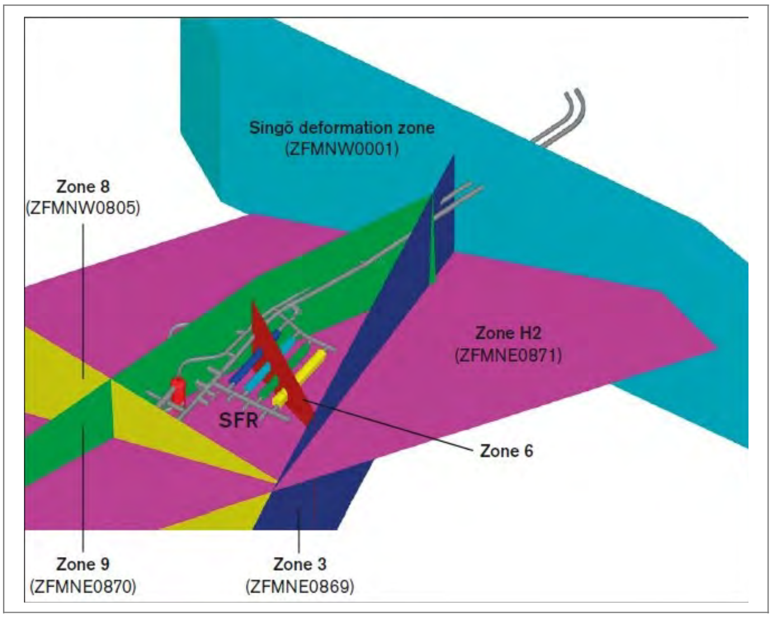

Figure 4.2 Interpreted configuration of brittle deformation zones at the Forsmark-SFR site, as viewed from the NE looking toward the SW. The structural model extends to a depth of 490 m from level 0 according to the RHB70 elevation system, but here the vertical extent of the deformation zones is illustrated only for a level directly above the SFR (figure from Holmén and Stigsson, 2001).

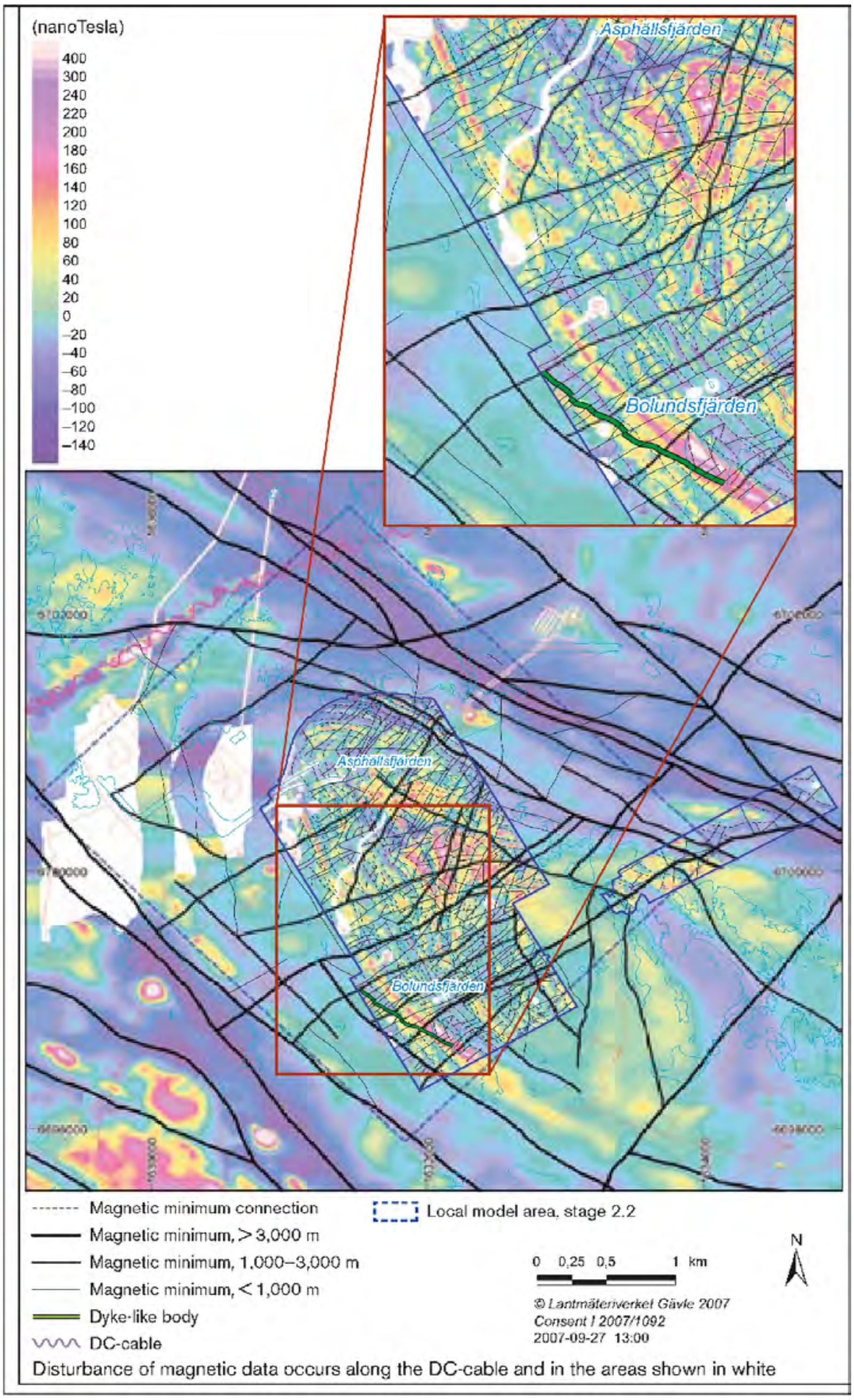

Figure 4.3 Low-magnetic lineaments in the Forsmark area (from Stephens *et al.*, 2007).

An updated structural model for the Forsmark SFR site includes 58 “updated geological structures ... which require hydraulic parametrisation” according to Öhman & Follin (2010). These are shown as grey zones in Figure 4.4. This indicates a significantly higher intensity of structures within the wedge than was recognized in the Forsmark-lens site-descriptive model (although it should be noted that this structural wedge was outside the main area of focus for the site-descriptive model). At present, as noted by Öhman & Follin (2010), there is little or no information on the hydraulic properties of these structures. SKB (2008, R-08-67) note that, based on experiences from the Forsmark-lens site as described by Stephens *et al.* (2007), the representativity of low-magnetic lineaments as indicators of deformation zones needs to be assessed, as some of these could represent rock types with low magnetic susceptibility due to oxidation of iron-rich minerals.

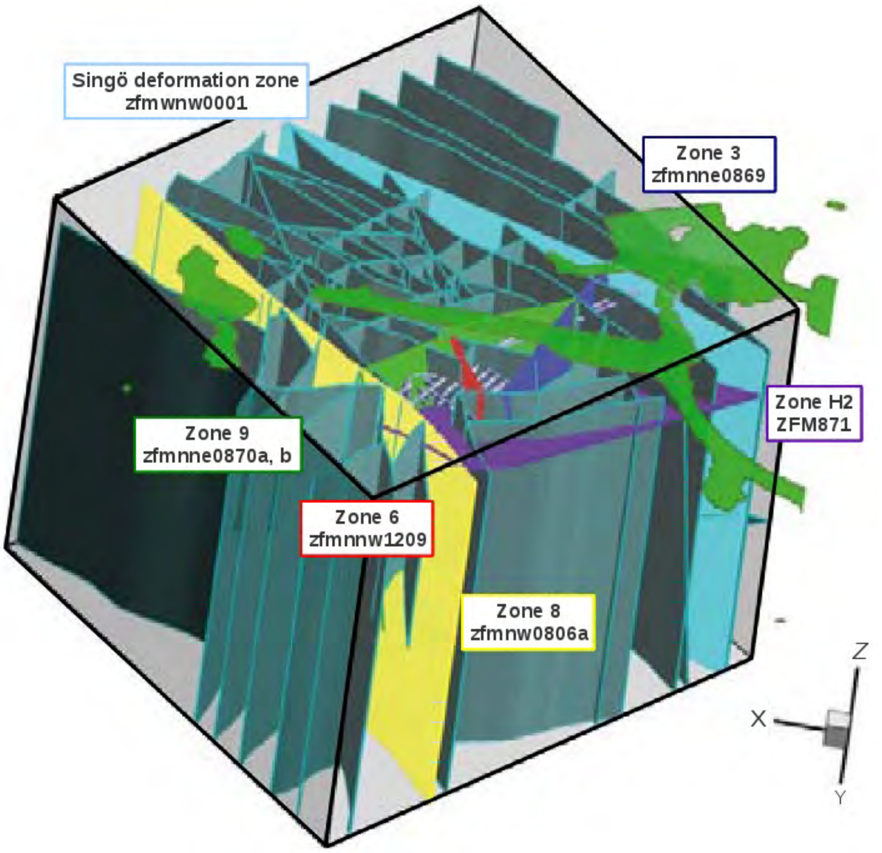

Figure 4.4 Deformation zones of the regional SFR domain (58) as defined in the preliminary structural model SFR v. 0.1. The zones that existed in the previous structural model of Axelsson and Mærsk-Hanson (1997) are shown in colours similar to those for the same zones in Figure 4.2, with both the earlier and current names of the zones. Figure from Öhman & Follin (2010, P-09-49). The view is from the N/NE. According to Öhman & Follin (2010), updated structures are from SKBdoc 1224847 - DZ_SFR_REG_v0.1_prelim, Version 0.1, 2010-06-08.

The Laxemar and Simpevarp areas have a differently oriented pattern of large-scale deformation zones (Figure 4.5), dominated by NE-striking, steeply to moderately dipping structures which are sub-parallel to the Äspö Shear Zone, and an intersecting set of E-W striking, southward dipping regional structures. On a large scale these structures have an anastamosing character, with NE-striking structures curving toward the east beyond the interference zone.

A set of N-S, steeply dipping regional structures occurring to the NW of the Äspö Shear Zone have been suggested by Wahlgren *et al.* (2008) to be possibly related to the NE-striking structures, as Riedel shears in a strike-slip system dominated by the NE-striking structures. Several of these N-S structures also have a radial configuration with respect to the younger granites (Götemar and Uthammar). The N-S set of structures are also associated with dolerite dykes which, when fractured internally or along their boundaries with the country rock, may be of hydrogeological significance.

The Simpevarp portion of the regional-scale structural model lies to the SE of the Äspö Shear Zone. In this area, N-S striking features longer than 1 km have not been found (the regional model contains one N-S deformation zone about 1 km long, which forms the strait between Ävrö/Jungfrun and the islands of Äspö and Hålö. Otherwise, the regional-scale fabric in the Simpevarp area is a series of elongated rock, apparent shear lenses bounded by the anastamosing NE- and E- striking deformation zones. This contrasts with the Laxemar area where deformation zones divide the area into an assemblage of more equidimensional blocks. Wahlgren et. al (2008) suggest that the Laxemar site can be viewed as part of a larger-scale "tectonic lens." bounded to the NW and SE by systems of NE-striking, broad ductile belts represented by the deformation zones ZSMNE011A-90 to the NW, and ZSMNE004A and ZSMNE005A to the SE.

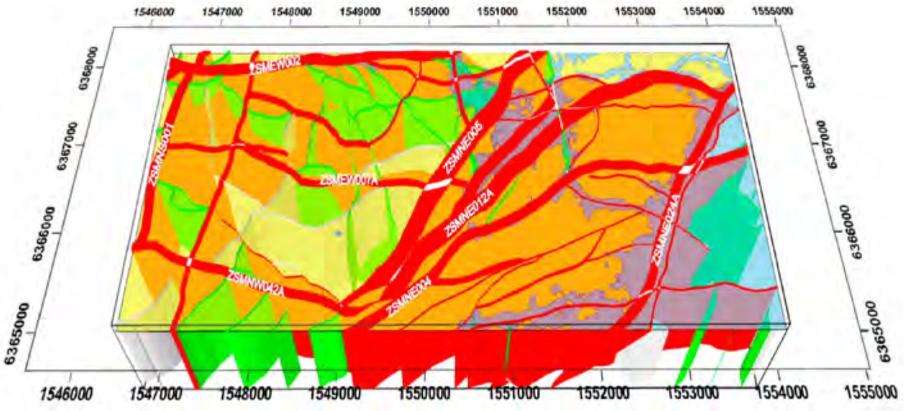

Figure 4.5 A 3-D view of large-scale deformation zones in the Laxemar regional model area (from SKB TR-06-09 Figure 4-37).

Hydraulic properties of deformation zones

In the hydrogeological site-descriptive models, the term “hydraulic conductor domain” (HCD) is used to distinguish hydraulically conductive deformation zones from the remainder of the bedrock, which is termed “hydraulic rock domain” (HRD). The correspondence of HCDs to geologically defined deformation zones is only approximate, as sometimes the significantly conductive part of a zone is just a small part of its geological thickness as observed in boreholes.

Forsmark-lens

Hydraulic transmissivities measured in deformation zones at Forsmark are presented by Follin (2008, R-08-95). As seen in Figure 4.6, measured values range from less than the measurement threshold (10^{-10} m^2/s or less) to a maximum of about 10^{-3} m^2/s. At any given depth down to 900 m, the highest measured transmissivities are associated with gently-dipping deformation zones. These gently-dipping zones show a trend of logarithmically decreasing transmissivity with depth.

For the more steeply dipping sets of deformation zones, the hydrogeological site-descriptive model for Forsmark (Follin *et al.*, 2007b) uses a trend of decreasing transmissivity with depth. While such a model can be fitted to the dataset, the evidence is ambiguous. For the steeply dipping sets of deformation zones in Figure 4.6, no clear trend with depth is obvious, although a few very high values (>$5\text{x}10^{-5}$ m^2/s) are obtained for depths of less than 150 m in WNW- and NW-striking deformation zones.

Among steeply dipping zones, the WNW-striking deformation zones are associated with most of the transmissivity measurements above 10^{-6} m^2/s, although ENE-striking zones are responsible for two such measurements and a NW-striking zone accounts for another.

At shallow depths of under 100 m (*i.e.* depths at which an SFR extension would most likely be located), transmissivities of 10^{-5} m^2/s or higher were recorded in all but one of the tested borehole-zone intersections, regardless of deformation-zone strike or dip.

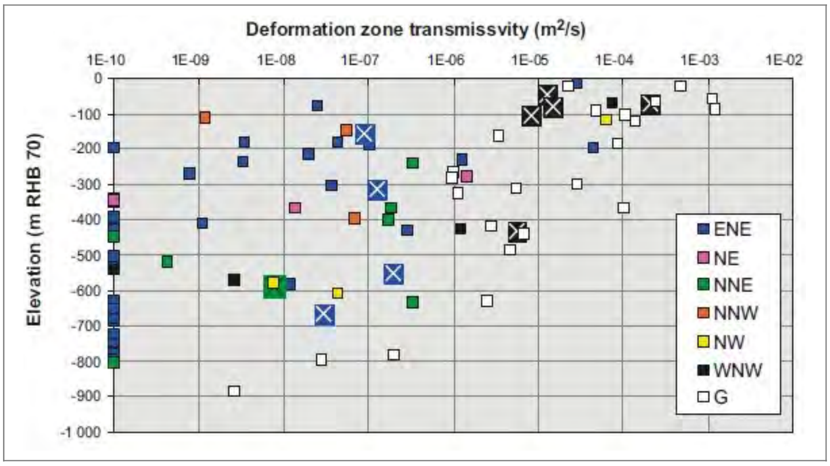

Figure 4.6 Deformation-zone transmissivities vs. depth for deformation zones at Forsmark. Tests with no measurable flow are assigned an arbitrary low transmissivity value of 10-10 m2/s in order to make them visible on the log scale. Figure from Follin (2008, R-08-95, Figure 5-3). Larger "X" symbols denote measurements that were made in the last stage of site characterisation proper to SDM-Site.

Forsmark-SFR

For the deformation zones around the SFR, early models developed by SKB made use of hydraulic conductivity values and zone thicknesses as given in Table 4.1. These are also presented here as transmissivities, for ease of comparison. Two of the deformation zones (Singö Zone and Zone 8) were evaluated as being heterogeneous across their thickness, with a higher-transmissivity "core" and lower-transmissivity outer parts. Another zone (Zone 3) was assessed as having anisotropic properties depending on whether flow was horizontal (along strike) or "vertical" (presumably along dip).

In later modelling, transmissivity estimates for the same zones have been obtained by calibration of a continuum model based on inflows to tunnels in the SFR (Holmén and Stigsson, 2001), and assuming homogeneous properties within the zones. From Table 4.1, it may be noted that the calibrated values are consistently lower than the initial estimates which were based on hydraulic testing in boreholes that intersected these zones. If the values from the calibrated models are correct, this would imply either that (1) the earlier hydraulic tests were fortuitously located in relative high-transmissivity portions of the deformation zones, or (2) effective averaging of the deformation zone properties, as they act in the site-scale flow system, is more strongly influenced by the low-transmissivity portions of these zones, than the averaging methods that were used for the early estimates. Alternatively, the transmissivity values estimated by calibration with respect to tunnel inflows might be too low, because the model neglected tunnel "skin" effects, which can occur due to a variety of causes including unsaturated-zone effects near the tunnel and hyperconvergence of channelized flow.

Most recently, Öhman and Follin (2009) have re-evaluated hydraulic data from the Forsmark-SFR area that were available prior to the initiation of the SFR extension programme. They present a new parametrization based on a trend in transmissivity with depth, assuming the same form of trend that was applied for the Forsmark(-lens) site descriptive model by Follin *et al.* (2007b). The motivation for applying this parametrization at Forsmark SFR is, according to Öhman and Follin (2009), to give a reasonable extrapolation of the SFR dataset which comes mainly from depths of less than 150 m, to the greater depths of up to 1100 m that are considered in the new, v.0.1 model of the Forsmark-SFR site.

Figure 4.7 shows the fitted trend in comparison with the reinterpreted transmissivities from HCD intercepts with boreholes. The validity of a systematic trend with depth is arguable. However, this plot illustrates the substantial heterogeneity within these deformation zones, particularly the gently dipping Zone H2 for which point measurements of transmissivity within the depth range 100 m to 200 m vary across two orders of magnitude.

Further evidence of HCD variability is suggested by comparing transmissivity estimates from single-hole hydraulic tests vs. interference tests, as summarized by Holmén and Stigsson (2001, SKB R-01-02, Tables 5.1 and 5.2). For a given zone, the interference-test estimates are systematically higher than the single-hole estimates, reflecting the likelihood that interference tests represent the most transmissive pathways between boreholes, rather than average properties within the tested deformation zones.

Table 4.1 Estimated hydraulic properties of deformation zones in local model of SFR. Adapted from SKB R-02-14, Table 3.3 (originally from SKB, 1993, Table 2-4). For the Singö Zone and Zone 8, net transmissivities are calculated as the sum of the transmissivities for different parts of the zones. For Zone 3, a geometric mean value of the anisotropic transmissivities is given. The transmissivity values in the last column are the based on values calibrated by Holmén and Stigsson (2001) and used by Odén (2009) in the SKB's v. 0.0 model for the SFR.

Hydraulic unit	**Breadth (m)**	**Dip**	**Hydraulic conductivity (m/s)**	**Transmissivity (m^2/s)**	**Calibrated Transmissivity (m^2/s)**
Singö Zone				2.4×10^{-5}	1.6×10^{-6}
SW part	14	90	5×10^{-7}	7×10^{-6}	
Core	2.5	90	4×10^{-6}	1×10^{-5}	
NE part	14	90	5×10^{-7}	7×10^{-6}	
Zone 3				8×10^{-5}	2.0×10^{-5}
Vertically	7	75 NW	3×10^{-6}	2×10^{-5}	
Horizontally	7	75 NW	5×10^{-5}	3.5×10^{-4}	
Zone 4	2.5	90	4×10^{-7}	1×10^{-6}	
Zone 6	2.5	90	4×10^{-7}	1×10^{-6}	
Zone 8				3×10^{-5}	4.0×10^{-6}
SW part	15	90	6×10^{-8}	9×10^{-7}	
Core	15	90	2×10^{-6}	3×10^{-5}	
NE part	10	90	2×10^{-8}	2×10^{-7}	
Zone 9	5	80 NE	4×10^{-8}	2×10^{-7}	2.0×10^{-8}
Zone H2	10	18 SSE	1×10^{-6}	1×10^{-5}	1.6×10^{-6}

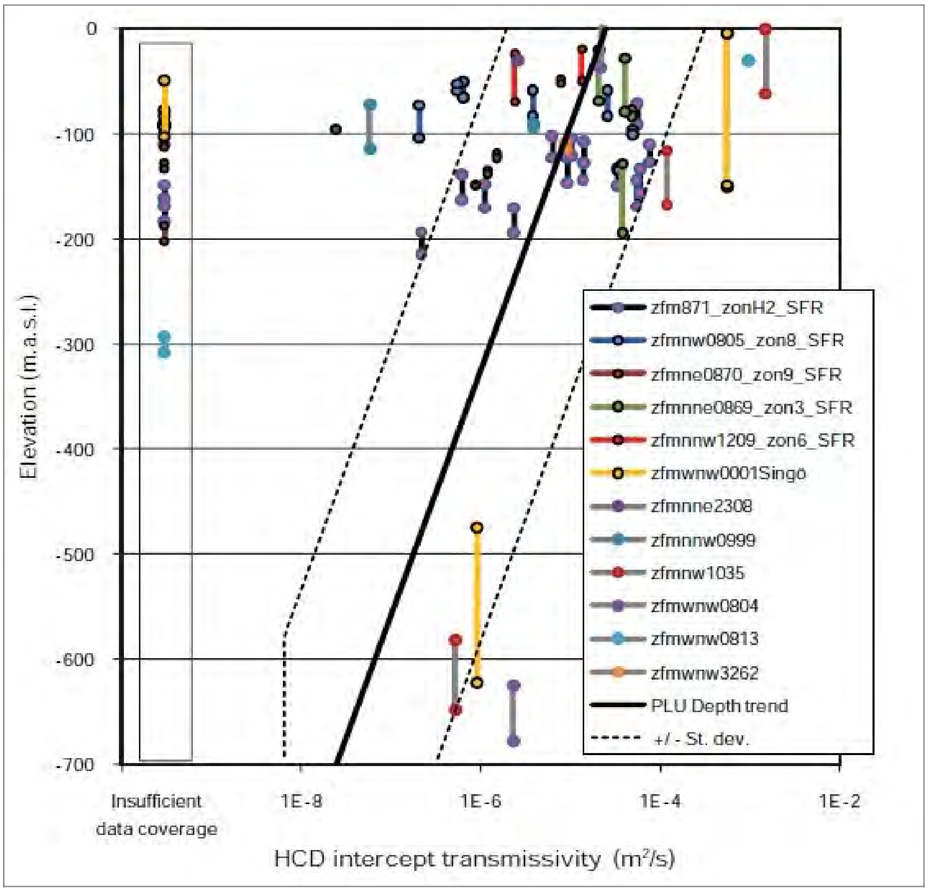

Figure 4.7 Transmissivities of deformation zones at Forsmark-SFR site, based on reinterpretation of older borehole data. HCD transmissivity as function of depth, shown with a depth trend according to Follin *et al.* (2007). No HCD transmissivity is calculated for intercepts with insufficient data coverage (shown next to y-axis). Data points show modelled elevation interval of HCDs. Figure from Öhman and Follin (2009, P-09-49 Figure 5-14).

Laxemar-Simpevarp area

Hydraulic properties of deformation zones within the Laxemar-Simpevarp regional area have been evaluated by Rhén *et al.* (2008). Measurements of transmissivity at borehole-zone intercepts have been analysed in terms of four major categories of deformation zones:

- Larger E-W striking zones;
- Smaller E-W striking zones;
- Larger zones of other orientations;
- Smaller zones of other orientations;

where the division between larger and smaller zones is based on whether the map traces extend for more or less than 2 km, respectively.

For each of these categories, trends in log transmissivity as a linearly decreasing function of depth have been fitted to the data (Figure 4.8). Rhén *et al.* (2008) note that heterogeneity is observed for deformation zones for which transmissivities have been measured at multiple borehole intercepts. For individual zones, the standard deviation of $\log_{10}(T)$ for individual zones ranges from 0.5 to 2, but the highest standard deviations are associated with zones with a very small number of data points. The fitted trends have been applied in a depth-dependent model (Figure 4.9).

As for the Forsmark area, deformation zone transmissivities in the range 10^{-4} m^2/s to 10^{-3} m^2/s are encountered in the shallow bedrock, particularly for the larger-scale zones (though for a few points in smaller zones). Values on the order of 10^{-5} m^2/s are more typical for the smaller-scale deformation zones.

In addition to the deformation zones, dolerite dykes associated with the N-S deformation zones are found in the western part of the Laxemar area. According to Rhén *et al.* (2008), the dolerite core of these dykes tends to be relatively impermeable, with hydraulic conductivity less than 10^{-9} m/s. However, the flanking contacts with granitic rocks tend to be highly conductive, with transmissivities of 1.2×10^{-5} m^2/s to 4.8×10^{-4} m^2/s. Thus along their strike and dip directions these dykes can act as significant conductors, but in the transverse direction, at least locally they may act as barriers to flow through the rock mass.

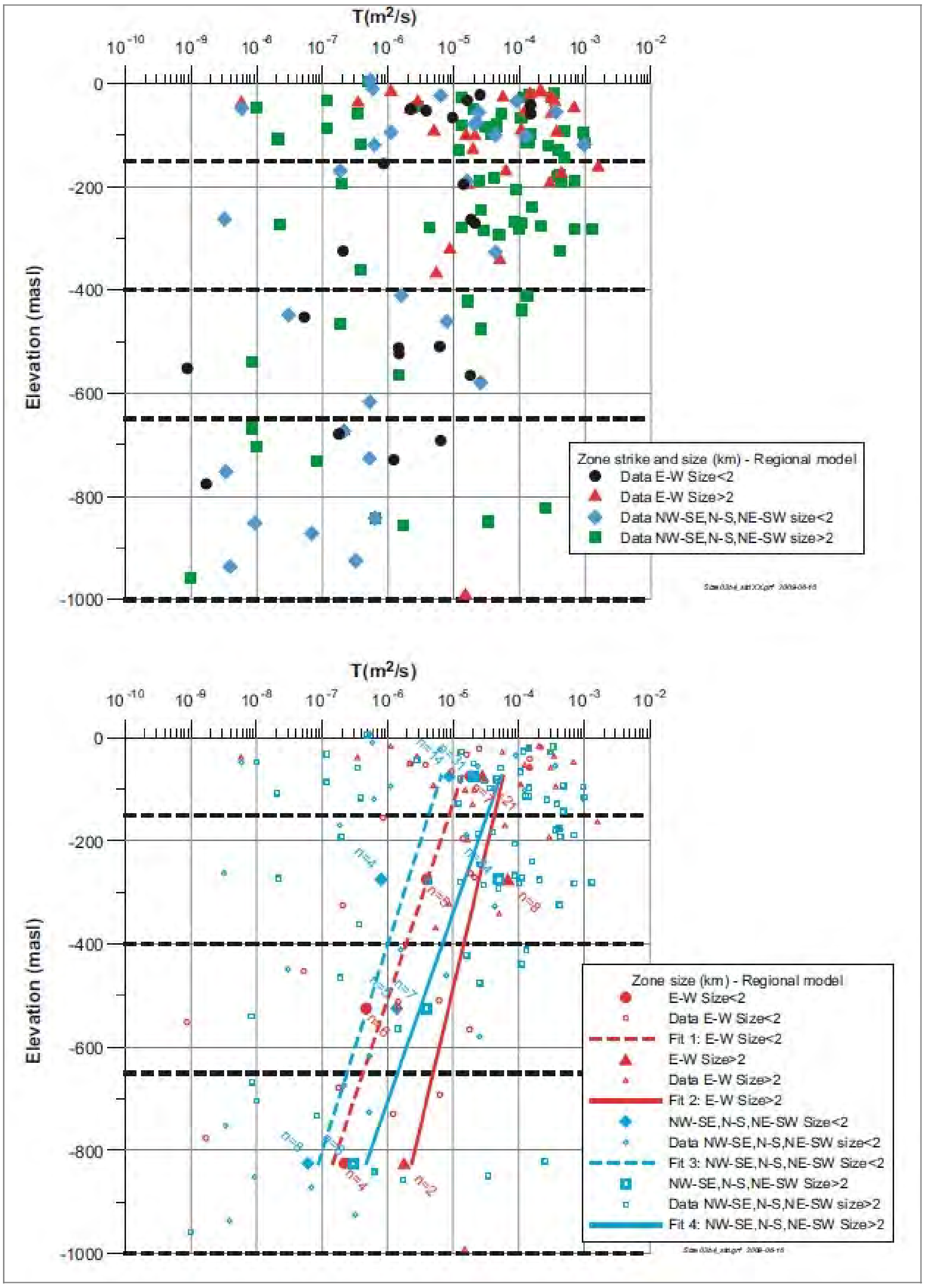

Figure 4.8. Deformation zone transmissivity (*T*) related to deformation zone strike direction and size, vs. elevation Mean of $\log_{10}(T)$ is plotted as well as the number of observations (n). Top figure shows data in regional model. Bottom figure shows regression line and data, regional model. Figure from SKB (2009, SKB TR-09-01, Figure 8-16).

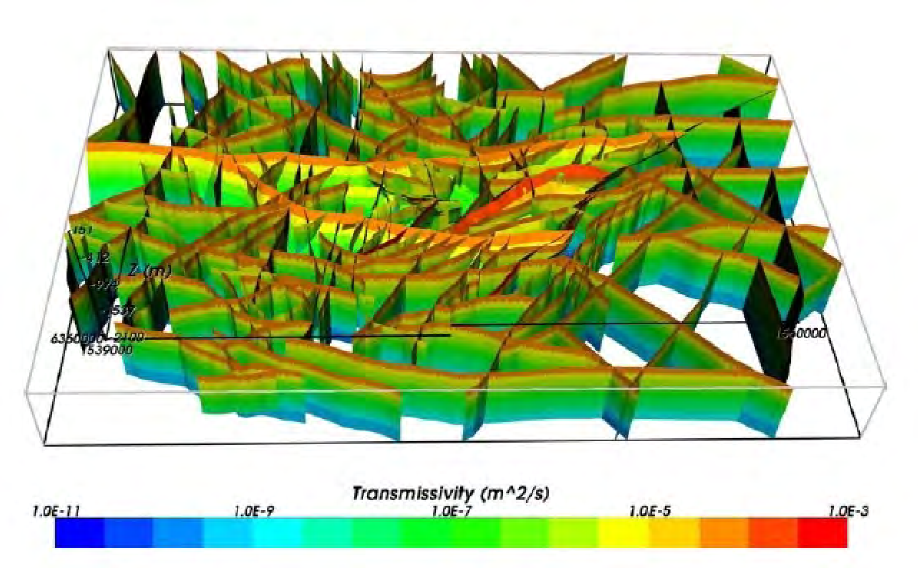

Figure 4.9 Deformation zone (HCDs) in the Laxemar regional-scale model, with inferred depth-dependent transmissivities. Oblique view from the south. The regional model volume used for groundwater flow simulations is shown in black; the area of this model is 21 km x 13 km with a bottom elevation at -2.3 km Figure from SKB (2009, SKB TR-09-01, Figure 8-25).

Bedrock excluding major deformation zones

The bedrock exclusive of major deformation zones is usually referred to as "rock mass" in SKB's documentation. The bedrock at all four of these sites is crystalline, and generally is effectively impermeable to groundwater flow in the absence of macroscopic fractures (the exception being one rock type, "vuggy granite" which is found in a few boreholes at Forsmark-lens, which has been altered by quartz dissolution to yield a skeletal rock of locally high permeability). Thus the hydraulic properties of the rock mass depend on the geometrical and hydraulic properties of the fracture system – specifically, on how these fractures connect to form networks on scales of meters to a kilometre or more.

The conceptual approach that has been used at the Laxemar, Simpevarp, and Forsmark-lens sites, and to a lesser extent at the Forsmark-SFR site, is the statistical discrete-fracture network (DFN) approach. The fundamental assumption of the statistical DFN approach is that, by building a statistical model that accounts for the geometry and hydraulic properties of individual fractures, networks of fractures can be constructed by stochastic simulation which reproduce, in a statistical sense, the hydraulic properties of the rock mass on the scales of interest. In particular, DFN models are often used to estimate effective continuum properties (*i.e.* effective hydraulic conductivity tensors, flow porosities, and flow-wetted surface, where these are valid for the scale of consideration).

A complete comparison of the statistical DFN models that have been developed for these sites would require stochastic simulations, and is beyond the scope of this report. Instead, the fracture systems are compared in terms of their general features. For the Forsmark-SFR site where models to date have been based mainly on continuum approximations, comparison is made in terms of the interpreted effective continuum properties.

At these sites, the principal information regarding permeability of typical bedrock ("rock mass") comes from hydraulic injection tests on fixed intervals of drill holes, and (at the Laxemar, Simpevarp, and Forsmark-lens sites) differential flow-logging using the Posiva Flow Log (PFL) has been used. Larger-scale hydrologic testing using interference tests in multiple drill holes has focused on the more permeable deformation zones, which have been discussed above. The single-hole methods essentially measure the local transmissivity of fractures at their intersections with the drill holes. Injection tests sample all conductive fractures. The PFL samples only those that connect to larger-scale networks, and thus the PFL is more indicative of fractures that participate in large-scale flow.

Fracture system geometry and fracture hydraulic properties

For all three of the sites for which DFN models have been presented (Simpevarp, Laxemar, and Forsmark-lens), fracture sets have been deduced primarily on the basis of fracture orientation.

Simpevarp

For Simpevarp, two alternative DFN models are presented in the preliminary site descriptive model (SKB, 2005). Both of these models use the same definition for a single sub-horizontal fracture set, but combine these with different assumptions regarding the sub vertical fracture sets (six sub vertical fracture sets, in each case). Alternative Model 1 includes three sets which are based on local lineaments, and three sets which are not, while in Alternative Model 2, all six sets are tied to the local lineament orientations. Both alternatives have a relatively high proportion of NE-striking fractures vs. NW-striking fractures, which reflects the larger-scale structural geological fabric. The most extensive fractures, however, tend to be in the N-S direction.

The Hydro-DFN models for Simpevarp did not distinguish among these seven different fracture sets, in either alternative, when assigning hydraulic properties. Instead, three different sub-models for fracture transmissivity were tested for all seven fracture sets: a log-normal distribution of transmissivity (uncorrelated to fracture length or size), a log-linear correlation between fracture length and transmissivity, and a semi-correlated model which includes a randomized "noise" term in the correlation.

Laxemar

At Laxemar, six different fracture domains were identified for different rock blocks and lithological units within the area (Figure 4.10). Four fracture sets (one sub-horizontal, and three sub vertical striking nominally N-S, ENE, and WNW) were identified by a combined analysis of fracture orientation data from all six domains. Then, for each of the four fracture sets in each of the fracture domains, coupled size-intensity models were developed as presented by La Pointe *et al.* (2007).

Overall, the sub-horizontal fracture set was found to have the highest intensity (after correcting for borehole directional bias), followed by the N-S, ENE, and WNW sub vertical sets in that order. However, the relative intensities of these sets and coupled size-scaling models vary between fracture domains. For example, according to the intensity statistics presented by La Pointe *et al.* (2007, Table 7.1.2), the N-S set is relatively strong in the fracture domains FSM_NE005 and FSM_S which are in the SE part of the Laxemar area, and also in FSM_W on the west side of the area. The WNW set is relatively strong in FSM_C in the central part of the site, and FSM_N in the northern part of the site.

Due to these variations in the intensity parameters, it should be expected that directional connectivities and anisotropy of effective hydraulic conductivities could vary between fracture domains. However, because the DFN geometric models for Laxemar are expressed in terms of power-law scaling models in which fracture intensity statistics are coupled with size-distribution scaling exponents and additional minimum and maximum radius parameters, evaluation of the hydrogeological implications by inspection is not straightforward.

The hydrogeological implications of the geometrical DFN models were assessed after a further step in which statistical models for fracture transmissivity (either correlated to, semi-correlated to, or uncorrelated to fracture size) for each fracture set were fitted by calibration of simulated flows to boreholes to obtain a statistical match to Posiva flow-log (PFL) anomaly data. The procedure is described by Rhén *et al.* (2008, R-08-78 Chapter 10). The models were developed for six Hydraulic Rock Domains (HRDs) which correspond to the fracture domains FSM_S, etc. but are denoted HRD_S, etc. in the hydrogeological model development. Within each HRD, models were calibrated for four different depth intervals (-1000 to -650 m.a.s.l., -650 to -400 m.a.s.l., -400 to -150 m.a.s.l., and -150 to 0 m.a.s.l.), resulting in 24 different Hydro-DFN model variants (one per fracture domain and depth class).

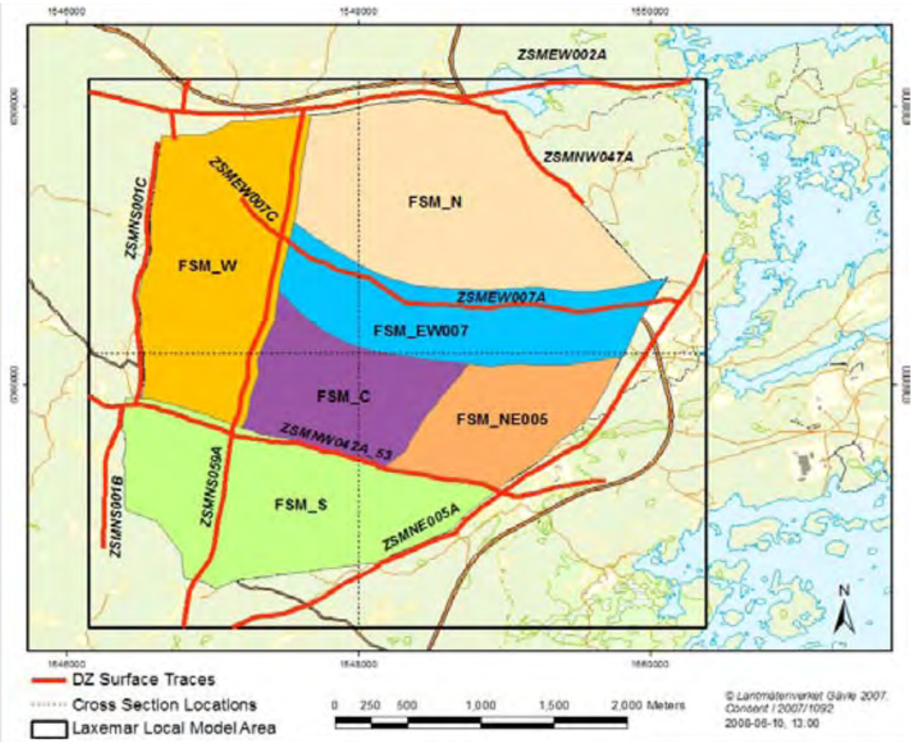

Figure 4.10 Fracture domains at Laxemar. All northings and eastings are in the Swedish RT90(25 gon W) co-ordinate system. Figure from La Pointe *et al.* (2007, SKB R-08-55, Figure 4-6).

Forsmark-lens

At Forsmark(-lens), six different fracture domains were identified for different rock blocks and lithological units within the area (Figure 4.11). Geological (geometrical) DFN models were developed by Fox *et al.* (2007) for four of these fracture domains: FFM01, FFM02, FFM03, and FFM06.

Fracture data from Forsmark show three broad groups of fractures by orientation, one of which is nominally horizontal while the other two are nominally vertical, striking NE- and NW-striking, with the NE-striking set dominant. The Geo-DFN model for Forsmark (Fox *et al.*, 2007, R-07-46) further divides these into as many as nine fracture sets, depending on the fracture domain. In contrast to Laxemar, fracture orientation distribution statistics for each set were derived independently by domain.

Coupled size-intensity models were developed following a methodology similar to that used for Laxemar. Three alternative models were presented in each case, to account for alternative assumptions regarding the relationship of large-scale fractures and fault zones inferred from lineament maps, to the smaller-scale fractures that could be observed on outcrops. The statistics of the fitted models are summarized in Fox *et al.* (2007, Section 7.3).

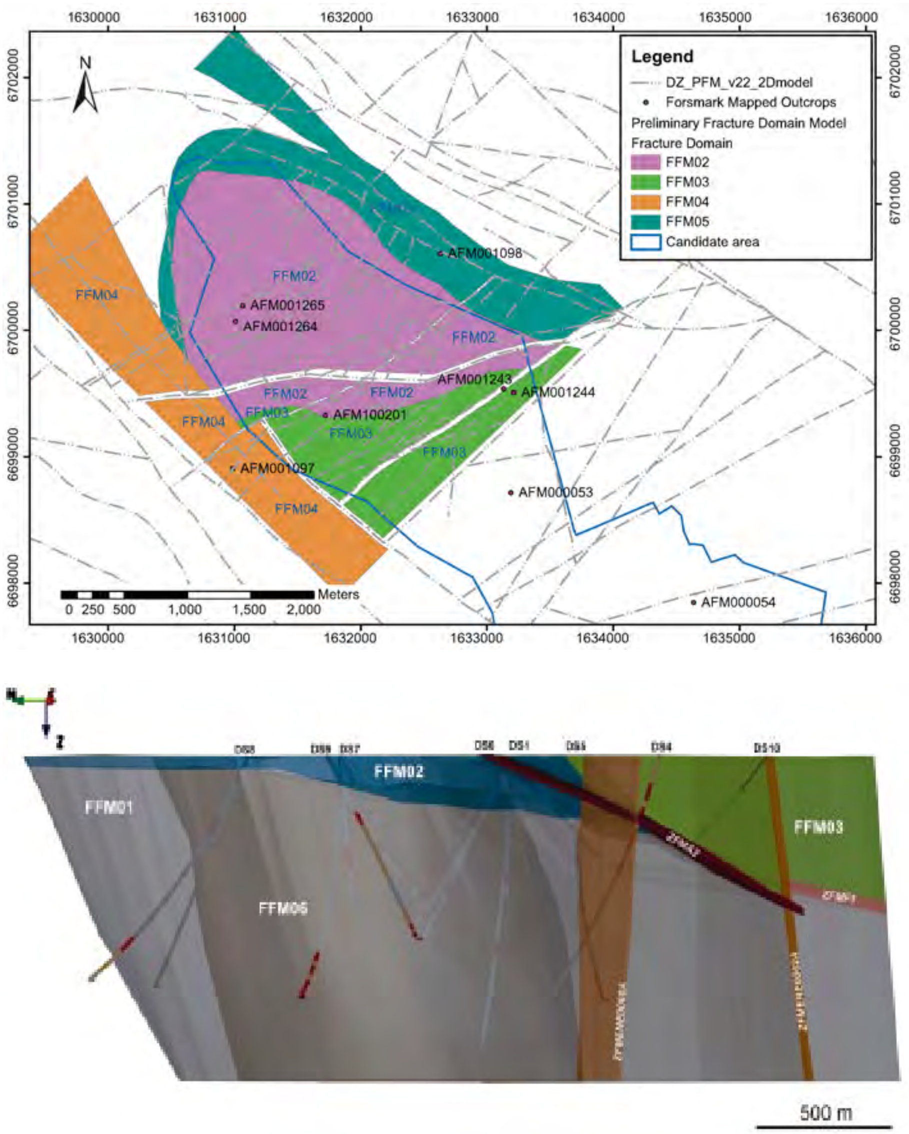

Figure 4.11 Fracture domain model for SDM Forsmark 2.2. Upper figure shows plan view of fracture domains at sea level. Lower figure shows a three-dimensional visualisation of the fracture domain model. Fracture domains FFM01, FFM02, FFM03, and FFM06 are coloured grey, dark grey, blue, and green, respectively. The gently dipping and sub-horizontal zones ZFMA2 and ZFMF1 as well as the steeply dipping zones ZFMENE0060A and ZFMENE0062A are also shown. Figures from Fox *et al.* (2007, R-07-46, Figure 1-2) and from Olofsson *et al.* (2007, R-07-15, Figure 5-7).

Investigation of fracture location processes at Forsmark included both simple Poisson processes (uniformly random in three dimensions) and fractal models which can produce more strongly clustered DFN simulations than are expected with a simple Poisson process. A small but possibly significant degree of fractal clustering is indicated by the DFN analysis.

Another important aspect of fracture location is whether small-scale fractures are more likely to be found in rock bordering deformation zones. Fractures that are interpreted as belonging to the “damage zone” or zone of influence for a brittle deformation zone were included in the zones, according to the methodology. However, some parts of the rock mass not included in these deformation zones were judged to be “affected by deformation zones.” Within these “DZ-affected” portions of the rock mass, fracture intensities were increased by factors in the range of 2 to 3 for some of the fracture sets, particularly in FFM01.

As for Laxemar, the hydrogeological implications of the geometrical DFN models were assessed after a further step in which statistical models for fracture transmissivity (correlated, semi-correlated, or uncorrelated to fracture size) for each fracture set were fitted by calibration of simulated flows to boreholes to obtain a statistical match to PFL anomaly data. The Hydro-DFN model calibration is presented by Follin (2008, R-08-95). These Hydro-DFN models are simplified substantially from the Geo-DFN models presented by Fox *et al.* (2007), in that only five fracture sets are considered. This simplification was partly because, in the PFL data, only three fracture sets are represented among flowing fractures (N-S striking, NE-striking, and sub-horizontal sets). The Hydro-DFN model also did not propagate the alternative models that included fractal scaling or influence of deformation zones.

In the Hydro-DFN model development, FFM01 and FFM06 were treated as a single unit, but divided into three depth intervals (-1000 to -400 m.a.s.l., -400 to -200 m.a.s.l., and -200 to 0 m.a.s.l.). FFM02 is only found at shallow depths (above -200 m.a.s.l.). FFM03, FFM04, and FFM05 were treated as a single unit, but divided into two depth intervals (-1000 to -400 m.a.s.l., and -400 to 0 m.a.s.l.). Thus ultimately the Hydro-DFN model consists of six different sub-models, defined for different fracture domains and depth intervals.

Effective hydraulic properties

Simpevarp

Block-scale modelling using the Hydro-DFN models for Simpevarp SDM v. 1.2 (SKB, 2005) yielded predictions for block sizes of 20 m and 100 m. For the 20 m scale, mean (log-scale) effective hydraulic conductivities were $3x10^{-9}$ m/s, plus or minus 1.1 to 1.4 orders of magnitude depending on assumptions regarding correlation between fracture size and transmissivity. For the 100 m scale, mean effective hydraulic conductivities were similar in magnitude but with more variation depending on the assumed correlation of transmissivity to fracture size.

The simulations indicate mild anisotropy in the horizontal direction (a factor of 3.2 or less), with a tendency for increased directional hydraulic conductivity in the E to SE direction. Hydraulic conductivity in the vertical direction is predicted to be less than the maximum horizontal conductivity, by a factor of 2.4 to 3.8 depending on scale and model assumptions. The Simpevarp model was not developed to account for possible transmissivity variations with depth. The predictions regarding anisotropy are likely sensitive to the assumption that all fracture sets share the same transmissivity distribution.

Laxemar

Rhén *et al.* (2008, R-08-78, Chapter 10 and Appendix A) present upscaled hydraulic properties for the Hydro-DFN models for four of the HRDs, for 20 m and 100 m block scales. The results are summarized in Table 4.2.

For shallow depths of less than 150 m, all or nearly all of the simulated blocks were found to be percolating, with median effective hydraulic conductivities of 0.9×10^{-7} m/s to 5×10^{-7} m/s for the 20 m scale, and similar values on the 100 m scale. The median conductivities decrease at greater depths, roughly by an order of magnitude per depth interval.

Nearly all of the 100 m scale blocks are percolating down to 650 m depth, but a reduction is seen in percolation percentages on the smaller, 20 m block scale. This reflects the increasing importance of the largest fractures at depths where the fraction of open fractures is decreased.

Estimates of anisotropy ratios are given by Rhén *et al.* (2008, R-08-78) only for the depth range -650 to -400 m.a.s.l. The maximum hydraulic conductivity in the horizontal direction is typically greater than that the vertical direction, by a median ratio of 1 to 1.65. Anisotropy in the horizontal direction is more pronounced, with median ratios of maximum vs. minimum horizontal hydraulic conductivity ranging from 2.6 to 9.7.

The predicted azimuth of maximum horizontal conductivity is generally between 90 and 150 degrees from North (E to SSE). This implies that the direction of minimum hydraulic conductivity – which contrasts with both the vertical and maximum horizontal conductivity – is typically in the N to ENE direction. In other words, these Hydro-DFN models predict that the effective hydraulic conductivity tensor ellipsoid (assuming that a tensor is applicable) has a minor axis in the SW-NE horizontal direction, and major axes which are nearly equidimensional, in the vertical plane striking roughly SE-NW.

Table 4.2. Summary of upscaled properties for Hydro-DFN models of fracture domains at Laxemar. Based on Tables 10-24 through 10-27 of Rhén *et al.* (2008, R-08-78), representing models based on open/partly-open fractures and semi-correlated model for fracture transmissivity as a function of fracture size.

Depth range (elevations above sea level)	**Domain**	**Percentage Percolating**		**Median Effective Hydraulic Conductivity (m/s)**	
Block scale		20 m	100 m	20 m	100 m
0m to -150 masl	HRD_C	98%	100%	8.5×10^{-8}	9.3×10^{-8}
	HRD_W	100%	100%	1.5×10^{-7}	1.6×10^{-7}
	HRD_EW007	100%	100%	1.0×10^{-7}	7.1×10^{-8}
	HRD_N	100%	100%	5.0×10^{-7}	6.6×10^{-7}
-150 masl to -400 masl	HRD_C	76%	100%	3.1×10^{-9}	4.8×10^{-9}
	HRD_W	59%	97%	1.1×10^{-9}	6.5×10^{-9}
	HRD_EW007	100%	100%	3.0×10^{-8}	4.1×10^{-8}
	HRD_N	95%	100%	5.5×10^{-8}	4.5×10^{-8}
-400 masl to -650 masl	HRD_C	67%	99%	6.2×10^{-10}	2.5×10^{-9}
	HRD_W	51%	97%	2.1×10^{-11}	1.4×10^{-9}
	HRD_EW007	99%	100%	1.4×10^{-8}	8.5×10^{-9}
	HRD_N	77%	100%	3.2×10^{-9}	5.2×10^{-9}
-650 masl to -1000 masl	HRD_C		32%		2.2×10^{-10}

Forsmark-lens

Effective block scale permeabilities for the hydrogeological DFN model used in SDM-Site Forsmark have not been presented in the same way as for Laxemar. A plot based on Hydro-DFN models for the version 2.2 site descriptive model indicates that values for the rock mass at 450 m depth (Follin *et al.*, 2007a, Figure 3-42, p. 70) are nearly all in the range 10^{-12} m/s to 10^{-9} m/s, and mainly below 10^{-11} m/s.

From the dominant orientations of the fracture sets in the Geo-DFN models (as discussed in Section 3.4), it might be expected that the principle directions of block-scale hydraulic conductivity tensors will be rotated about 45 degrees from the cardinal directions toward the NE at Forsmark. This aligns with the coordinate systems that have been chosen for hydrogeological modelling.

In the target volume for the spent-fuel repository, evidence from boreholes indicates that the bedrock is extraordinarily tight, with few water-conducting fractures, compared to the shallow rock. The PFL records measurable flows in only about one feature per 250 m of borehole, for depths greater than 400 m. However, the existence of connected flow paths in such sparsely fractured rock is noteworthy as a constraint on hydrogeological conceptual models.

The uppermost 150 m of the bedrock at Forsmark is recognized for having extensive horizontal fractures or sheet joints, which produce very high yields in shallow boreholes (median value of 12,000 litres per hour in the first 22 percussion-drilled boreholes, about 20 times the median yield of domestic water wells in nearby areas outside of the candidate area. This part of the bedrock has nearly uniform groundwater levels close to 0.5 m.a.s.l., and showed extensive and rapid transmission of drawdowns during a large-scale pumping test. For these reasons, the uppermost 150 m of the bedrock within the candidate area is treated as a “shallow bedrock aquifer” in SDM-Site. This is assigned a heterogeneous hydraulic conductivity based on values measured in the nearest wells, but typical values are on the order of 10^{-5} m/s.

In simulations of the shallow bedrock at Forsmark-lens, Bosson *et al.* (2010) used hydraulic conductivity values that were imported directly from a bedrock hydrological model that included simulations of the Hydro-DFN component on an 80 m block scale, by Joyce *et al.* (2010, SKB R-09-20). In areas where horizontal sheet joints occur, hydraulic conductivities in the horizontal direction are commonly in the range 10^{-6} m/s to 10^{-4} m/s. Vertical hydraulic conductivities in the shallow part of the rock mass are much lower, in the range 10^{-10} m/s to 10^{-8} m/s.

Forsmark-SFR

Effective hydraulic conductivity values for the rock mass at the SFR site have been estimated by a variety of methods other than the DFN approach. The model of (SKB, 1993) as reproduced in SKB R-02-14, Table 3.3 (originally from SKB, 1993, Table 2-4). gave the following depth-dependent models for hydraulic conductivity in the case of 3-D flow modelling:

Rock mass I.	$K = 8.87\times10^{-6}\,D^{-1.30}$ (3-D flow), where D = vertical depth below sea level.
Rock mass II.	Above 40 m depth:
	$K = 4\times10^{-7}$ m/s above the repository; 8×10^{-8} m/s in other areas.
	Below 40 m depth:
	$K = 9.30\times10^{-5}\,D^{-1.80}$ (3-D flow), where D = vertical depth below sea level.

Holmén & Stigsson (2001) treated the rock mass as two areas in their model of flow through the existing SFR facility. For the area bounded by Zones 3, 6, 8, 9 (*i.e.* the rock block containing the SFR), hydraulic conductivity was evaluated from hydraulic test data as 6.8×10^{-7} m/s (arithmetic mean) and 4.0×10^{-7} m/s (geometric mean). For the portion of the model outside of these zones, the corresponding values were 1.5×10^{-7} m/s (arithmetic mean) and 8.4×10^{-8} m/s (geometric mean).

Holmén & Stigsson (2001) also estimated an effective hydraulic conductivity for radially convergent flow through the rock mass, toward the BMA de-position tunnel in which a presumed steady-state inflow of 9.3 litre/minute was measured; this approach yielded an estimated hydraulic conductivity of $5x10^{-9}$ m/s. However, this method is sensitive to assumptions regarding tunnel skin effects due to grouting, two-phase flow, and convergent network effects.

Öhman and Follin (2009, P-09-49) raised a question as to whether the horizontal sheet jointing seen in the Forsmark-lens site extends across the Singö zone and into the SFR domain; this issue has not been resolved.

Öhman and Follin (2009) noted that the HRD below 56 m.a.s.l. is significantly less transmissive than the HRD above 56 m.a.s.l.. However, noting that the existing hydraulic data extended only down to about 200 m.a.s.l., they questioned whether this difference should be interpreted as part of a continuous depth trend extending deep into the bedrock, or if it reflects a shallow geologic process (such as glacial unloading).

SKB (2008, R-08-67) raise a further question as to whether contacts between rock types, in particular amphibolite contacts, could act as water-conducting features in the rock mass.

5. Groundwater flow

The general pattern of groundwater flow for each area, based on modelling studies and other evidence, is summarized below. To avoid unnecessary repetition, the two Forsmark-area sites are discussed together as a single area, but with comments on the two sites within this area. Laxemar and Simpevarp sites are treated together in the same way.

Paleohydrologic circumstances

Forsmark area

At depth, the bedrock in the Forsmark area contains very old, deep “shield brines” with salinity and density higher than modern or known ancient sea waters. The origin of these brines is uncertain; hypotheses include rock-water interactions on very long time scales. SKB (2008, R-08-67) have also suggested that saline groundwater forming by exclusion of salt from freezing during periods of permafrost (*e.g.* during the onset of Weichselian glaciation ca. 100,000 years ago) would have also come into contact with older brines as it sank due to density contrasts with less saline groundwater below the permafrost zone. Whatever the origin, these deep brines have presumably limited the penetration depths of younger waters of lower salinity and density.

On-land portions in the Forsmark-lens portion have emerged from below the Baltic within the past 3000-2500 years and are still just a few meters above sea level on average, while the Forsmark-SFR portion is still covered by the sea except for a few islands and causeways. The area was covered by continental glaciers in the Weichselian glaciation, until the onset of deglaciation ca. 13,000 y ago. It is inferred that glacial meltwater infiltrated the bedrock as the ice margin retreated, leaving the Forsmark area submerged below the Baltic Ice Lake. This situation continued until about 11,000 years ago when rising global sea levels brought a connection to the North Atlantic, and the area was submerged below the mildly saline Yoldia Sea, followed by a transition to the freshwater glacial lake Ancylus around 10,200 years ago. The saline Littorina Sea covered Forsmark, starting at 9500 y ago and reaching a maximum salinity of about 15‰ at about 6500-5000 y ago, after which salinity transitioned to modern Baltic levels.

Laxemar-Simpevarp area

In contrast to the Forsmark area, the Laxemar-Simpevarp area was not ice-covered during the Weichselian glaciation. However, the area is below the highest glacial-period shoreline, and thus was submerged about 50-100 m deep below the Baltic Ice Lake as glaciers began to retreat from their nearest approach. The highest parts of the regional model area began to emerge from the sea around 11,400 year ago, shortly after the transition of the Baltic Ice

Lake to mildly saline Yoldia Sea waters 11,000 years ago, and before the transition to the freshwater glacial lake Ancylus around 10,200 years ago. However the lower-elevation areas including Simpevarp and the eastern part of Laxemar remained inundated through the Littorina Sea stage. SKB (2009, TR-09-01) suggest that salinity of Littorina waters over eastern Laxemar were likely diluted by freshwater streams flowing into elongated coastal bays (corresponding to modern topographic lineaments), so the maximum salinity of the Littorina stage was probably not fully realized on the local scale. Meteoric waters began to infiltrate the upper portions of the Laxemar area as early as 10,000 years ago, and the lower portions beginning around 5000 years ago.

As for Forsmark, the bedrock at Laxemar-Simpevarp contains much older, deep “shield brines” of much higher salinity and density, which have limited the penetration depths of younger waters of lower salinity and density.

Impacts of paleohydrology on present-day flow

Past conditions influence present-day groundwater flow, primarily in terms of how they influenced the salinity and hence density of waters that remain in the bedrock. The denser relict waters impede circulation of less dense meteoric waters to repository depths. The general process taking place at all of the terrestrial sites (Laxemar, Simpevarp, and Forsmark-lens), and eventually at the one mostly submerged site (Forsmark-SFR) is build-up of a blanket of freshwater due to infiltration of meteoric waters. As the land continues to rise, the thickness of this freshwater layer increases, and the resulting increase in pressure gradually pushes saline groundwater out toward the sea. The conceptual situation just off the coastline, in the case of Forsmark-SFR, is illustrated in Figure 5.1.

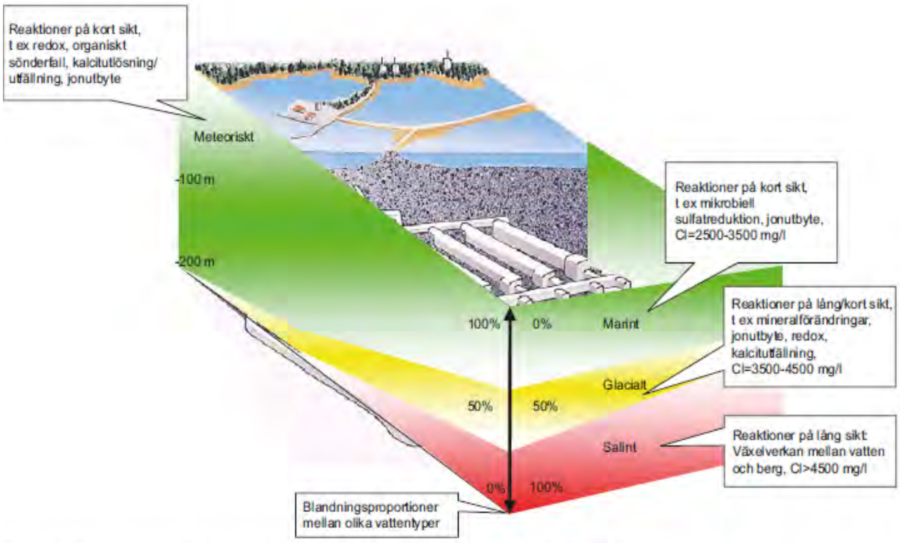

Figure 5.1 Conceptual model of dominant groundwater types at the Forsmark-SFR site. Figure from SKB R-08-67, Figure 9-7. Swedish text in boxes describes the reactions that are considered most important for hydrogeochemical modelling of the site.

Mixing between these waters can occur by advective dispersion in the most transmissive fractures and deformation zones, a relatively rapid process. However in the less conductive portions of the bedrock, mixing is governed mainly by diffusion which requires very long time scales for equilibration. Groundwater models and geochemical data presented for Forsmark by SKB (2008) indicate a disequilibrium between the relatively mobile water in the most transmissive fractures and deformation zones, versus less mobile water in tighter portions of the bedrock. In the Laxemar area, flushing of saline and brackish waters, as well as older glacial meltwaters, is interpreted as continuing to the present day.

Groundwater flow models of the Forsmark-lens area have been calibrated with respect to observed salinities (TDS) in drill holes. The resulting models show some agreement in terms of general trends with depth, but also differences. For example (SKB, 2008 p. 273) a transition to high salinity in excess of Littorina water is predicted just below 600 m depth in drill hole KFM03A, but this is not seen in the data until the depth interval 800-900 m; an interval of low-salinity water (with a pronounced density inversion compared to shallower depths) is predicted for depths from about 230 m to 400 m in KFM01D, but the data show a rather steady increase with depth through this interval.

These difficulties in predicting transitions in salinities are understandable. The differences between models and observation, in terms of where the interfaces between waters of different salinities are found, are functions both of site properties that govern advection through the more transmissive features (*e.g.* fracture zone transmissivities, extents, and connectivity) and site properties that govern diffusive exchange (effective block sizes for low-permeability rock bounded by flowing fractures, and effective diffusivities in these less permeable blocks, which in turn depends on the connectivity characteristics of networks of smaller and less transmissive fractures). All of these site properties can reasonably be expected to be heterogeneous, resulting in patterns that are difficult to predict using models in which some of these parameters are treated as homogeneous, and where the spatial pattern of variation of other parameters is not well characterized.

Regional groundwater flow and recharge/discharge

Groundwater flow on the regional scale near these sites is presumed to be driven by topographic differences between inland areas and the coast. The significance of regional groundwater flow for an underground repository located near the coast has been a subject of long debate in the Swedish nuclear waste program, since the potential influence of regional flow on local models was pointed out by Voss and Andersson (1991).

In a landscape with laterally homogeneous bedrock properties, modelling studies indicate that regional flow could hypothetically persist across very large scales. For the highly simplified case of a landscape that slopes uniformly toward the coast, the expected pattern is for recharge inland, and flow of deep groundwater via paths of tens or hundreds of kilometres to a discharge area at the coastal interface with saline water. Local topographic variation introduces local-scale groundwater recharge-discharge cells which are superimposed on the regional-scale flow. Voss and Provost (2001) showed that, for laterally homogeneous bedrock, even in an undulating landscape such as eastern Småland, and considering the influence of deep saline brines, very long regional-scale flows could theoretically occur; they suggested that if areas of regional-scale recharge could be identified, these could be favourable sites for locating a nuclear-waste repository.

Subsequent modelling studies sponsored by SKB (Holmén *et al.*, 2003; SKB, 2003; Ericsson *et al.*, 2006; Ericsson and Holmén, 2010) have considered the consequences of bedrock heterogeneity (including regional-scale deformation zones) and topographic resolution. These modelling studies demonstrated that these factors could reduce the influence and predictability of regional-scale flow. They suggest a flow pattern that is more dominated by local recharge-discharge cells on the scale of a few km, for depths of 500 m or more, which calls into question the predictability of regional recharge locations.

The modelling results of Ericsson *et al.* (2006) did indicate that, for a variety of assumptions regarding bedrock heterogeneity, portions of the Laxemar site did tend to act as discharge areas, implying relative direct paths to the biosphere from a repository. Similarly, smaller-scale regional models of the Simpevarp and Laxemar areas (Follin *et al.*, 2005; Hartley *et al.*, 2005; Hartley *et al.*, 2006b) and the Forsmark area (*e.g.* Follin *et al.*, 2005; Hartley *et al.*, 2006a; Geier, 2008; Geier, 2010) predict fairly direct upward flow from hypothetical repositories at these sites, in the current coastal configuration. The Forsmark-SFR site is also expected to have fairly direct discharge to the surface in the current coastal setting, although this is expected to change with coastal recession over the design life of the LILW facility (SKB, 2008, R-08-67).

For the purpose of the present study – a simple evaluation of general hydrogeological circumstances at these sites without focusing on specific locations for a LILW within the site – the most defensible approach is to assume that the LILW facility will be located within a discharge environment, either on a local or regional scale.

Site-scale flow in the regolith and shallow bedrock

Forsmark-lens

Groundwater levels in the regolith at Forsmark are typically within one meter of the surface, with near-surface flow controlled by small-scale, undulating topography (Werner *et al.* 2007; Johansson 2008). Recharge to the bedrock is dominated by a surplus of precipitation relative to the rate of infiltration that is allowed by vertical hydraulic conductivity in the shallow bedrock. During summer months when evapotranspiration by plants typically exceeds precipitation, water levels in the regolith may drop below lake levels, resulting in direct recharge of groundwater from the lake beds (Grolander, 2009, SKB R-09-47).

Till layers are anisotropic with higher horizontal than vertical hydraulic conductivity. The shallow bedrock (uppermost 150 m) is also highly anisotropic due to a system of extensive horizontal sheet fractures. Consequently shallow groundwater flow is dominantly via relatively shallow flow paths, with little recharge to the deeper bedrock. The sheet fractures also tend to intercept groundwater discharge from the deeper bedrock and carry it toward the Baltic.

Interactions between deep and shallow groundwater have been studied by Johansson (2008). Within the tectonic lens, groundwater levels in the Quaternary deposits are generally higher than groundwater levels in the bedrock in most seasons, although during some dry summer periods, this situation can be reversed. Water levels in both bedrock and regolith show a pattern of covariation along with precipitation and evapotranspiration, but the hydraulic connection between regolith and bedrock is very limited. Within the bedrock, water levels are well equalized across the lens area. Chemical characterisation of the waters encountered in most wells in the regolith within the lens area indicate fresh water or altered meteoric groundwater.

At Drilling Site BP 4 which is outside (inland of) the tectonic lens, near Lake Gällsboträsket, a different pattern was observed, with groundwater levels generally higher in the bedrock than in the regolith. This suggests an upward groundwater flow (discharge) from the deeper bedrock in this area, possibly due to upwelling of regional flow caused by the extremely low permeability of the deep bedrock within the tectonic lens. Chemical characterisation of the water in three shallow wells in this area indicate an influence from relict marine groundwater, with high chloride concentrations; a fourth shallow well showed indication of influence of deep saline groundwater.

Forsmark-SFR

The groundwater flow situation within the SFR area is less well characterised than the situation in the Forsmark-lens area on land. Presumably pressures within the Quaternary deposits on the sea floor have minimal lateral gradients due to the uniform upper boundary condition imposed by the sea level, and hence there should be little flow within these layers. However, boreholes that intersect the sub-horizontal deformation zone, H2, registered excess heads of +0.11 m and +0.61 m in relation to mean sea water level, after correcting for density differences (Hagconsult, 1982; Carlsson et al, 1987). Although Carlsson *et al.* (1987) suggest that the reported excess head might be too high “due to the measurement and evaluation technique,” excess heads should also be expected if groundwater is discharging to the Baltic in this area, as suggested by the Forsmark-lens model that was developed later.

With continued land rise in the area, the coastline is expected to recede from the SFR area far enough that, within 4000 years, a pseudo-steady-state situation is expected to be attained for groundwater flow. During the period in which the SFR continues to be covered by the sea, regional groundwater flow as well as flow through the rock volume containing the facility is expected to be small, with an upward direction (SKB, 2008, R-08-67). As the coastline recedes, the magnitude of groundwater flow is expected to increase while the direction of flow from the facility will become more horizontally directed.

Laxemar-Simpevarp area

Groundwater levels in the Laxemar-Simpevarp area are correlated to topography but less closely tied to surface elevations than at Forsmark. Recharge is thought to occur in higher areas with exposed bedrock or thin till. Precipitation and snow melt are the main source of recharge, but lakes may also act as recharge sources during dry periods.

Water-balance calculations for the Laxemar-Simpevarp area using the MIKE-SHE model based on 608 mm/yr precipitation (Bosson *et al.*, 2008) indicates that net area-averaged groundwater recharge from the unsaturated zone to the saturated zone (mainly Quaternary sediments) is 226 mm/yr. Net recharge from Quaternary deposits to the bedrock is calculated as 7 mm/year (averaged across the model area), with area-averaged recharge to the bedrock (within recharge areas) of 35 mm/yr and area-averaged discharge from the bedrock (within discharge areas) of 28 mm/yr.

Interactions between groundwater in the regolith and in the bedrock have been been evaluated by Werner *et al.* (2008). For nearly half of the evaluated locations, results show that groundwater level in the bedrock is higher than the groundwater level in the Quaternary deposits, indicating an upward gradient of groundwater from the bedrock (*i.e.* discharge setting). For an equal number of sites, a downward gradient (recharge setting) is indicated. According to Grolander (2009, SKB R-09-47), chemical indications of discharging deep groundwater have been found at just two locations: below the sea in Granholmsfjärden, and below Lake Frisksjön.

6. Evaluation

Simple evaluation of groundwater flow

A “simple evaluation” approach, as demonstrated by Dverstorp *et al.* (1996) provides a transparent way of characterising the capacity of crystalline bedrock to act as a barrier to release of radionuclides from a nuclear waste repository. The approach is based on identifying physically plausible bounds on groundwater flow, based on elementary hydrologic principles in combination with reasonable bounds on site properties. As shown by Geier *et al.* (2002) for the context of a spent-fuel repository, a simple evaluation may bound the key uncertainties equally or nearly as well as much more complex (and hence less transparent models) of site-scale groundwater flow.

Groundwater flux q [L T-1] is arguably the most important hydrological parameter for determining safety. High q implies a greater potential for exposure of engineered barriers to changing geochemical conditions, and for rapid transport of radionuclides from leaking engineered barriers to the biosphere.

Flux is evaluated from site data including: maximum potential head differentials (from local and regional topography), location and orientation of major fracture zones (from structural geologic models of each site), estimates of hydraulic conductivity K [L T-1] for the rock mass, and estimates of transmissivity for major fracture zones, which are drawn from prior interpretations of hydrological tests in boreholes. The flux is estimated by a simple application of Darcy's law for one-dimensional flow:

$$q = K \Delta h / L$$

where Δh [L] is the maximum potential hydraulic head differential, and L [L] is the transport distance from the radionuclide source to the discharge point.

For a conductive structure such as an individual fracture or a fracture zone, Darcy's law is expressed in terms of the groundwater flowrate per unit width of the structure:

$$Q = b_s q = T \frac{\Delta h}{L}$$

where $T = K b_s$ [$m^{2/}s$] is the transmissivity and b_s [m] is the effective thickness of the structure.

Radionuclide transport in the far field depends upon both q and the configuration of the fracture-system pore space. As shown by Dverstorp *et al.* (1996), a simple evaluation of geologic-barrier potential can be developed based on flux through a variety of simple, idealized models for pore geometry, to yield results of an effective transport resistance parameter:

$$F = a_w L / u$$

where a_w [L^{-1}] is fracture surface area per unit volume of mobile water, and u [$L\ T^{-1}$] is the fluid velocity of the water through the pore space (equal to q divided by the porosity). High values of F imply high surface areas available for sorption and matrix diffusion, in relation to advection of solute, and hence the possibility for high retardation of sorbing species.

For the present goal of comparing hydrologic circumstances at four hypothetical LILW disposal sites, with widely varying degrees of characterisation of the shallow bedrock (particularly the Forsmark-SFR site as compared with the other three sites), little is gained by extending a simple evaluation to calculate ranges of F values. Therefore the present application of this approach is limited to a simple evaluation of groundwater flux.

Each site is assumed to contain a LILW repository through which groundwater flows and eventually discharges at a point on the ground surface. Groundwater passes through the host rock of the repository, which includes fractured rock mass, deformation zones, and a permeable backfill in a representative repository tunnel. The geometry of flow paths from the repository to the discharge point is based on consideration of typical deformation zone spacings at the sites. A plausible set of transport pathways is postulated to scope the range of q that could occur within the constraints of the interpreted structural models.

Gradients at repository depth are selected based on a supposition that either: (a) the regional gradient applies; or (b) the maximum local head occurs undiminished in the repository, and minimum local head occurs at the repository discharge point (the ground surface or a high-transmissivity fracture zone). The former is the simplest and most reasonable assumption, which would not require anomalous configurations of fractures and surface conditions. The latter assumption results in the maximum possible gradient through the repository, under present climatic and surface conditions.

Possible flow path properties are chosen in each of three ways (Figure 6.1):

Path 1: For a case where the repository tunnels are located to avoid major deformation zones, upward and downward flow is assumed to be via the nearest up-gradient sub-vertical deformation zone, with horizontal flow via the rock mass through the repository, then on to the nearest down-gradient deformation zone via which flow discharges to the surface.

Path 2: For flow via only the rock mass, K along the discharge path is equal to that of the rock mass at repository depth;

Path 3: For flow via minor fracture zones (which are presumed to be unavoidable in construction, although major deformation zones can be avoided), the transmissivity along the discharge path is assumed to be uniform.

The first case represents a "reasonable" situation assuming that site-characterisation efforts are adequate to avoid the major transmissive deformation zones. This or the second assumption gives a minimal estimate of q for a given gradient, particularly for cases where the data suggest that hydraulic conductivity increases by a few orders of magnitude towards the surface. The last case is somewhat pessimistic, assuming that minor deformation zones can neither be avoided nor sealed by grouting around the repository.

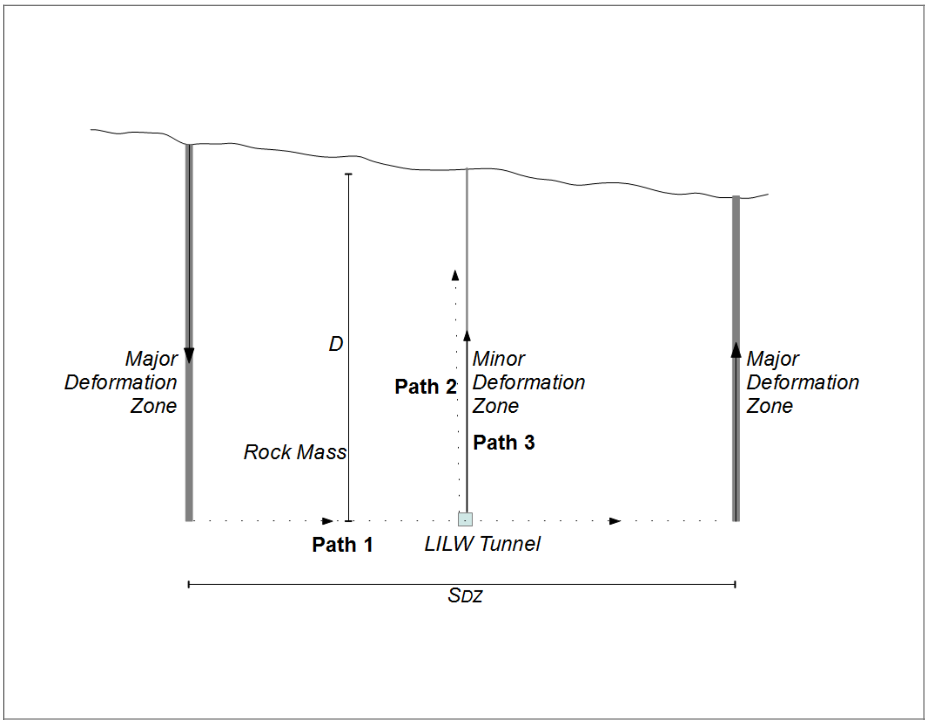

Figure 6.1 Schematic illustration of flow paths considered in the simple evaluation.

Parameter estimates for the different flow paths and flow path segments, based on the data cited in foregoing sections of this report, are listed in Table 6.1. Note that the maximum local topographic head differential for Forsmark-SFR applies only for future times when the sea has retreated; under current conditions the maximum head differential is much less.

For Path 1 which takes into account the backfill in the tunnel, the following tunnel properties are assumed:

Tunnel width $W = 15$ m

Tunnel height $H = 12$ m

Backfill hydraulic conductivity $K = 1\text{x}10^{-5}$ m/s

Results in terms of Darcy flux for a repository depth $D = 80$ m (the depth of the current SFR) are given in Table 6.2; similar but overall slightly lower results are obtained for an alternative depth $D = 150$ m. Results for Path 1 are emphasized as representing the most "reasonable" case.

Estimates of transport resistance F are also given for Path 1, based on a range of flow-path geometry models as evaluated by Dverstorp *et al.* (1996). Note that these estimates of F do not take into account the transport resistance of the SFR tunnels themselves, although their properties are accounted for in terms of flow resistance along Path 1.

The models for flow-path geometry include simple and compound fractures, stepped fractures, and breccia-filled fractures. The most extreme model presented by Dverstorp *et al.* (1996), tube-like channels, is not considered in these estimates. Although this model is of interest for evaluating worst-case scenarios for a high-level (spent-fuel) repository, where a discrete channel might connect to an individual waste canister, it is less relevant for a LILW repository where releases to the biosphere depend on larger flow volumes than could be supported by a single channel.

For an objective comparison between the sites, the maximum realistic values for Darcy flux and the minimum values of transport resistance for Path 1 are of greatest interest. The Forsmark-lens site yields the highest predicted fluxes and also the lowest minimum transport resistances, due to the very high horizontal hydraulic conductivity in the shallow bedrock. Forsmark-SFR and Laxemar yield similar maximum Darcy flux predictions (within a factor of two), but the minimum value of transport resistance for Forsmark-SFR is a factor of seven lower than that for Laxemar or Simpevarp. The relatively favorable results for Simpevarp are mainly a result of the low local topographic relief, combined with interpreted low bedrock conductivity at shallow depths. To some extent the latter may reflect the limited state of characterisation.

Qualitative comparison of sites

A qualitative comparison of the sites is given in tabular form in Table 6.3.

Table 6.1 Parameters for simple evaluation of flow paths.

	Hydraulic gradient $\Delta h/L$		Δh_{max}	Major deformation zone transmissivity T_{DZ} (m^2/s)		Deformation zone spacing S_{DZ} (m)	Rock mass hydraulic conductivity Horizontal K_{RM} (m/s)		Rock mass hydraulic conductivity Vertical K_v (m/s)	Minor deformation zone transmissivity T_{MDZ} (m^2/s)
	Regional	Local	Local	Low	High		Low	High		
Forsmark-SFR	0.00125	0.005	20	2E-7	1E-3	400	1E-7	7E-7	7E-7	1E-07
Forsmark-lens	0.00125	0.005	20	1E-5	1E-3	500	1E-8	1E-5	1E-8	1E-07
Laxemar	0.005	0.01	30	1E-7	1E-3	800	1E-7	5E-7	1E-7	1E-07
Simpevarp	0.005	0.01	10	1E-7	1E-3	500	1E-9	1E-7	1E-7	1E-07

Table 6.2 Darcy flux and transport resistance ranges for an LILW tunnel at 80 m depth.

	All Paths		**Path 1**		**Path 1**	
	Minimum	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
	***q* (m/s)**	***q* (m/s)**	***q* (m/s)**	***q* (m/s)**	***F* (s/m)**	***F* (s/m)**
Forsmark-SFR	3.7E-11	1.8E-07	3.7E-11	3.5E-08	2.5E+09	3.8E+16
Forsmark-lens	1.2E-11	3.8E-07	1.2E-11	3.8E-07	3.6E+08	8.2E+15
Laxemar	1.5E-10	6.3E-08	1.5E-10	1.9E-08	1.8E+10	5.3E+16
Simpevarp	4.8E-12	1.3E-08	4.8E-12	2.0E-09	6.7E+10	6.2E+16

Table 6.3 Comparison of hydrogeological characteristics of sites.

Property	Forsmark-SFR	Forsmark-lens	Laxemar	Simpevarp
Setting	Coastal mainland site with low topographic gradients and strong influence of Baltic		Coastal mainland site with moderate topographic gradients and moderate influence of Baltic	
Quaternary cover	Mainly glacial till, some glacial clay and artificial fill. Not characterised on substantial parts of site due to coverage by sea.	Mainly glacial till, silty to clayey (less permeable), up to 15 m deep. Bedrock exposure sparse. Gyttja-lined lakes.	Sandy-gravelly till with moderate bedrock exposure. Esker in western part of site. Organic deposits in valleys formed by deformation zone traces.	Sandy-gravelly till with moderate bedrock exposure. Organic deposits in valleys formed by deformation zone traces.
Shallow bedrock	Unclear whether shallow bedrock is similar to Forsmark-lens.	Very highly transmissive, treated as "shallow bedrock aquifer."	Sheet jointing near surface but less pronounced than for Forsmark.	Sheet jointing near surface but less pronounced than for Forsmark.
Relation of water table to bedrock surface	Site below sea level.	Nearly flat within site, generally within 0.5 m of ground surface	Mostly within 1 m of topography but deeper under hills.	Mostly within 1 m of topography but deeper under hills.
Gently dipping brittle deformation zones	One gently-dipping deformation zone (H2) has been recognized.	Gently SE dipping brittle deformation zones (thrust-faulting origin but reactivated) are important to the hydrogeological models.	Gently-dipping zones present but less influential for models.	
Steeply dipping brittle deformation zones	High density of magnetic lineaments indicated, but remain to be verified as deformation zones.	Several dozen have been identified and verified. NW-trending fabric on large-scale.	Relatively sparse, quasi-orthogonal network with NE-trending zones prominent.	NE-trending zones prominent, linking with E-W zones as main structural fabric on large scale.
Underground openings at/near site	SFR low- and intermediate-level waste facility exists at site.	SFR low- and intermediate-level waste facility on north side of Singö zone.	Äspö Hard Rock Laboratory nearby to east.	CLAB facility at shallow depth; Äspö Hard Rock Laboratory nearby to north.
Anisotropy of rock-mass hydraulic conductivity	Poorly understood.	Strong horizontal anisotropy in uppermost 150 – 200 m of bedrock.	Enhanced conductivity in vertical and SE-NW directions predicted by DFN models.	Moderately enhanced horizontal conductivity predicted by DFN models.
Coupled density-dependent flow and diffusion	Important due to current location below sea, and complex effects during subsequent land rise.	Disequilibrium between pore waters and waters in conductive fractures limited by matrix diffusion.	Less important due to slower rates of coastline recession and greater topographic contrast.	Less important due to slower rates of coastline recession and greater topographic contrast.
Block-scale hydraulic conductivity	Continuum based estimates but no DFN-derived values.	Not explicitly presented.	DFN-based estimates for various depth ranges (see Table 4.2).	Preliminary DFN-based estimates available.
Quaternary history, especially in most recent glaciation cycle	Ice-covered during Weichselian glaciation, mainly submerged through present day.	Ice-covered during Weichselian glaciation, recently emergent land areas.	Not ice-covered during Weichselian glaciation, but below highest shoreline.	Not ice-covered during Weichselian glaciation, but below highest shoreline.

7. Conclusions

All four of the hypothetical LILW sites discussed in this report – Forsmark-SFR, Forsmark-lens, Laxemar, and Simpevarp – are coastal sites with low to moderate relief, and relatively thin, discontinuous Quaternary deposits overlying granitic bedrock of low permeability which limits infiltration to the deep groundwater system. Local climates are broadly similar with winter snow accumulations and spring snow melt being a major influence on shallow hydrologic conditions.

The three sites which have been considered as possible sites for spent-fuel repositories – Simpevarp, Laxemar, and Forsmark-lens – and particularly the latter two have been more thoroughly characterised in comparison with the Forsmark-SFR site, for which information is limited both due to coverage of most of the area by the Baltic, and by less intensive investigations to date.

The two sites in the Forsmark area are situated in an area with relatively rapid land rise due to post-glacial isostatic rebound. This, in combination with the very low relief, implies a more dynamically evolving hydrologic situation, with greater influence of both modern and relict marine waters, in comparison with the Laxemar-Simpevarp area. This also implies greater uncertainties regarding landscape evolution in the Forsmark area, particularly for anthropogenic global warming scenarios which could result in re-inundation of the Forsmark-lens area, as well as land areas near Forsmark-SFR.

Although broadly similar in terms in terms of lithology, rock ages, and tectonic histories, the Forsmark area differs from the Laxemar-Simpevarp area in terms of degree of deformation, and tectonic fabric. Lithologic and tectonic differences also are noticeable between each pair of sites in each of these areas.

These differences influence patterns of deformation zones and smaller-scale fractures, and can be expected to influence hydrologic properties including the magnitude and anisotropy of effective hydraulic conductivity on various scales. However, prediction of the consequences is dependent on complex fracture-network models, and these have not been presented at the same level of development or level of detail for all sites.

A simple evaluation of Darcy flux and transport resistance yields a conclusion that the Forsmark-lens site has highest predicted fluxes and also the lowest minimum transport resistances, due to the very high horizontal hydraulic conductivity in the shallow bedrock. This indicates that the Forsmark-lens site is the least optimal for a LILW disposal facility in the shallow bedrock, due to the high hydraulic conductivity of the shallow bedrock (in contrast to the deep bedrock). The Laxemar and Simpevarp sites compare favourably to the Forsmark-SFR site in terms of the minimum value of transport resistance, although estimates are within roughly an order of magnitude.

For rock at shallow depths (less than 200 m) such as are most likely to be feasible for a LILW facility, the Forsmark-lens site stands out as a potentially high-flux site due to extensive subhorizontal sheet joints which result in very high horizontal hydraulic conductivity. A comparable system of subhorizontal sheet joints has thus far not been encountered in boreholes to investigate areas that are under consideration for Forsmark-SFR expansion.

The areas under consideration for Forsmark-SFR expansion, to the SE of the existing SFR, are in a structural wedge between a major regional deformation zone (the Singö Zone) and a major splay of the same zone. This wedge shows on magnetic maps as an area of low-magnetic anomaly, suggesting that it might be an area with relatively high intensity of smaller-scale deformation zones, fracturing, and/or alteration.

8. References

The publications found by this approach, which are judged to be of relevance for hydrological description of at least one of the four sites, are included in the list of references below. The following two-letter codes:

FM	Forsmark-lens
FR	Forsmark-SFR
LX	Laxemar
SM	Simpevarp

when given in square braces after a reference, indicate the sites for which a given report is relevant.

Axelsson, C-L., Ekstav, A., Lindblad Påsse, A., 2002. SFR - Utvärdering av hydrogeologi. SKB R-02-14. [FR]

Bosson, E., Gustafsson, L-G, and Sassner, M. 2008. Numerical modelling of surface hydrology and near-surface hydrogeology at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-09. [FM]

Bosson, E., Sassner, M., Sabel, U., and Gustafsson, L-G, 2010. Modelling of present and future hydrology and solute transport at Forsmark. SR-Site Biosphere. SKB R-10-02. [FM]

Brydsten, L., 1999. Shore line displacement in Öregrundsgrepen. SKB TR-99-16. [FM,FR]

Brydsten, L., Engqvist, A., Näslund, J-O., and Lindborg, T., 2009. Expected extreme sea levels at Forsmark and Laxemar-Simpevarp up until the year 2100. SKB TR-09-21.

Carlsson L., Grundfelt, B., and Winberg, A., (1987) Hydraulic modelling of the final repository for reactor waste (SFR). Evaluation of the groundwater flow situation at SFR. SKB Progress Report SFR 86-07, May 1987. Swedish Nuclear Fuel and Waste Management Co., Stockholm.

Dverstorp, B., Geier, J. & Voss, C., 1996. Simple evaluation of groundwater flux and radionuclide transport at Äspö (SITE-94). SKI Report 96:14, Swedish Nuclear Power Inspectorate, Stockholm, Sweden.

Ericsson, L., Holmén, J., Rhén, I., and Blomquist, N., 2006. Storregional grundvattenmodellering – fördjupad analys av flödesförhållanden I östra Småland. Jämförelse av olika konceptuella beskrivningar. SKB R-06-64. [LX, SM]

Ericsson, L.O., Holmén, J., 2010. Storregional grundvattenmodellering – en känslighetsstudie av några utvalda konceptuella beskrivningar och förenklingar. SKB R-10-43. [LX,SM]

Follin, S., Stigsson, M., and Svensson, U., 2005a. Regional hydrogeological simulations for Forsmark - numerical modelling using DarcyTools. Preliminary site description Forsmark area - version 1.2. SKB R-05-60. [FM,FR]

Follin, S., Stigsson, M., and Svensson, U., 2005b. Variable-density groundwater flow simulations and particle tracking – numerical modeling using DarcyTools. Preliminary site description Simpevarp subarea – version 1.2. SKB R-05-11. [SM]

Follin, S., Johansson, P-O., Hartley, L., Jackson, P., Roberts, D., and Marsic, N., 2007a. Hydrogeological conceptual model development and numerical modelling using CONNECTFLOW, Forsmark modelling stage 2.2. SKB Report R 07-49, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden. [FM]

Follin S, Levén J, Hartley L, Jackson P, Joyce S, Roberts D, Swift B, 2007b. Hydrogeological characterisation and modelling of deformation zones and fracture domains, Forsmark modelling stage 2.2. SKB R-07-48, Svensk Kärnbränslehantering AB.

Follin, S., 2008. Bedrock hydrogeology Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-95, Swedish Nuclear Fuel and Waste Management Co., Stockholm. [FM]

Follin, S., Hartley, L., Marsic, N., 2008. Hydrogeological conceptual model development and numerical modelling using CONNECTFLOW, Forsmark modelling stage 2.3. SKB R-08-23, Swedish Nuclear Fuel and Waste Management Co., Stockholm.

Follin, S., Levén, S, Hartley, L., Jackson, P., Joyce, S., Roberts, D., and Swift, B., 2007. Hydrogeological characterisation and modelling of deformation zones and fracture domains, Forsmark modelling stage 2.2. SKB Report R-07-48, Swedish Nuclear Fuel and Waste Management Co., Stockholm. [FM]

Fox, A., La Pointe, P., Hermanson, J, and Öhman, J., 2007. Statistical geological discrete fracture network model: Forsmark modelling stage 2.2. SKB Report R-07-46, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden. [FM]

Geier, J., 2008. Discrete-feature modelling of groundwater flow and solute transport for SR-Can review. SKI Report 2008:11, Swedish Radiation Safety Authority, Stockholm.[FM,LX]

Geier, J., 2010. Discrete-feature model implementation of SDM-Site Forsmark. SSM Report 2010:05, Swedish Radiation Safety Authority, Stockholm.[FM]

Geier, J., Voss, C.I., and Dverstorp, B., 2002. Conceptual uncertainty in crystalline bedrock: is simple evaluation the only practical approach? In *Calibration and Reliability in Groundwater Modelling: A Few Steps Closer to Reality* (Proceedings of ModelCARE’2002 (Prague, Czech Republic, June 2002). IAHS Publ. no. 277.

Hagconsult, 1982. Geologiska undersökningar och utvärderingar för lokalisering av SFR till Forsmark. SFR 81-13, Del 1. Hagconsult AB, Stockholm, Sweden.

Hartley, L., Hoch, A., Hunter, F., Jackson, P., and Marsic, N., 2005. Regional hydrogeological simulations – Numerical modelling using CONNECTFLOW. Preliminary site description Simpevarp sub area – version 1.2. SKB R-05-12. [SM]

Hartley, L., Hunter, F., Jackson, P., Gylling, B., and Marsic, N., 2005. Regional hydrogeological simulations – Numerical modelling using CONNECTFLOW. Preliminary site description Laxemar subarea – version 1.2. SKB R-06-23. [LX].

Hartley, Lee; Hoch, Andrew; Jackson, Peter; Joyce, Steve; McCarthy, Rachel; Rodwell, William; Swift, Ben; Marsic, Niko, 2006a. Groundwater flow and transport modelling during the temperate period for the SR-Can assessment Forsmark area - version 1.2. SKB R-06-98. [FM]

Hartley, Lee; Hoch, Andrew; Jackson, Peter; Joyce, Steve; McCarthy, Rachel; Swift, Ben; Gylling, B., and Marsic, Niko, 2006b. Groundwater flow and transport modelling during the temperate period for the SR-Can assessment Laxemar subarea - version 1.2. SKB R-06-99. [LX]

Hedenström, Anna; Sohlenius, Gustav; Strömgren, Mårten; Brydsten, Lars; and Nyman, Helena, 2008. Depth and stratigraphy of regolith at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-07. [FM, FR]

Holmén, J., and Stigsson, M, 2001. Modelling of future hydrogeological conditions at SFR. SKB R-01-02. Svensk Kärnbränslehantering AB.

Holmén, Johan G; Stigsson, Martin; Marsic, Niko; Gylling, Björn, 2003. Modelling of groundwater flow and flow paths for a large regional domain in northeast Uppland. A three-dimensional, mathematical modelling of groundwater flows and flow paths on a super-regional scale, for different complexity levels of the flow domain. SKB R-03-24. [FM,FR].

Lindgren, M., Pettersson, M., Karlsson, S., Moreno, L., 2001. Project SAFE. Radionuclide release and dose from the SFR repository. SKB R-01-18. Svensk Kärnbränslehantering AB.

IPCC, 2001. *Climate Change 2001: Synthesis Report*. Core Writing Team, Watson, R.T., ed., Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Core Writing Team, Pachauri, R.K., and Reisinger, A., (eds.), IPCC, Geneva, Switzerland, 104 pp.

Johansson, P-O., 2008 Description of surface hydrology and near-surface hydrogeology at Forsmark. Site descriptive modelling SDM-Site Forsmark. SKB R-08-08 [FM]

Johansson, P-O.; Öhman, Johan, 2008. Presentation of meteorological, hydrological and hydrogeological monitoring data from Forsmark. Site descriptive modelling SDM-Site Forsmark. SKB R-08-10. [FM]

La Pointe, P., Fox, A., Hermanson, J, and Öhman, J., 2007. Geological discrete fracture network model for the Laxemar site. Site Descriptive Modelling. SDM-Site Laxemar. SKB Report R-08-55, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden. [LX]

McEwen, T. and de Marsily, G., 1991. The Potential Significance of Permafrost to the Behaviour of a Deep Radioactive Waste Repository. SKI 1991:08. [All]

Nyman, H., Sohlenius, G., and Strömgren, M., 2008. Depth and stratigraphy of regolith. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-06. [LX, SM]

Odén, M., 2009. Site investigation SFR, Hydrogeological modelling at SFR using DarcyTools, Site description SFR version 0.0, SKB P-08-94, Svensk Kärnbränslehantering AB.

Olofsson, I., Simeonov, A., Stephens, M., Follin, S., Nilsson, A-C., Röshoff, K., Lindberg, U., Lanaro, F., Fredriksson, A., and Persson, L., 2007. Site descriptive modelling Forsmark, stage 2.2. A fracture domain concept as a basis for the statistical modelling of fractures and minor deformation zones, and interdisciplinary coordination. SKB Report R-07-15, Swedish Nuclear Fuel and Waste Management Co., Stockholm.

Pettersson, M., Skagius, K., and Moreno, L., 1999. Analysis of radionuclide migration from SFL 3-5. SKB R-99-14. [FR]

Rhén, I., and Hartley, L., 2008. Bedrock hydrogeology Laxemar. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-92. [LX]

Rhén, I, Forsmark, T., Hartley, L., Jackson, P., Roberts, D., Swan, D., and Gylling, B., 2008. Hydrogeological conceptualisation and parameterisation. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-78. [LX]

SKB, 1992. SKB 91: Final disposal of spent nuclear fuel. Importance of the bedrock for safety. SKB Technical Report 92-20, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB, 2000a. Förstudie Oskarshamn. Slutrapport [LX,SM]

SKB, 2000b. Förstudie Östhammar. Slutrapport [FM,FR].

SKB, 2001. Project SAFE Compilation of data for radionuclide transport analysis. SKB R-01-14. [FR]

SKB, 2003. Grundvattnets regionala flödesmönster och sammansättning - betydelse för lokalisering av djupförvaret. SKB R-03-01.

SKB, 2005a. Preliminary site description. Simpevarp subarea - version 1.2. SKB R-05-08. [SM]

SKB, 2006a. Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main report of the SR-Can safety assessment. SKB Technical Report TR-06-09, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden. [LX,FM]

SKB, 2006b. Climate and climate-related issues for the safety assessment SR-Can. SKB TR-06-23. [All].

SKB, 2008a. Site description of Forsmark at completion of the site investigation phase. SKB Technical Report TR-08-05, Swedish Nuclear Fuel and Waste Management Co., Stockholm. [FM,FR]

SKB, 2008b. Geovetenskapligt undersökningsprogram för utbyggnad av SFR. SKB Report R-08-67, Swedish Nuclear Fuel and Waste Management Co., Stockholm. [FR]

SKB, 2008c. Site Investigation Oskarshamn 2002-2007. [LX,SM]

SKB, 2008d. Site Investigation Forsmark 2002-2007. [FM,FR]

SKB, 2008e. Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark. SKB TR-08-05, Swedish Nuclear Fuel and Waste Management Co., Stockholm. [FM, FR]

SKB, 2009a. Site description of Laxemar at completion of the site investigation phase. SDM-Site Laxemar. SKB TR-09-01. [LX]

SKB, 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. SKB Technical Report TR-11-01, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKI, 1996. SKI SITE-94. SKI Report 96:36, Swedish Nuclear Power Inspectorate, Stockholm, Sweden.

Stephens, M.B., Fox, A., LaPointe, P., Simeonov, A., Isaksson, H., Hermanson, J., Öhman, J., 2007. Geology Forsmark. Site descriptive modelling, Forsmark stage 2.2. SKB R-07-45. Svensk Kärnbränslehantering AB. [FM,FR]

Stephens, M.B., Simeonov, A., Isaksson, H., 2008. Bedrock geology Forsmark, Modelling stage 2.3. Implications for and verification of deterministic geological models based on complementary data. SKB R-08-64, Svensk Kärnbränslehantering AB.

Söderbäck, B. (ed.), 2008. Geological evolution, palaeoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas. Site descriptive modelling. SDM-Site. SKB R-08-19. [All]

Thomson, G., and Miller, B., 2005. SFR 1 - Post closure radionuclide release and dose calculations. SKB R-05-81. [FR]

Tirén S.A. and Beckholmen, M. 2009. Displacement along extensive deformation zones at the two SKB sites: Forsmark and Laxemar. Unpublished report for SSM.

Wahlgren, C-H. Curtis, P., Hermanson, J., Forssberg, O., Öhman, J., Fox, A., La Pointe, P., Drake, H., Triumf, C-A., Mattson, H., Thunehed, H., and Juhlin, C., 2008. Geology Laxemar. Site descriptive modelling. SDM-Site Laxemar. SKB R-08-54. [LX,SM]

Werner, K., Johansson, P-O., Brydsten, L., Bosson, E., Berglund, S., Tröjbom, M., and Nyman, H., 2007. Recharge and discharge of near-surface groundwater in Forsmark. Comparison of classification methods. SKB R-07-08. [FM, FR]

Werner, K., Öhman, J., Holgersson, B., Rönnback, K., and Marelius, F., 2008. Meteorological, hydrological and hydrogeological monitoring data and near-surface hydrogeological properties data from Laxemar-Simpevarp. Site descriptive modelling SDM-Site Laxemar. SKB R-08-73. [LX, SM]

Werner, K., 2009. Description of surface hydrology and near-surface hydrogeology at Laxemar-Simpevarp. Site descriptive modelling SDM-Site Laxemar. SKB R-08-71. [LX, SM]

Vidstrand, P., 2003. Surface and subsurface conditions in permafrost areas – a literature review. SKB TR-03-06.

Voss, C., and Andersson, J., 1991. Some Aspects of Regional Flow of Variable-Density Groundwater in Crystalline Basement Rock of Sweden. SKI 1991:09.

Voss, C.I., and Provost, A.M., 2001. Recharge-area Nuclear Waste Repository in Southeastern Sweden. Demonstration of Hydrogeologic Siting Concepts and Techniques. SKI 01:44. [LX,SM]

Öhman, J., and Follin, S., 2010. Hydrogeological modelling of SFR. Data review and parameterisation of model version 0.1. Site investigation SFR. SKB P-09-49. [FR]

Öhman, J., 2010. Site investigation SFR, Hydrogeologic modelling of SFR v 0.1, Influence of the ridge on the flow fields for different target volumes. SKB R-09-43, Svensk Kärnbränslehantering AB. [FR]

2012:49

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se