R-08-101

Confidence assessment

Site descriptive modelling SDM-Site Laxemar

Svensk Kärnbränslehantering AB

Juni 2009

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Preface

The Swedish Nuclear Fuel and Waste Management Company (SKB) is undertaking site characterization at two different locations, the Forsmark and Laxemar-Simpevarp areas, with the objective of siting a geological repository for spent nuclear fuel. An integrated component in the characterization work is the development of a Site Descriptive Model (SDM) that constitutes a description of the site and its regional setting. The model addresses the current state of the geosphere and the biosphere as well as the ongoing natural processes that affect their long-term evolution.

The objective of this report is to assess the confidence that can be placed in the Laxemar site descriptive model, based on the information available at the completion of the surface-based investigations (SDM-Site Laxemar). In this exploration, an overriding question is whether remaining uncertainties are significant for repository engineering design or long-term safety assessment and could successfully be further reduced by more surface-based investigations or more usefully by explorations underground made during construction of the repository.

Procedures for this assessment have been progressively refined during the course of the site descriptive modelling, and applied to all previous versions of the Forsmark and Laxemar site descriptive models. They include assessment of whether all relevant data have been considered and understood, identification of the main uncertainties and their causes, possible alternative models and their handling, and consistency between disciplines. The assessment then forms the basis for an overall confidence statement. Applying specific protocols and the conduct of associated workshops have proven to provide an excellent forum for overall cross-discipline integration and to provide insights to the modeling teams on what their uncertainties are and which of these uncertainties could affect other users.

The site descriptive modelling work as well as the confidence assessment work has been performed within multi-disciplinary project groups. All individuals and experts contributing to the outcome of this work are gratefully acknowledged. The following individuals and expert groups contributed to the project and/or to this report:

- Johan Andersson and Anders Winberg – coordination and integration.
- Carl-Henric Wahlgren, Philip Curtis, Aaron Fox – geology.
- Eva Hakami, Rolf Christiansson – rock mechanics.
- Jan Sundberg, John Wrafter – thermal properties.
- Ingvar Rhén – hydrogeology and hydrology.
- Marcus Laaksoharju, John Smellie, Eva-Lena Tullborg, Bill Wallin and the other members of the ChemNet group – hydrogeochemistry.
- James Crawford and co-workers – transport properties.
- Björn Söderbäck and co-workers – chemical properties of the surface system.
- Johan Andersson – remaining site-specific uncertainties and their handling.
- Peter Wikberg, Karl-Erik Almén and the site investigation team at Laxemar.

Johan Andersson is specifically acknowledged for his ambitious and devoted efforts as a driving force for making this work and report possible. Johan Andersson is also the editor of this report.

In earlier site descriptive models throughout the site characterization programme, the documentation of the confidence and uncertainty assessment work has been found in a specific chapter in the Site Description Report. In conjunction with this final product, SDM-Site, the confidence assessment work has been introduced as a stand-alone report supporting the SDM-Site Laxemar report.

Anders Ström
Site Investigations – Analysis

Summary

The objective of this report is to assess the confidence that can be placed in the Laxemar site descriptive model, based on the information available at the conclusion of the surface-based investigations (SDM-Site Laxemar). In this exploration, an overriding question is whether remaining uncertainties are significant for repository engineering design or long-term safety assessment and could successfully be further reduced by more surface-based investigations or more usefully by explorations underground made during construction of the repository.

Procedures for this assessment have been progressively refined during the course of the site descriptive modelling, and applied to all previous versions of the Forsmark and Laxemar site descriptive models. They include assessment of whether all relevant data have been considered and understood, identification of the main uncertainties and their causes, possible alternative models and their handling, and consistency between disciplines. The assessment then forms the basis for an overall confidence statement.

The confidence in the Laxemar site descriptive model, based on the data available at the conclusion of the surface based site investigations, has been assessed by exploring:

- Confidence in the site characterization data base,
- remaining issues and their handling,
- handling of alternatives,
- consistency between disciplines and
- main reasons for confidence and lack of confidence in the model.

Generally, the site investigation database is of high quality, as assured by the quality procedures applied. It is judged that the Laxemar site descriptive model has an overall high level of confidence. Because of the relatively robust geological model that describes the site, the overall confidence in the Laxemar Site Descriptive model is judged to be high, even though details of the spatial variability remain unknown. The overall reason for this confidence is the wide spatial distribution of the data and the consistency between independent data from different disciplines. While some aspects have lower confidence this lack of confidence is handled by providing wider uncertainty ranges, bounding estimates and/or alternative models to repository engineering and long term safety assessment. It is judged that most, of the low confidence aspects have little impact on repository engineering design or for long-term safety. It may also be noted that the feedback requirements from SR-Can to the site modelling are now met in the completed site investigations, subject to levels of uncertainty that are viewed as acceptable.

Only a few data points and a few types of data have been omitted from the modelling, mainly because they are judged less relevant and reliable than the data considered. Inclusion of data from outside the Laxemar subarea might have enhanced confidence in the regional model, but only at the locations of the data and these changes in confidence would have been of little significance in relation to implications for the local model area and would not, therefore, have been of any real significance to design or safety assessment. These omissions are judged to have little or no negative impact on confidence in the Laxemar subarea model. In fact, identification of unreliable data and their elimination should have a positive effect on confidence.

Poor precision in the measured data is judged to have a limited impact on uncertainties in the site descriptive model, with the exceptions of interpretation and combination of borehole and outcrop fracture data and general uncertainties in sorption data.

Some, potential biases in the data are identified.

- There is a non-uniform distribution of borehole data across the local model area. In particular there are few boreholes in the most southern parts of Laxemar. Also, drilling activities have focused on the interpreted major lineaments and not all possible local deformation zones have been investigated by drilling.
- Since there are only surface data on fracture sizes and, by necessity, no data from a potential repository depth, fracture size data are biased and especially those of the gently dipping ones. This necessitates considering a range of uncertainty in the geological DFN-model that could only be reduced by data obtained from underground investigations.
- There are few water chemistry samples from the low transmissive parts of the fractures and minor deformation zones, even though more data are now available from rock matrix porewater studies (KLX03, KLX08, KLX17A). Furthermore, a potential source of bias includes contamination from drilling fluid. Such biased data have been corrected by using back-calculations, but the representativity may be still questioned.
- There is some measurement bias in the transport, especially sorption, data.

Overall, there is limited measurement bias in the data. Bias due to poor representativity is much reduced compared with earlier model versions, but some still remains. The impact on uncertainty can be estimated and is accounted for in the modelling. The limited remaining bias is thus not judged to be a major factor for defining the degree of confidence that can be placed in the model.

Some uncertainties remain in the Laxemar site descriptive model. Most of them are quantified or at least bounded by alternative models or assumptions. The impacts of the quantified or bounded uncertainties are to be assessed in the design and safety assessment.

The block conductivities resulting from the current hydrogeological DFN are judged to be realistic, but details of the upscaling are still uncertain. It is noted that the true inflow distribution and the actual need for grouting in the underground constructions can only be fully determined during construction and as assessed by pilot holes and probe holes during tunnel excavation.

The presence of a chemical reaction zone in the surficial parts of the rock can probably be used to argue for stable redox conditions also during glacial episodes. It appears that the deepest penetration of the redox front during the Quaternary was limited to about 50–100 m. There is less confidence in the potential for buffering against dilute groundwaters.

Many hypotheses proposed in earlier versions of the site descriptive modelling are now discarded or handled by bounding assumptions. Nevertheless, five hypotheses have had to be retained with alternative models developed and propagated to engineering design and safety assessment. They concern the geological DFN models, transmissivity and connectivity of deformation zones, upscaling and correlation between fracture size and transmissivity in the hydrogeological DFN model, processes for sulphate reduction and effects of connectivity, complexity and channelling on distribution of flow (F-factor).

Another prerequisite for confidence is consistency, or at least no conflicts, between the different discipline model interpretations. Furthermore, confidence is enhanced if aspects of the model are supported by independent evidence from different disciplines. Essentially all identified interactions are considered in the site descriptive modelling work. Furthermore, the interdisciplinary feedbacks provide qualitative and independent data support to the different discipline-specific descriptions and thus enhance overall confidence.

Only data obtained from underground excavations are judged to have the potential to further significantly reduce uncertainties within the potential repository volume. Specifically, the following aspects are highlighted:

- The range of size distribution and size-intensity models for fractures at repository depth can only be reduced by data from underground excavations. Mapping fractures from the underground openings will allow statistical modelling of fractures in a DFN study at depth and testing of current alternative hypotheses on the fracture size distribution.
- Uncertainties in stress magnitude will be reduced by observations and measurements of deformation with back analysis during the construction phase. Complementary direct measurements using short boreholes in different directions may also be performed from underground.
- A more detailed subdivision of the rock types obtained from tunnel mapping will enable thermal optimisation of the repository.
- There is little point in carrying out hydraulic tests in additional surface-based boreholes. The next step in confidence building would be to predict conditions and impacts from underground tunnels. Tunnel (and pilot hole) data will provide information about the fracture size distribution at the relevant depths. The underground investigations will also provide possibilities for short-range interference tests at relevant depth.
- Uncertainties in understanding chemical processes may be reduced by assessing results of underground monitoring (groundwater chemistry; fracture minerals etc) taking into account the effects of drawdown and inflows during excavation.
- The hydrogeological DFN fitting parameters for fractures within the repository volume can only be properly constrained by additional flowing or potentially open fracture statistics obtained from tunnel mapping. Surface outcrop statistics are not relevant for properties at repository depth. During underground investigations the flowing fracture frequencies in tunnels, and investigations of couplings between rock mechanical properties and fracture transmissivities may give clues to the extent of in-plane flow channelling. This will lead to more reliable models for transport from the repository volume, particularly over the first 5–15 m from canister positions, which may have the greatest impact on overall radionuclide release rates.

Uncertainties outside the repository volume are larger, but are judged to be of less importance. Generally, it is judged that the confidence in the Laxemar site descriptive model has reached such a level that the body of data and understanding is sufficient for the purposes of safety assessment and repository engineering at this stage. Furthermore, the key characteristics of the undisturbed site are adequately understood prior to any major disturbance of excavation.

Contents

1 Introduction

This report is a confidence assessment of the site descriptive model (SDM) for the Laxemar site. The approach to the assessment builds on the methodology applied to earlier versions of the site descriptive modelling, but has been developed to more directly address the confidence in the SDM at the conclusion of the surface-based site investigation.

1.1 Setting and overview of the site descriptive model

Laxemar is part of the Simpevarp candidate area located in the municipality of Oskarshamn, about 320 km south of Stockholm. The Simpevarp candidate area is divided into two parts, the Simpevarp subarea, concentrated on the Simpevarp Peninsula and the Laxemar subarea located on the mainland west of the Simpevarp Peninsula, see Figure 1-1. Site descriptive models for the Simpevarp subarea were developed /SKB 2004, 2005/ followed by development of a site descriptive model for Laxemar /SKB 2006a/. Based on the developed site-descriptive models and associated preliminary safety evaluation /SKB 2006b/, SKB selected Laxemar for further study /SKB 2007/.

The Laxemar subarea is approximately 4 km long and 4 km wide. The south-western part of the Laxmar subarea was selected as the focused area for the complete site investigation work in 2006.

Investigations have been in progress at Laxemar since early 2004 and have provided data to one principal data freeze during the initial site characterization phase (Laxemar 1.2) and three additional data freezes (Laxemar 2.1, 2.2 and 2.3, respectively) during the complete site characterization phase. The current SDM-Site Laxemar site-descriptive model is based on the last of these data freezes

The surface investigations undertaken comprise aerial photography, aerial and surface geophysical investigations (partly of high resolution), lithological mapping of the rock surface, mapping of structural characteristics, investigations of Quaternary deposits including marine and lacustrine sediments in lakes and in the Baltic Sea, meteorological and hydrological monitoring and measurements, hydrochemical sampling and analyses of precipitation, surface waters and shallow and deep groundwaters, as well as various ecological inventories and investigations.

Borehole data in support of the Laxemar site description come from 46 core-drilled boreholes ranging in depth from about 100 m to 1,000 m (KLX02 is the longest with a length of about 1,700 m) and making up a total borehole length of about 20,950 m. However, actual site characterization data are only available from about 18,155 m, since no data exist from the uppermost telescope drilled (usually the upper approximately 100 m portions of the boreholes). The database also contains results from investigations in 43 percussion-drilled boreholes, with a total borehole length of about 6,412 m, and some 189 monitoring wells in the Quaternary deposits (i.e. the so-called soil monitoring wells).

In addition to results from standardised borehole measurements (drilling logs, image logs and core logs) in cored and percussion holes, information from more specialised investigations has also been collected. These specialised investigations include resistivity logging for establishing the *in situ* formation factor, measurements of groundwater flow, cross-hole interference tests and investigations of rock matrix porewater. Rock stress measurements from overcoring, hydraulic fracturing, hydraulic tests on pre-existing fractures and studies of borehole breakouts and other types of fallout structures in the borehole wall have been performed in several of the boreholes. Furthermore, the database include data from several types of laboratory investigations carried out on samples of intact rock material and selected fracture samples from these boreholes. The soil monitoring wells have provided time-series data on groundwater levels and water chemistry, as well as information on the stratigraphy of the Quaternary deposits in the area. Time-series data of hydraulic head have also been acquired in the bedrock by means of multi-packer systems in the cored boreholes, and in some cases also in percussion holes.

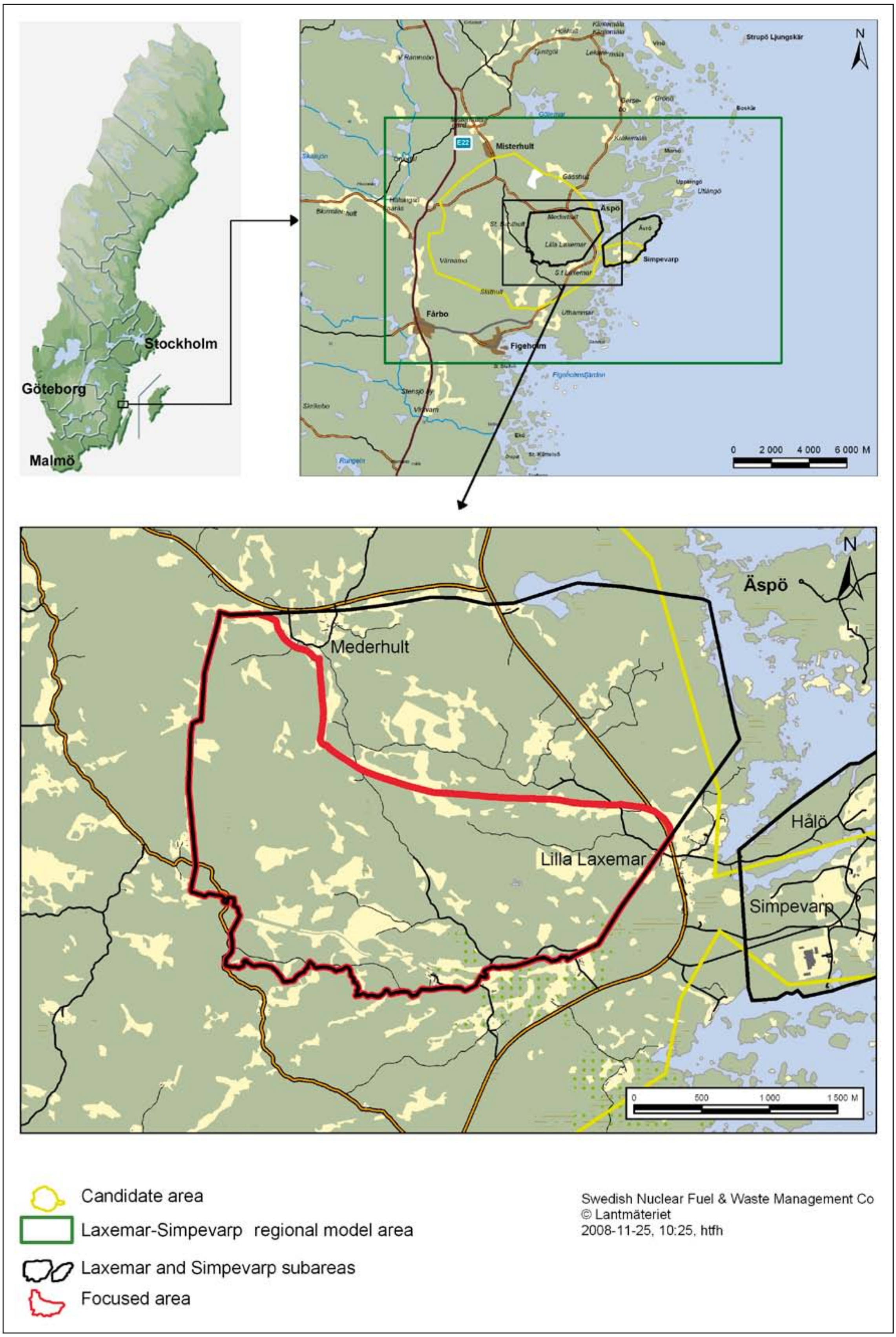

Figure 1-1. *Overview of the Laxemar-Simpevarp regional model area and identification of the Simpevarp and Laxemar subareas.*

The Laxemar-Simpevarp area is dominated by igneous rocks that formed c. 1,800 million years ago. The bedrock is more or less well preserved, although a non-uniformly distributed weak foliation is commonly present. The most prominent ductile structures in the Laxemar-Simpevarp area are discrete, low-temperature, brittle-ductile to ductile shear zones of mesoscopic to regional character, the most prominent ones being two zones oriented northeast which flank the candidate area. Subsequently, the rock mass has been subject to repeated phases of brittle deformation, under varying regional stress regimes, involving reactivation along earlier formed structures.

The geological modelling of the site has addressed three aspects that serve the needs of different users; rock domains describing the lithological distribution, deformation zones and fracture domains (describing fracturing between deterministic deformation zones). The geological model forms the geometrical framework for the thermal, rock mechanics, hydrogeological, hydrogeochemical and bedrock transport models. For reference, Figure 1-2 shows an overview of the geological model, for details see /Wahlgren et al. 2008/.

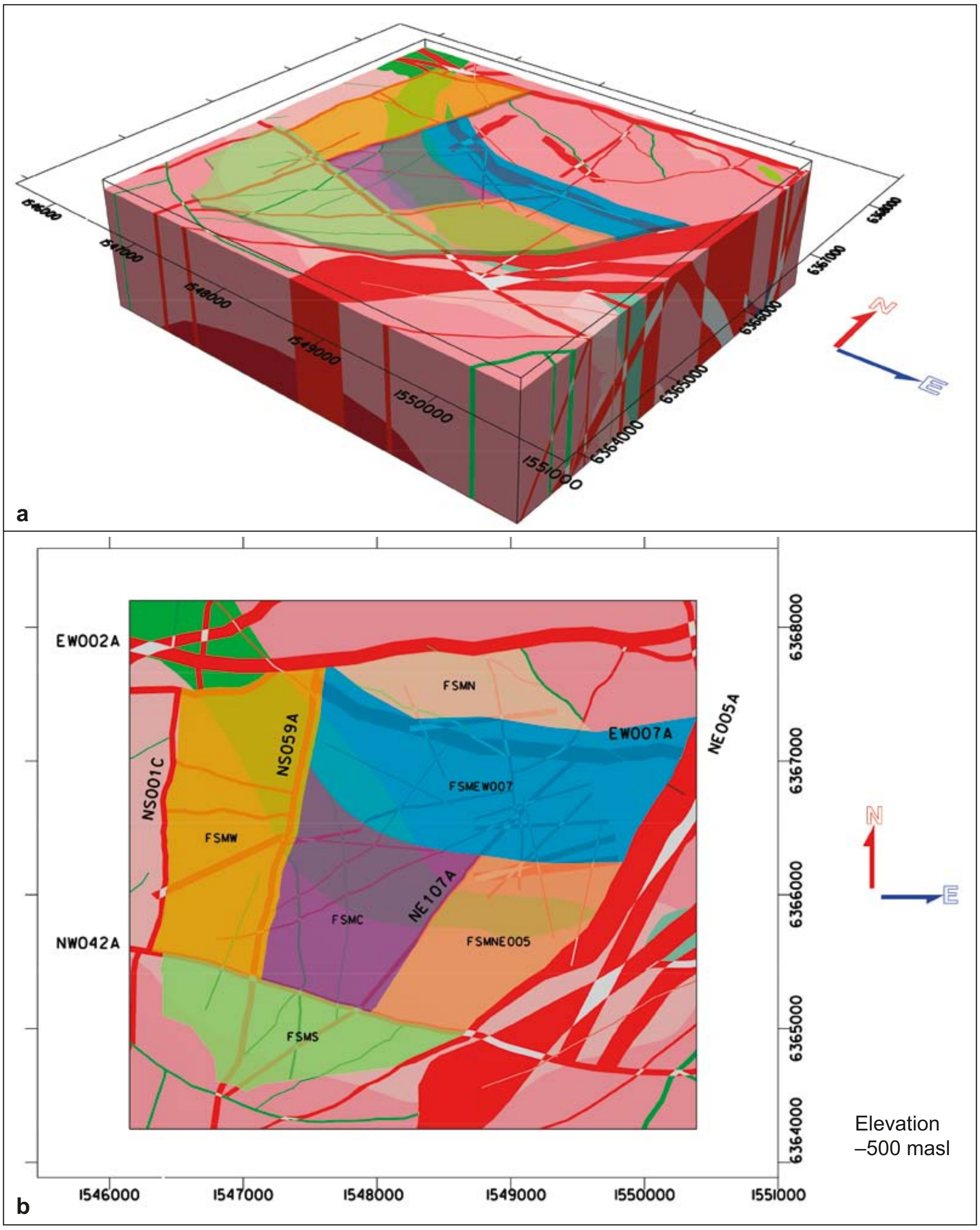

Figure 1-2. Integration of rock domains, fracture domains and deterministic deformation zones in the Laxemar local model volume. A) 3D view towards northwest. b) Horizontal section at –500 m.

1.2 Need for uncertainty and confidence assessment

A site descriptive model will always contain uncertainties, but a complete understanding of the site is not required. The site characterization should continue until the reliability of and confidence in the site descriptive model has reached such a level that the body of data and understanding is sufficient for the purposes of safety assessment and repository engineering, or until the body of data shows that the rock at the site does not satisfy the predefined requirements.

This means that it is necessary to assess the uncertainties and the confidence in the modelling on a continuous basis. Procedures for this assessment have been progressively refined during the course of the site descriptive modelling, and applied to all previous versions of the Forsmark and Laxemar site descriptive models, see e.g. /SKB 2006a/. They include assessment of whether all data are considered and understood, identification of the main uncertainties and their causes, possible alternative models and their handling, and consistency between disciplines. The assessment then forms the basis for an overall confidence statement.

Since the surface-based site investigations are now being concluded and the site descriptive model of the selected site, i.e. either Forsmark or Laxemar, will support a licence application to start construction of a spent nuclear fuel repository, the confidence assessment needs to extend its focus. Essentially the assessment needs to address whether the confidence in the site descriptive model, with its uncertainties, is sufficiently high for this intended purpose.

1.3 Scope and objectives

The objective of this report is to assess the confidence in the Laxemar site descriptive model based on the information available at the conclusion of the surface-based investigations (model version SDM-Site Laxemar). In this exploration an overriding question is whether remaining uncertainties are:

- significant for repository engineering design or long-term safety assessment;
- could successfully be further reduced by more surface-based investigations or more efficiently and effectively by explorations conducted underground.

1.4 How much confidence is needed?

As set out in the geoscientific programme for investigation and evaluation of sites /SKB 2000/, the site investigations should continue until the reliability of the site description has reached such a level that the body of data is sufficient to adequately support safety assessment and repository engineering, or until the body of data shows that the site does not satisfy the requirements. Overall, the site investigations need to continue until no essential safety issues remain that could not be solved by local adaptation of layout and design.

1.4.1 Properties and conditions of importance for long-term safety

Only some site properties are important for long-term safety. In summary, SKB's safety assessment SR-Can /SKB 2006c, Section 13.7/, considering both the Forsmark and Laxemar sites based on the available data and models at the time, provides the following feedback to site investigations and site modelling:

- To ensure mechanical stability of deposition holes, it is a necessary condition that deposition holes are located further than an appropriate respect distance from *deformation zones with surface trace lengths longer than 3 km*. It is thus necessary to identify and outline the geometry of such zones that could intersect or border the potential repository volume.
- Mechanical stability of canisters also requires that deposition holes are not intersected by large fractures or deformation zones. This is achieved by selecting deposition holes according to preset criteria. However, the efficiency of these criteria depends both on the *geological and hydrological DFN models of the potential repository volume* and there has to be sufficient confidence in these models. While the importance of representing large fractures correctly in site models is stressed, it is also noted that the likelihood of identifying and avoiding these structures determines their final impact on safety.

- High *in situ stress in relation to the Uniaxial Compressive Strength (UCS*) of the intact rock may result in spalling of deposition holes, both during construction and later, after deposition, due to the added thermal load. Thus, confidence in the stress and strength (UCS) modelling is essential.
- *Thermal conductivity and in situ temperature* determine, together with the repository layout, the buffer peak temperature.
- *Groundwater flow at the deposition hole scale* has a large impact on repository performance. It both affects the stability of the buffer and the copper canister as well as the release of radionuclides for the case of a breached canister. The correlation between fracture size and transmissivity also need to be studied. The site descriptive modelling should focus on the hydrogeological DFN-modelling of the potential repository volumes. There is comparatively little need for a DFN-description outside these volumes.
- The *chemical environment* directly controls the evolution of the repository. The most important parameters are redox properties, salinity and ionic strength, which directly affect the canister and buffer safety functions. Other factors to consider are the groundwater content of potassium, sulphide and iron(II), as they might affect the chemical stability of the buffer and the canister. Available hydrogeochemical data are clearly sufficient to prove that suitable conditions prevail at both sites today and also during the temperate period that should persist for the next few thousand years. More challenging is predicting the groundwater composition during a glacial cycle. Further attention to the *overall conceptual model* and more interaction with the hydrogeological modelling is needed.
- The *biosphere model* used in SR-Can, was as far as possible based on site data and the surface and near-surface description.

This feedback from SR-Can also demonstrates the necessity to develop sufficient understanding of the processes and mechanisms governing the general evolution of the site.

1.4.2 Repository design and engineering needs

A repository design including a site-specific layout is developed based on the site descriptive model. However, experience from the preliminary step /Janson et al. 2006/ showed the need for extracted information regarded as relevant to design, expressed in a way adapted to construction engineers, being mostly external consultants having only limited acquaintance with SKB terminology and methodologies. For this reason, SKB now develops a Site Engineering Report (SER) for each site, interpreting the site descriptive models for the design engineers. The main purpose of the SER is to present rationale and guidelines for the design that are focused on constructing a repository, operational issues and safety assessment issues that impact construction and operations. The SER performs the following functions:

- It recommends design parameters for e.g. rock support and grouting, based on the site descriptive model, but adapted to reflect engineering practice. Typically, these design parameters concern main deformation zones, fracturing, rock mechanics properties and hydrogeological conditions to be expected underground.
- It assesses and presents conditions that may place constraints on the layout from the safety assessment point of view. Typically, this relates to respect distances to deformation zones, thermal dimensioning and application of avoidance criteria for deposition holes with respect to large fractures and unacceptable hydraulic conditions.
- It recommends ranges for the repository depth, based on feedback from SR-Can /see SKB 2006c, Section 13.6.8/ and an provides an assessment of engineering feasibility. Factors of importance for repository depth include geometry of deformation zones requiring respect distances, mechanical stability (stress and rock strength), thermal properties and hydraulic conditions.

The SER is later used, together with the SDM, to develop a design and layout of the repository. For the design to be used as a basis in the licence applications the geological constraints and engineering guidelines provided in SER cover the site adaptation of the final repository with respect to: (1) deformation zones to be avoided and rock mass conditions at depth, (2) parameters that affect the depth and areal size of the repository, and, (3) a description of ground conditions for assessment of constructability. However, all aspects of the site need not be known at this time and instead the observational method will be applied to gradually update the design as data from the underground excavations become available.

The observational method is a risk-based approach to underground design and construction that employs adaptive management, including advanced monitoring and measurement techniques, to substantially reduce costs while protecting capital investment, human health, and the environment. In simple cases this means that design for reinforcement and grouting is adapted to the conditions actually observed underground. A much more complex, but essential part of the observational method for the final repository, is to adapt the underground excavation to meet demands on long term safety, e.g. when placing deposition and orienting deposition tunnels or deposition holes. The design process using the observational method has several steps and is constantly updated during each step, as more information becomes available. During the design steps, the inherent complexity and variability in the geological setting prohibits a complete picture of the ground structure and quality to be obtained before the facility is excavated. Thus, during design, statistical methods may be used to evaluate the sensitivity of the design to the variability as well as the quality of the existing data. This is most important during the early stages of design when trying to quantify project risks and cost estimates. As new data are acquired during subsequent investigations, the site descriptive model will be updated and the parameter distributions refined.

Finally, it should be noted that acccording to the KBS-3 method, the potential repository will be placed somewhere between 400–700 m depth, depending on site conditions. This means that it is especially important to reach a good understanding of conditions at these depths in the area of more detailed study.

1.5 Procedure for assessing confidence and uncertianty

In order to assess the uncertainty and confidence, work procedures (protocols) have been developed. The protocols are expressed as tables with questions to address. The protocols aim at exploring:

- Confidence in the site characterization data base, see Chapter 2;
- Remaining issues and their handling, see Chapter 3;
- Handling of alternatives, see Chapter 4;
- Consistency between disciplines, see Chapter 5;
- The main reasons for confidence and lack of confidence in the model, see Chapter 6.

The protocols are based on those applied in relation to the previous versions of the Forsmark and Laxemar site descriptive models, but have been revised and refocused.

The assessment was carried out in a stepwise manner as summarised below:

- Uncertainty, confidence and consistency between disciplines have been a standard agenda item at the regular site descriptive modelling team meetings, held approximately one each month throughout the site modelling project. These meetings, with constant participation of the different discipline experts and chaired by the site descriptive modelling project manager, identified issues of concern, followed up progress in resolving these issues, and helped informed cross-discipline understanding of the site.
- A trial run of the assessment was conducted in September 2007, where the full site modelling team, together with some key representatives from safety assessment and repository engineering, held a joint workshop, providing preliminary answers to the questions set out in the assessment protocols, see above. This trial run allowed minor adjustments to the protocols and also provided important guidance for the completion of the site modelling effort.
- About a year later, i.e. at the end of the site modelling processes. in early August 2008, the updated assessment protocols were submitted to the designated discipline experts in the modelling team. Each expert answered the questions relating to her or his subject.

- About a month later (i.e. in September 2008) the full site modelling team, together with some key representatives from safety assessment and repository engineering, held a joint workshop, where the answers were discussed, revised and complemented. The participants are identified in the preface to this report. A key aspect of this workshop is that it allowed direct feedback from other disciplines and from the safety assessment and repository engineering users on the suggested input from each subject expert. All questions and answers were assessed and a consensus formulation to each answer was reached and documented on-line.
- The answers from the workshop have then been compiled and edited into this report (see preface). Before review, the report was also submitted to the discipline experts of the modelling team for a factual check and corrected as necessary.

This means that the final answers to the protocol questions, as documented in this report, represent *the integrated consensus view of the modelling team*. Thereby, this report can sometimes reach conclusions beyond the conclusions reached within each modelling subject, especially regarding integration between the disciplines.

2 Confidence in the site characterization data base

Checking the quality and uncertainty in the database – and whether the modelling has taken this into account is the first step in the overall uncertainty and confidence assessment. Consideration of all data, accounting for potential spread, biases or other causes of inaccuracy, is needed for confidence. However, poor accuracy in data need not necessarily imply large uncertainties in the resulting site descriptive model. What is important to consider is whether the impact of poor data can be bounded in the modelling description.

2.1 Auditing protocol for use of site data

The site investigation database for Laxemar is extensive and the quality of the primary data is assured by various procedures. Full references to the reports describing the data and the quality control applied are given in the SDM-Site Laxemar report /SKB 2009/. Nevertheless, the users of the primary data, i.e. the site modellers, need also check their confidence in these data, even if a basic confidence is established by the quality procedures applied when producing the primary investigation data.

A protocol, in the form of questions, has been developed for checking the use and quality of available data sources. The questions, see below, are essentially the same as in the assessment of earlier versions of the site descriptive modelling, with some simplifications and modifications to make them more straightforward to address. Since data used for the modelling are referenced in Chapter 2 of the SDM-Site main report, the question on what data have been used is now dropped. The questions on accuracy and bias are also somewhat modified. The following questions are addressed:

- If available data have not been used – what is the reason for their omission (e.g. not relevant, poor quality, …)?
- (If applicable) What would have been the impact of considering the non-used data?
- List data (types) where accuracy or precision is judged low – and answer whether inaccuracies are quantified (with reference to supporting documents).
- Is there bias in the data – and if so could it be corrected for?

The answers to these questions are summarised and discussed in the following subsections.

It should also be noted that the SDM models generally build on a multitude of data. The data support for the models is addressed in the different modelling reports, and summarised in Chapter 2 of the SDM-site main report. It is not repeated here.

2.2 Non-used data

Generally, the site descriptive model needs to consider all relevant data. However, data of questionable reliability or irrelevant data can be discarded without loss of confidence. For a given application, it may also be justified to omit data if the omissions lead to less favourable estimates ("conservative estimates"). However, such omissions cannot be made in the site descriptive modelling processes, since a proper assessment as to whether a property is given conservative values can only be judged by the users, e.g. safety assessment or engineering.

2.2.1 Geology

The following geological data have not been used:

- *Boremap mapping of available percussion boreholes* has not been fully evaluated within the rock domain modelling because of lack of drill core and thereby a more uncertain identification of rock types and because of the limited borehole lengths.
- *Modal and geochemical analyses from KLX01 and KLX02* that were generated prior to site investigation have not been used due to uncertainty in the used rock nomenclature.
- There has not been full use of the *rock type data sampled at Äspö HRL* for the geological models due to the variable quality in these data.
- *Data from areas adjacent to the Laxemar local model volume*, i.e the Simpevarp peninsula and Äspö HRL shaft and tunnels, have not been used in DFN modelling or verification. The use of these data is deemed inconsistent with the specified limits of the geological DFN model (valid inside fracture domains as defined in the Laxemar local model area). Data from Äspö stem from the eastern side of the Äspö shear zone and represents different rock types and a different structural domain.
- *Fracture data from percussion holes* are not used for the geological DFN-modelling. Fracture records from percussion holes are not of the same quality as from cored holes. In addition, the drilling method is likely to produce more drilling-induced fractures or artificial re-opening of older fractures. Finally, in percussion-drilled holes, there are only BIPS image logs (no drill core). This makes the interpretation of fractures and fracture properties very uncertain.
- The use of *hydraulic information from fractures* was omitted in the geological DFN modelling, since these data are handled by the Hydrogeological DFN team. This is in full-accordance with model strategy agreed upon by SKB, but has consequences in terms of integration with other models.
- There is limited use of *trench outcrop data in the geological DFN*. Trenches are used to build fracture domain and fracture orientation models, but are not used to build size/intensity/spatial models due to extreme size censoring of the data.

Generally, only few data have been omitted from the geological modelling, mainly because they are judged less reliable than the data considered. These omissions are judged to have little or no negative impact on confidence. In fact, identification of unreliable data and their elimination should have a positive effect on confidence. These omissions should thus, if anything, enhance confidence. However, the following points need to be noted:

- It is possible that Äspö tunnel-wall maps might shed additional light on the size distribution of sub-horizontal fractures. However, Äspö is likely in a different tectonic domain and therefore may display different size-intensity relationships than the rocks at Laxemar.
- The use of additional percussion-drilled holes is not likely to add significantly to our understanding of sub-horizontal fractures. It might be useful for understanding the sizes of MDZs and deformation zones, if the investigation was coupled with geophysics and hydraulic tests. However, the omission of inclusion of percussion drilled holes likely has little effect on the geological DFN.
- Use of hydraulic information from fractures in the geological DFN would lead to better correspondence between the geological and hydrogeological DFN, but at the expense of traceability. It is understood that the geological and hydrogeological DFN cannot be totally similar, since the hydrogeological DFN deals with a subset of all fractures. Artificial fitting of the geological DFN to the hydrogeological data could thus imply unwanted bias.
- It is possible, but highly improbable, that the use of the trace data from the trenches could offer additional insights into fracture sizes in other domains. By and large, the trenches are in domains that already have detail-mapped fracture outcrops in them.

2.2.2 Rock mechanics

The following rock mechanics data have not been used:

- *Information from percussion boreholes (however this information is considered in the geological model).* These data were judged insufficient and irrelevant for determining rock mass mechanical properties. The percussion boreholes do not provide data of importance for rock mechanics, such as frequency, orientation, aperture, roughness and infillings of the fractures. Furthermore, the percussion boreholes reach only shallow depth (around 100 m) and are thus of minor interest.
- *Old drill core mapping data and laboratory testing results from Äspö HRL.* The rock code categories and mapping format is different from the site investigation data. Furthermore, the variation in rock type properties makes the Äspö data less relevant for Laxemar modelling. In addition, some Äspö data have already been used during the development of the methodology.

Generally, only few data have been omitted from the rock mechanics modelling. The description of spatial variation in fracture intensity and the description of occurrence, thickness and crude characterization of fracture zones may have resulted in a more detailed description of the near-surface rock mass if the percussion boreholes were utilized, but this is of little importance. Inclusion of Äspö data would have lead to more certain descriptions of the intact rock, rock mass and the deformation zones in the area around the Äspö HRL, but again this is not relevant for the Laxemar model.

2.2.3 Thermal

The following thermal data have not been used:

- *Laboratory measurements of thermal conductivity from Äspö HRL.* These data are largely excluded from consideration since these samples showed somewhat different thermal and petrophysical properties compared to Laxemar.
- *Thermal conductivity data from 10 samples mapped as quartz monzodiorite in KSH01A and KAV04A.* These had anomalous densities and are deemed not to be representative of quartz monzodiorite in Laxemar.
- *Heat capacity determined from TPS measurements for several rock types.* The reason is low precision compared with determinations with the calorimetric method.
- *Several modal analyses.* Data were excluded from analysis because: older samples were defined according to a different rock classification system, some results were judged uncertain/less reliable (thermal programme from KAV01, KSH01A and KSH02) and some surface samples were collected outside the local model area. In addition, thermal conductivity calculations based on modal composition (SCA method) has lower quality compared to measurements and were not used if sufficient measurements were available. Instead, the modal analyses contributed to an understanding of the variability of thermal conductivity within rock types, especially as regards alteration.
- *Temperature loggings (fluid temperature and temperature gradient) for several boreholes.* Borehole loggings in the Simpevarp subarea have been excluded. In Laxemar, several boreholes were excluded either because of large errors associated with the measurement probe or insufficient time between drilling and temperature logging. In Laxemar, the following boreholes have not been used: KLX01, 03, 04, 06, 07A, 10, 11A, 12A, 13A, 15A, 17A, 19A and 21B.
- *Boremap data for boreholes KLX01, KLX06 and KLX09A have not been used in the geological simulations.* These boreholes are situated in the northern part of Laxemar and are not considered representative of the geology in the central and southern parts, which is the focus of the thermal model. For the same reason density logs from the same boreholes have not been analysed.

Only few relevant data have been omitted from the thermal modelling, mainly because they are judged less reliable or relevant than the data considered. Omission of Äspö data is judged to have resulted in slightly improved models. Excluding the anomalous quartz monzodiorite data is judged to have resulted in slightly improved models. Excluding indirectly determined heat capacity data has resulted in more precise models. A more extensive use of modal analyses would have resulted in less reliable TRC models. The impact of not using the Simpevarp temperature logging data has not been evaluated. Using all the borehole temperature loggings in Laxemar would have resulted in a less reliable measure of the average temperature (with higher variation) at repository depth. However, the number of approved boreholes in Laxemar is small. Nevertheless, the omissions are judged to have little negative impact on confidence. Excluding boremap and density data from the northern part of Laxemar is judged to have resulted in slightly improved models.

2.2.4 Hydrogeological

The following hydrogeological data have not been used:

- *Old data from Äspö, Hålö, Ävrö and Mjälen:* Äspö HRL holes drilled from tunnel have only been used for assessing properties of deterministically defined deformation zones and it is recognised that there is potential for more use of the Äspö HRL data. Clab data have not been used at all since they are judged to be of little significance.
- *Some very old data from the Simpevarp peninsula:* The quality is judged poor. Some of the available data are likely relevant to the Simpevarp subarea, such as measured inflow rates to the Clab facility, but are not relevant for Laxemar.
- *Dilution test data:* These data have not been used for calibrating the hydrogeological DFN but have been addressed within the transport modelling.

Generally, omitted data concern conditions outside the potential repository volumes now considered. The neglect of Clab data has a minor impact since they cover a small area and a depth down to about 50 m below surface. However, the data may contribute to the understanding of near-surface conditions, at least in the Simpevarp subarea. The description of Äspö (i.e. outside the Laxemar subarea) could have been improved (more detailed and better calibrated) based also on Äspö HRL data. The hydraulic DFN modelling methodology could have been tested more thoroughly. Alternatives for possible anisotropic conditions, similar to those seen in the Äspö HRL could have been tested. However, the Äspö data from surface drill boreholes lack some of the hydraulic tests (PFL) used during the site investigations, which would complicate such tests. Had such data been available, the integrated hydrogeological and geologic interpretation of the model could have benefited.

2.2.5 Hydrogeochemical

The following hydrogeochemical data have not been used:

- *Äspö HRL data:* These data have not been used, since these data reflect a dynamic system being disturbed by the HRL. Furthermore, old Äspö HRL data are part of the overall Nordic database, used as a basis for conceptual modelling and comparisons.
- *Observations judged to be of lesser quality:* Such data have been excluded from the detailed modelling, but are still considered.

Omission of Äspö data is judged to have limited impact on the overall modelling of the Laxemar area. All data could be used for an overall qualitative assessment of the distribution of water types etc. When possible, the non-representative data have been used for checking the impact on the visualisation and the overall understanding of the site. Clearly, omission of the less reliable data should, if anything, enhance confidence.

2.2.6 Transport

The following transport data have not been used:

- *Äspö data with questionable representativity or interpretation:* Such data were excluded already in SDM Simpevarp 1.2 owing to issues concerning representativity. In particular, the use of sorption/diffusion data for altered Äspö diorite to generically represent all altered rock materials at the Laxemar site was found to be insufficiently supported to be of use.

While some of the Äspö HRL data (from the TRUE Block Scale experiment) are of high quality, it is unclear whether Äspö HRL data are representative for the Laxemar subarea. Although not included in the retardation model for SDM-Site Laxemar, Äspö HRL data will be considered in the data selection process for Safety assessment.

2.2.7 Near-surface

The following near-surface data have not been used:

- *Sonde data on chemistry in surface systems:* These data are omitted since some parameters (redox, chlorophyll, turbidity, light) may have low accuracy.
- *Surface-chemistry data from observation points with short time series*: These data have been omitted in order to avoid bias in annual estimates. A qualitative assessment of these data does not suggest any conflicts with the accepted data set.
- *Parts of some hydrology time series from soil tubes and percussion boreholes:* These data have not been used in some analyses due to disturbed conditions.
- *Discharge measurements at the station downstream of Lake Frisksjön:* These data have not been used due to large uncertainties in the rating curve.
- *Airborne geophysical data:* These data have not been used in the assessment of the Quaternary deposits depth model due to poor quality.
- *Zooplankton data from Lake Frisksjön:* These data were not used because they relate to few and unrepresentative samples.

Generally, only a few data have been omitted from the near surface modelling, mainly because they are judged less relevant and reliable than the data considered. These omissions should thus, if anything, enhance confidence.

2.3 Precision

Poor precision in measurement data, i.e. high spread around the "real value", is one potential source of uncertainty in the SDM. It is thus important to identify data where precision is low and, if possible, also to devise means of how to quantify the uncertainties arising from these problems.

2.3.1 Geology

Precision is judged to be low for the following geological data (see further /Wahlgren et al. 2008/ and for issues related to the geological DFN-model /La Pointe et al. 2008/).

- *Identification of rock type and fracture filling in percussion boreholes:* These data are considered to be of significantly lower quality than corresponding data from the cored boreholes. Furthermore, the identification of fractures in the percussion boreholes is solely based on BIPS images, and accordingly the measured fracture intensity in these boreholes is judged to be too low. The precision has not been quantified but qualitatively there is a difference in the data quality from the percussion boreholes as compared to the cored boreholes.
- *Coding of the Boremap data:* Some errors presumably exist, e.g. coding of some rock types. It is not possible to quantify precision. These potential minor mistakes are judged to be of subordinate importance and to have no effect on the modelling work.
- *Uncertainty in the deviation measurements of the boreholes*: These uncertainties follow through subsequent steps of measurement and interpretation of oriented structural data that are key input data to the interpretation of deformation zones. The uncertainty in the borehole orientation, fracture orientations and interpreted deformation zones are all quantified and are carried over to the Geological DFN by not using data with an average orientation uncertainty > 10° /Munier and Stigsson 2007/.
- *Judgements made, in connection with the interpretation work to produce co-ordinated and linked lineaments:* This has a fundamental effect on the lineament length and therefore also on the modelled length of deformation zones. It is not possible to quantify the degree of precision. However, the resolution of the underlying data set has increased dramatically during the project with a commensurate rise in precision. The problem is addressed by traceable, quantitative stepwise interpretation from surface maps of topography and geophysics to the final lineament map and by utilising different lineament interpretation groups.

- *Process of linking lineaments:* The process is uncertain since the degree of continuity of a lineament or associated structure is directly linked to the scale of study. This means that judgements of length and size of associated structures are uncertain. Such uncertainties are quantified by the use of confidence levels and spans in the deformation zone property tables and descriptions.
- *Outcrop traces and lineaments shorter than 1,000 m:* Such traces and lineaments were used in the geological DFN, whereas two-dimensional sections of deformation zones were not used in the parameterisation of the geological DFN. Confidence in longer lineaments drilled or indicated in outcrops is fairly high, but confidence in smaller-scale lineaments (~< 250 m) is lower. As not every smaller-scale lineament has been mapped at the ground surface or in boreholes, it is not possible to say with absolute certainty that a given lineament trace < 1,000 m in length represents a fracture or a fault; they could also represent glacial features, dykes, zones of magnetized rock, or other geological/geomorphological structures, see also Section 3.2.5.
- *No or very limited data on the size of sub-horizontal fractures.* The only data on the size of sub-horizontal structures comes from outcrop data and a limited subset of deformation zones or seismic reflectors. Uncertainty is addressed as different size models for different fracture domains. Uncertainty is quantified in the geological DFN as potential variability in P_{32}.
- *Identification of deformation zones in single-hole interpretation.* It is judged that the zones identified in the single-hole interpretations are indeed zones. However, there are probably additional deformation zones that could be "distilled" from the rock mass fracturing and, thus, improve the understanding of the clustering. However, there is also fracturing in the rock mass that is not connected with deformation zones. These limitations in the single-hole interpretation are considered in the evaluation of the uncertainty in the DFN-model.
- *Orientation of deformation zones in single-hole interpretation.* The orientation is not given, but directions of fractures in these zones have a high precision. The latter aid in the interpretation of the geometry of individual borehole intercepts and provide support to the overall geometry of an interpreted (deterministic) deformation zone.
- *Interpretation of open/sealed fractures in outcrops.* The interpretation of fracture aperture (open, partly open, and sealed) in cored boreholes has relatively high accuracy due to the combination of BIPS and core mapping. However, the identification of whether fractures mapped on outcrops are open or sealed is more uncertain and potentially less precise. The geological DFN is parameterised for all fractures (open and sealed), so it is not affected by any potential uncertainty in outcrop apertures. The hydrogeological DFN is built from borehole data and does not use surface fracture data; it is therefore not affected by uncertainty in apertures derived from the mapping of fractures in outcrop.
- *Interpretation and combination of borehole and outcrop fracture data* are uncertain since the two data types are mapped in different fashions and at different resolutions (size cut-offs). The geological DFN makes assumptions regarding the distribution of fracture size and intensity to deal with this, but the assumptions have not been rigorously tested through field mapping. The size model for fractures is the most uncertain aspect of the geological DFN. This uncertainty has been quantified in the geological DFN report /La Pointe et al. 2008/.

Despite this long list, poor precision in geological data is judged to be of low importance. Errors and levels of imprecision are sufficiently quantified for the subsequent data analyses.

2.3.2 Rock mechanics

As further discussed by /Hakami et al. 2008/, precision is judged low for the following rock mechanics property data:

- *Normal stiffness:* The precision of the experimental set up and methodology is not quantified, but by comparing results from different methods it is judged that currently achieved precision is acceptable.

- *Shear stiffness:* A new experimental set up has been used and the methodology report updated. The precision of the new experimental set up and methodology is not quantified, but by comparing results from different methods it is judged that currently achieved precision is acceptable.
- *Tilt test data:* There is a large scatter in results from the tilt test – laboratory shear tests are given more weight in the modelling.
- *Maximum (horizontal) principal stress magnitude from the hydraulic fracturing measurement method:* The limited precision of this method is not quantified. However, other stress measurements (overcoring and HTPF) provide estimates of the major principal stresses.

The limited precision in the above rock mechanics data is handled in the uncertainty assessment of the rock mechanics model and the various contributions are judged to be minor contributors to the overall uncertainty.

2.3.3 Thermal

Precision is judged low for the following thermal data:

- *Thermal conductivity calculations based on modal analyses (SCA method):* These data are considered less precise than those based on laboratory measurements. The SCA data have been used only for TRC 33A, 33B, 58 and 102. For these TRCs the precision is hard to quantify due to lack of other comparable data and inherent non-quantified uncertainties in the method. However, there is a tendency for the standard deviation of the SCA values to be higher than that of measured samples.
- *Density logging data:* The random noise in the density logging data is generally rather high, which influences the subdivision of the Ävrö granite into Ävrö quartz monzodiorite and Ävrö granodiorite, as well as the calculations of thermal conductivity of Ävrö granite (not used for the TRC models). This noise has been quantified. Both this noise and the applied filtering step influence the variograms describing spatial correlation, particularly for short lag distances.
- *Anisotropy in thermal conductivity:* This has not been determined in the laboratory. However, field measurements of thermal conductivity (at a larger scale, < 5 m) have been used to evaluate anisotropy. The variation in anisotropy factor is large and related to lack of knowledge concerning the orientation of the foliation plane at the site of the individual *in situ* measurements. The lower bound of the anisotropy factor at a larger scale is 1. The upper bound is not quantified.

The limits to the precision in the above thermal data are handled in the uncertainty assessment of the thermal model and are judged to be minor contributors to the overall uncertainty.

2.3.4 Hydrogeology

There are potential limits in the precision of the following hydrogeological data:

- *Results from Wire-Line-tests or airlift-pumping:* Such data generally have less precision than other hydraulic tests but are still useful if no other tests are available. In most cases these data are not used in the modelling as injection tests at 100 m scale have been available.
- *Orientation of flowing fractures:* The uncertainty in orientation of flowing fractures has been assessed. Different hydraulic test methods and different evaluation methods used in the long core holes have been cross plotted and compared, which broadly provide uncertainty estimates of individual measurements and overall confidence that the basic parameter, i.e. transmissivity, is reasonably correctly estimated by /Rhén et al. 2008/.

This is handled in the uncertainty assessment of the hydrogeological model, see /Rhén et al. 2008/. Poor precision in the data is judged to be a minor contributor to the overall uncertainty in the hydrogeological model.

2.3.5 Hydrogeochemistry

With some exceptions (e.g. surface/near-surface dilute waters with contents close to the detection limit) there are very few examples of poor precision in the representative data set /Laaksoharju et al. 2009/. The precision of major components, stable isotopes is judged to lie within (± 5–10%). The effect of such errors on the interpretation is checked in the explorative analyses. The surface/near-surface accuracy for charge balance is ±10%. These judgements are in turn used as input to the uncertainty assessment of the hydrogeochemical model.

2.3.6 Transport

Precision is judged low for the following transport data:

- *Sorption data:* General uncertainties included in the evaluation concepts for sorption coefficients and diffusivities are addressed and discussed in the supporting report /Crawford and Sidborn 2009/. Methodological biases, for example, inherent in the use of small samples of crushed rock to investigate the properties of intact rock *in situ* are acknowledged as a major source of uncertainty.
- *In situ resistivity measurements:* Although formation factors derived from *in situ* resistivity measurements are considered to have a high level of precision, their accuracy depends on the assumed water composition of the pore fluid. This composition is uncertain owing to possible disequilibrium between matrix porewater and groundwater sampled in fractures and used as a proxy. Additional measurement artefacts related to, for example, surface conduction may bias the results of the *in situ* measurements, although the overall effect is thought to be small.
- *Diffusivity data:* A relatively high level of measurement precision is achieved in laboratory measurements of diffusivity based upon both through diffusion and electrical resistivity data. Systematic differences between the methods indicate a methodological bias, which is consistent and bounded. Additional investigations are ongoing to more fully understand the reasons for the discrepancy.

These findings are handled in the uncertainty assessment of the transport model, see /Crawford and Sidborn 2009/.

2.3.7 Near-surface

Precision is judged low for the following near-surface data:

- *Concentrations of some chemical elements and compounds.* Precision is generally low (but is not quantified) for elements and compounds where concentrations are near the detection limits.
- *Calculated element flows in the sea.* These data may have poor precision, since estimates are based on concentrations extrapolated from a limited number of sampling sites, and from modelled water flows between basins.
- *Discharge measurements, mainly at stations with natural sections.* The precision is estimated using data from other stations.
- *Groundwater levels and hydraulic conductivity data.* These data have low spatial resolution and/or short time series – their precision is not quantified.
- *Vegetation parameters used in the modelling of evapotranspiration:* Sensitivity to these parameters has been tested and found to be low.
- *Map of Quaternary deposits outside the Laxemarån catchment area and outside the local model area:* There is low spatial resolution of data on stratigraphy of the Quaternary deposits, their depths and physical properties.
- *Biomass in the root zone:* The precision is estimated using generic data.

The findings are handled in the uncertainty assessment of the near-surface model, see /Söderbäck and Lindborg 2009/.

2.4 Bias

Bias, i.e. to what extent the mean of the measured data deviates from the true mean, is another contributor to uncertainty. Potential biases in data need to be identified. There are typically two kinds of biases in the data, biases in the measurement technique and bias introduced by poor representativity of the data. The impact on uncertainty needs to be considered and it needs to be judged whether this impact can be estimated with confidence.

2.4.1 Geology

There is judged to be significant bias in the following geological data:

- *Representativity of regional scale data:* For the local scale, i.e. the volume of interest for the potential repository, there is no bias in data coverage (surface and boreholes). However, in the regional scale, there are few data from areas covered by the sea and, thus, the location and extent of the sedimentary cover rocks in the sea area is uncertain. This cannot be corrected for, but the sedimentary rocks do not extend west of the deformation zone ZSMNE024A. Furthermore, the bedrock information in the regional model area on land is only of reconnaissance character.
- *Surface based geophysics in the NW and SE corners of the regional model:* These data have lower resolution, but the corners are of less concern in the model. Also, the new bathymetry data increase the detail along the coastline – i.e. the previous bias noted in e.g. model version Simpevarp 1.2 is no longer a significant concern.
- *Reflection seismic data from the surface:* Such data focus on gently dipping structures. There is also a limited coverage of the local model area by seismic surveys, particularly in southern Laxemar.
- *Distribution and orientation of boreholes in the local model area:* There is an non-uniform distribution of borehole data across the local model area. In particular, there are few boreholes in southern Laxemar. Furthermore, drilling activities have focused on the identified major lineaments and not all possible local major deformation zones have been investigated by drilling. In both cases, this has been addressed to a certain extent by focussed, surface based, geophysical surveys. The array of cored boreholes at Laxemar now encompasses a wide-enough distribution of orientations (vertical, steeply, and moderately-dipping boreholes) such that orientation sampling bias is now minimized. In addition, the use of both Wang's C_{13} factor /Wang 2005/ and Terzaghi correction for estimating fracture P_{32} from borehole P_{10} is a significant advance compared to Laxemar 1.2 /Hermanson et al. 2005/, where compensation for borehole orientation bias was made through stochastic simulation.
- *Spatial distribution of detailed fracture mapping at the surface.* There is an non-uniform distribution of trace map data across the local model area. In particular, detail-mapped fracture outcrops only exist for three (FSM_N, FSM_NE005, and FSM_W) of the six fracture domains within the Laxemar local model area. Trench studies cover the southern portion of a fourth fracture domain (FSM_EW007), but are significantly less useful in the determination of fracture size due to the limited width of the trenches.
- *Data gap in size between deterministically modelled deformation zones and outcrop fractures:* This gap has been reduced, but not eliminated, through the addition of lineaments in the size range 100 m–564 m from high-resolution magnetic surveys and LIDAR data, thereby supporting the power law scaling assumption at Laxemar. There is still a data gap at the ~10 m–100 m scale. In addition, there is no size information for sub-horizontally dipping fractures and MDZ in the size range 10 m–564 m. The geological DFN model is based solely on the size model from the outcrop fractures (i.e. potentially biased towards smaller fractures, but not proven). However, the geological DFN verification efforts /La Pointe et al. 2008/ suggest that the size model for MDZ is reasonable.
- *Fracture data from the southern part of Laxemar:* There is a paucity of data, in particular fracture size data, in the southern part of the Laxemar local model volume (FSM_S).

These biases are accounted for in the geological modelling, see /Wahlgren et al. 2008/.

2.4.2 Rock mechanics

There is judged to be some bias in the following rock mechanics property data (see also /Hakami et al. 2008/:

- *Directional bias from boreholes:* Even though there is a relatively wide distribution of borehole orientations, as noted previously, there may still be directional bias in the rock mechanics data. Drill core samples were essentially only obtained from sub-vertical boreholes.
- *Sparse data coverage:* The data coverage in the southern Laxemar subarea is sparse. However, the lithological model indicates homogeneity within the southern rock domain (RSMD01). The spatial variability and mix of different rock types in rock domain RSMM01 give rise to a fairly large uncertainty in the rock type proportions. This means that there could be a bias in the mechanics properties, if the available boreholes are not representative of the whole domain.
- *One borehole with direct stress measurements*. There is a potential bias in the stress model of the focused volume, because it relies strongly on results from one borehole located in the south-east of this volume. The model, /Hakami et al. 2008/, has a fairly large uncertainty span around the measurement results from this borehole, but the mean value maybe biased if the borehole is not representative of the mean stress of the area.

The potential biases are accounted for in the rock mechanics modelling, see /Hakami et al. 2008/.

2.4.3 Thermal

There is judged to be significant bias in the following thermal data and interpretations /Sundberg et al. 2008/:

- *Poor representativity in TPS data for some subordinate rock types with few samples:* The analysed drill core samples may not fully cover the representative distribution of the subordinate rock types.
- *SCA data used in the thermal models for some rock types (TRC 33A, 33B, 58 and 102):* There is a potential bias in these data, mainly due to the sparsness of the dataset, limitations in the method, and degree and impact of alteration. However, the limited amount of comparable data does not justify any correction.
- *Potential bias in density logging data used in the thermal modelling:* This bias has influenced the subdivision of the Ävrö granite. The bias should not have any significant influence on spatial correlation models as long as boreholes are treated separately. Evaluation of the bias has been made and a correction was applied to some boreholes. Further, all data related to deformation zones according to the Extended Single Hole Interpretation (ESHI) have been removed.
- *Potential bias in some temperature loggings:* The approved temperature loggings in Laxemar show small variations at repository depth. However a small bias may be present due to errors associated with the logging equipment or due to logging being performed before temperatures in the boreholes had stabilized.
- *The anisotropy factor:* This is based on field measurements of thermal conductivity and is underestimated due to non-optimal orientation of the measurement in relation to the foliation plane. A correction has been applied based on the orientation of the measurements in relation to the foliation.

These biases are accounted for in the thermal modelling, see /Sundberg et al. 2008/.

2.4.4 Hydrogeology

There is judged to be significant bias in the following hydrogeological data and interpretations:

- *Orientation of boreholes:* The core holes are more or less sub-vertical and may introduce a window effect in the borehole transmissive feature statistics. Due to the relatively few observations at depth, this is more of a problem for hydrogeology than for the geological mapping. Hence, the structural model of the rock between the deformation zones may be biased. This effect could have been addressed by incorporating more boreholes with other orientations.

- *Data from near-surface rock:* There are rather few data in the near-surface rock system. There are few data at detailed scale in the first 100 m of the long cored boreholes apart from a few short core-drilled holes. The core drilled holes are mostly confined to two small drilling sites. This leads to uncertainties in describing the connections between the surfacial and deeper groundwater flow system.
- *Spatial coverage:* The spatial coverage is judged fair within the Laxemar subarea, but there are few data within individual Rock Domains or Fracture domains and at depth, causing uncertainties within individual domains, especially at depth. These possible biases could only be corrected by obtaining data more data from more boreholes), but the uncertainties could be estimated and are judged sufficiently bounded at this stage.

These biases are accounted for in the hydrogeological modelling and affects the uncertainties in the model, see /Rhén et al. 2008/.

2.4.5 Hydrogeochemistry

There is judged to be bias arising in the following areas affecting the hydrogeochemical data /Laaksoharju et al. 2009/:

- *Very deep data (> 1,200 m):* The data for assessment of conditions at depth below 1,200 m originates from a single borehole, KLX02.
- *Data from low transmissive parts of the fractures and minor zones:* There are relatively few samples from these parts, but some data are available from the rock matrix studies made in boreholes KLX03, KLX08, KLX17A. A potential source of bias in these data is contamination from drilling fluid. Such biased data have been corrected by using back calculations, but the representativity of the samples may still be questioned.
- *Sulphide data:* Old data from Äspö and KLX01 may be incorrect due to analytical uncertainties, but more likely from pumping effects (new sulphide data are available) and sampling difficulties. Analytical uncertainties are assessed by using different laboratories for comparisons.

These biases are accounted for in the hydrogeochemical modelling, see /Laaksoharju et al. 2009/. The uncertainty is partly handled by insight and process understanding from other sites (Forsmark; Olkiluoto) and by considering time series data from the monitoring programme, which will indicate the effects from e.g. artificial mixing and reactions.

2.4.6 Transport

There is judged to be significant bias in the following transport data:

- *Description of channelling in the hydrogeological DFN-model:* The bias "built into" these models due to their inability to represent physically meaningful channelling phenomena is a well known source of uncertainty. This may have an impact upon calibrated fracture length intensity relations and resulting transmissivity distributions. This is partly handled by the sensitivity analyses on the impact of different channelling hypotheses.
- *Potential impact from disturbed (stress release) of laboratory samples:* This would imply too high diffusivities etc in the laboratory samples compared with *in situ* values. There are possibly some indications of the degree of bias, which is seen by comparing *in situ* and laboratory formation factor data. This difference can, in principle, be used to correct the bias, but the precision and bias of the *in situ* data also needs to be considered.
- *Limited amount of transport property data:* The amount available do not give a sufficiently detailed view of intrinsic material property variability to rigorously distinguish between rock types in a quantitative sense. It is thought, however, that differences in groundwater chemistry (both temporal and spatial variations) overwhelmingly dominate over variations in sorptive properties. For similar groundwater compositions the sorptive properties of the rock matrix do not seem to vary significantly between different rock domains. The diffusive properties of the rock as indicated by *in situ* resistivity measurements suggest a relatively small spatial variability of matrix effective diffusivity that is well bounded even under consideration of possible methodological biases.

- *The retardation properties of altered rock (sorptive and diffusive properties) in close association with fracture surfaces:* The retention capacity is thought to be enhanced relative to the unaltered rock matrix.

These biases are accounted for in the transport modelling, see /Crawford and Sidborn 2009/.

2.4.7 Near-surface

There is judged to be significant bias in the following near-surface data:

- Sampling of water in Quaternary deposits is limited to till.
- There are no hydrochemical data from Quaternary deposits in recharge areas.
- There are few groundwater-level data from high-altitude areas.
- Measurements of hydraulic conductivities of sediments and peat are under-represented; correction has been made by use of generic data.
- Most data on depth of the Quaternary deposits are from the central parts of the investigation area, which means that detailed knowledge about the depth in the peripheral parts of the area is missing.
- Few sampling points for biota imply a potential bias in the data. To reduce the bias, the methodology has been to apply stratified sampling in type areas.

These biases are accounted for in the near-surface modelling, see /Söderbäck and Lindborg 2009/. Their impact on uncertainty is judged moderate.

2.5 Assessment

Generally, the site investigation database is of high quality, as assured by the quality procedures applied. Only a limited number of data are judged to have poor precision or be biased and this is judged to have little impact on model uncertainty.

Only a few data points and a few types of data have been omitted from the modelling, mainly because they are judged less relevant and less reliable than the data considered, even if inclusion of data from outside the Laxemar subarea could locally have enhanced confidence in the regional model. These omissions are judged to have little or no negative impact on confidence in the Laxemar modelling work. In fact, identification of unreliable data and their elimination should have a positive effect on confidence.

Poor precision in the measured data are judged to have limited impact on uncertainty in the site descriptive model, with the following exceptions:

- Interpretation and combination of borehole and outcrop fracture data are uncertain since different mapping techniques have different resolutions (cut-offs). The geological DFN makes assumptions regarding the distribution of fracture size and intensity to deal with this, but the assumptions have not been rigorously tested through field mapping. The size model for fractures is the most uncertain aspect of the geological DFN. This uncertainty has been quantified in the geological DFN report.
- General uncertainties in sorption data are included in the evaluation concepts for sorption coefficients and diffusivities and are addressed and discussed in the supporting report /Crawford and Sidborn 2009/ and /Selnert et al. 2009/.

Since these examples of poor precision are identified and considered in the modelling, they have only a small negative impact on confidence.

Some, potential biases in the data are identified.

- There is a non-uniform distribution of borehole data across the local model area. In particular there are few boreholes in southern Laxemar. Also, drilling activities have focused on the interpreted major lineaments and not all possible local major deformation zones have been investigated by drilling.
- Possibly, the most important bias relates to data on fracture sizes. The problem is especially acute for the gently-dipping fractures and MDZ at repository depth, where there no data can be obtain from surface mapping or airborne geophysics. This necessitates considering a range of uncertainty in the geological DFN-model that could only be reduced by data obtained from the underground.
- There are few water chemistry samples from the low transmissive parts of the fractures and minor zones, though more data are now available from rock matrix studies. Furthermore, a potential source of bias includes contamination from drilling fluid. Such biased data have been corrected by using back calculations, but their representativity may be still questioned.
- There is potential bias in the sulphide data.
- There are some methodological biases in the transport data, especially in the sorption data. For example, the inherent use of small samples of crushed rock to investigate the properties of intact rock *in situ* are acknowledged /Crawford and Sidborn 2009/ as a major source of uncertainty.

Overall, there is limited measurement bias in the data. Bias due to poor representativity is much reduced compared with earlier model versions, but some still remains. The impact on uncertainty can be estimated and is accounted for in the modelling. The limited remaining identified bias is thus not judged to be a major factor in defining the degree of confidence that can be placed in the model.

3 Remaining issues and their handling

For confidence, it is essential to identify remaining uncertainties of importance and to quantify them to the extent that their impact on safety and engineering can be assessed.

3.1 Auditing protocol

In order to assess confidence in the subsequent safety assessments, it is essential to *establish how much we know about the site and how confident we are based on present knowledge* and present assessments. This is addressed by identifying remaining uncertainties of importance and answering the following questions for each such issue:

- Why is the issue important? Does it affect key parameters for safety assessment or engineering? Is it essential for understanding (note that it must be of importance to qualify as an issue)?
- What is the state of current knowledge and what is the cause of uncertainty?
- How is uncertainty quantified?
- How should it be handled in the safety case? Is the uncertainty sufficiently bounded? Does it concern details that will be better resolved by investigations from underground investigation, or would additional surface-based investigations significantly reduce the uncertainty?

All answers need to be justified.

It may be noted that these questions are substantially modified compared with the questions on uncertainty considered in model version Laxemar 1.2 /SKB 2006a/. It was decided to substantially modify the uncertainty auditing protocol in order to ensure that the effort spent in addressing uncertainties concerns important issues – rather than details. Details and minor uncertainties are discussed in the various discipline specific modelling reports supporting SDM-Site Laxemar. References to these reports are given in the different discipline sections below. The basic format is taken from the tables concerning key issues used in model stage 2.1 /SKB 2006d/, but the questions asked are modified to better serve as input to an overall assessment of confidence in the site descriptive model.

3.2 Geology

A few major uncertainties remain in the geological model /Wahlgren et al. 2008/ and in the geological DFN model /La Pointe et al. 2008/. They are discussed in the following subsections.

3.2.1 Confidence and adequacy in the subdivision of Rock Domains in the potential repository volume

Improved definitions and descriptions of more homogeneous rock domains may enable reduction of the variance in thermal and mechanical properties.

The subdivision into rock domains is judged to be well established in the local model area, particularly in the potential repository volume, both at the surface and at depth. The uncertainty relates to the location of the rock domain boundaries at depth between the boreholes, in particular for the boundary between RSMM01 and RSMA01, since there is no sharp contact between the Ävrö granite (RSMA01) and the Ävrö quartz monzodiorite (RSMM01), including the appearance of diorite/gabbro that also characterizes RSMM01. The uncertainty in the rock domain model relates to a certain degree to the orientation, but in particular to the spatial distribution of subordinate rock types, i.e. fine-grained granite, pegmatite and fine-grained diorite-gabbro (composite intrusions) and dolerites (including possible existence of additional dykes).

Outside the local model area i.e. in the regional model, the uncertainty is high in respect of both to the existence and geometry of rock domains, since only reconnaissance surface data and no subsurface information are available. It might be possible to create a new domain division with a domain focused on diorite-gabbro. However, the three-dimensional geometry of such a domain would be highly complex and would anyway not be of importance for repository performance or design.

Uncertainties in geometrical boundaries between RSMM01 and RSMA01 are estimated to lie within ±100 m of the modelled boundary, whereas the boundary between RSMM01 and RSMD01 is more well defined /Wahlgren et al. 2008/. The orientation of subordinate rock types has been evaluated by use of the orientation of rock contacts in the drill cores (Boremap data). There is large uncertainty in the distribution and size of gabbro bodies within the RSMM01 domain, but this is covered by the uncertainties in assigned properties included in property tables provided. The uncertainty in the rock domain model in the regional model volume is not quantified. There is also an uncertainty in the determined rock type proportions. This uncertainty is especially high in rock domain RSMM01 but low in RSMD01.

A verification of the uncertainty in the location of rock domain boundaries could be made by comparing prediction and outcome from drilling additional cored boreholes, but a more detailed verification could anyway be made during underground excavation. The spatial distribution of subordinate rock types is taken care of in the geological simulation carried out in connection with the thermal modelling/simulation. Any remaining uncertainties will have to be resolved and managed during potential underground excavation and construction phase.

3.2.2 Alteration of intact rock

Alteration of intact rock possibly affects the mechanical and thermal properties by lower density, higher porosity and reduced strength. Oxidised rock often has reduced mechanical strength.

Oxidation is present in all three rock domains varying between 10 and 25% by volume. The uncertainty relates to the spatial distribution and what is the effect on e.g. thermal and rock mechanical properties between what is classified as fresh, faint, weak, medium and strong alteration (based only on qualitative inspection of the drill core during the mapping). The effect may be in different directions, e.g. strong alteration may imply higher thermal conductivity but lower mechanical strength. It should be noted that "red staining" is usually related to fracturing, whereas saussuritization is not. The latter also affects rock portions unaffected by fracturing. Mapping is done by inspection of the drill core and there is a risk of misinterpreting altered rock as intact rock.

The uncertainty is not quantified, although its importance for the thermal and rock mechanics properties is assessed by the rock mechanics and thermal modelling teams.

Uncertainty could be reduced by using data from the mapping of the drill cores relating to type, extent, and intensity of alteration in the "intact rock" between deformation zones. The uncertainty in the percentage of the altered volumes is still difficult to quantify but is managed appropriately by making conservative assumptions in the rock mechanics and thermal property assignment.

3.2.3 Occurrence, geometry, character and properties of deformation zones, with trace length > 3 km, inside the potential repository volume

The location and size of suitable deposition volumes need to be defined for layout studies and for Safety assessment. The number of deformation zones and their trace lengths are important, but their absolute positions are not considered critical since only zones with trace lengths larger than 3,000 m are really layout determining since only those require a respect distance. All deformation zones of all sizes are important for the site groundwater flow modelling and associated chemistry matching.

Overall there is high confidence in the existence and location of the larger, layout-determining deformation zones, but due to heterogeneity, there is relatively high uncertainty in their character and physical properties. The length versus thickness relationship is weak and the lateral extent of modelled deformation zones not linked to lineaments is particularly uncertain. The uncertainty in the selected threshold thickness for deterministic modelling of deformation zones, only identified in isolated boreholes, has an impact on the geological and hydrogeological DFN models. Similarly, this class of deformation zone has a high uncertainty in all properties other than existence.

Uncertainty is quantified by the use of confidence classes and, where appropriate, spans of likely values for individual zone properties. Deformation zone properties have in part to be based on ensemble statistics from groupings of possible deformation zones inferred to have similar characteristics.

3.2.4 Occurrence of sub-horizontal zones inside the potential repository volume

As already noted in the previous section, it is important to be able to identify deformation zones, especially if they have an area corresponding to a trace length longer than 3 km. This also applies to sub-horizontal zones.

It is not a straightforward matter to identify the lateral extent of this type of deformation zone since often they do not have clearly identifiable intercepts with the ground surface. In addition, if such deformation zones are segmented and later offset by movements along steeply dipping deformation zones, which is considered highly likely, then the interpretation and estimation of their effective extent and 'size' is extremely difficult and consequently highly uncertain. It is noteworthy that although the Äspö HRL, CLAB and OKG underground facilities lie to the east of the regional Äspö shear zone, in a slightly different tectonic regime, no major gently dipping deformation zone has been identified in these underground facilities, including the Äspö spiral access ramp and shafts down to c. –450 m elevation.

There are some seismic indications of gently dipping features in the target repository volume but these are not established as major deformation zones. Most of these gently dipping reflectors lie well below the level of interest for the potential repository. The implications of "reflector M1" that does lie in the elevation range of interest, being a potential gently dipping deformation zone in the south-central part of the focused area has been assessed, including exploration of alternative interpretations of the data. It is generally concluded that shallow dipping deformation zones are present in the potential repository volume but no local major or larger zone has been identified. In particular, reflector M1 is interpreted to mark the upper boundary of a thick 'package' of similarly oriented MDZs and mafic intrusions.

The existence of the gently dipping deformation zones is of high confidence. However, at the elevations of interest they are considered to lie within the local minor deformation zone size range.

Due to their limited sizes, there is no need to directly consider gently dipping zones for repository layout, but preparedness for their existence and managing of them if found during excavation is needed.

3.2.5 Minor deformation zones

Minor deformation zones (MDZ) will occur inside the potential repository volume. Since the MDZ population is likely to include structures that are larger than 75 m equivalent radius, they make up the "discriminating features" i.e. zones not allowed to intersect a deposition hole. Furthermore, the MDZ also have potential to affect flow and migration since they are likely associated with increased hydraulic conductivity. The important issue is rather how we can increase our understanding when we encounter MDZ in boreholes. The problem is to be able to distinguish between large fractures, MDZs and larger zones in cores. Do we have enough representative data to make such a decision?

The size distribution of sub-horizontal MDZ is taken from outcrop fractures. Lineaments, if assumed to represent deformation zones, are modelled as vertically dipping, since there is no dip information in the LIDAR and ground magnetic data. Thus, there is no direct information available on the size of sub-horizontal MDZs.

On the surface, MDZs cannot be distinguished from larger deformation zones except in terms of length. In boreholes, MDZ properties, including thickness, character (brittle, ductile, composite) are identical to those of larger deformation zones. The identification of MDZ in boreholes is based on two factors: 1) can the zone be traced between boreholes or between the surface and a borehole, and 2) on weak apparent thickness/length criteria. The establishment of a reliable trace length versus thickness relationship is extremely difficult and more realistically only weak relationships or tendencies are likely to be identified as has been presented for Laxemar. True thickness and true lengths are needed to establish a reliable thickness/size relationship in boreholes. Estimation of true thickness requires analysis of the orientation of MDZ sections, which can be very difficult to quantify and highly uncertain. This means that the extent, shape, and orientation of MDZ exposed only in boreholes is very uncertain and very difficult to calculate.

It should also be noted that MDZ properties (conductivity, mechanical stiffness, aperture, etc) are not treated in the geological DFN model, this is left to downstream model users.

The MDZ are modelled statistically as part of the geological and hydrogeological DFN models. However, the uncertainty in the size distribution for the MDZ is large. Alternative size models based on outcrop data are instead used to bound uncertainty, and are carried through DFN verification and uncertainty analyses. The uncertainty in size of sub-horizontal MDZ is not explicitly treated since it is difficult to assess using only surface based data. The identification of MDZ in boreholes is controlled by BIPS/Boremap/Extended Single Hole Interpretation protocols. The limits (thickness) of MDZ in cored boreholes are delineated using 'expert judgment'; there are no objective controls on uncertainty. The length/thickness correlation is based solely on deterministic deformation zones, and may not be correct for MDZ due to insufficient data. Consequently, there exists a risk that a structure observed in a cored borehole and classified as an MDZ may in fact represent a deformation zone with a length > 1,000 m. On the other hand, the possibility exists that some of the deterministically modelled deformation zones that are based solely on a single intercepts in boreholes, may in fact represent structures smaller than the fixed 1,000 m size (representing the designated cut-off in size between deterministic deformation zones and MDZ) assigned to deterministic deformation zones interpreted from singular borehole intercepts with a true thickness of 10 m or more.

The uncertainty surrounding MDZ is quite large and is nearly impossible to address without additional data that can only be obtained during underground construction (tunnels or large-diameter shafts), potentially combined with additional geophysics (specifically 3D seismic reflection data similar to that gathered for oil reservoir assessment), and additional surface mapping efforts at larger (10 m–1,000 m) scales. Nevertheless, it is believed that the uncertainty here is contained inside the general size-intensity uncertainty of the Geological DFN and its various alternative models. We will never be able to predict the locations and geometries of MDZ in an absolute sense, but we have the necessary tools to do the work stochastically.

Specific criteria would need to be developed for the identification of MDZ structures in boreholes, canister holes, and on tunnel walls in case this is judged necessary. MDZs need to be investigated at more than one point location before better estimates of their sizes can be made. This is really only possible during the initial tunnelling and site construction phases.

3.2.6 Geological DFN model inside the potential repository volume

Improved confidence in the DFN model is needed to enhance understanding of the investigated site. The geological DFN model is primarily used for assessing the degree of utilisation (in repository engineering) and the probability of mechanical damage due to shearing (in safety assessment). Elements of the geological DFN are utilized by numerous downstream modelling teams including the hydrogeological DFN and the rock mechanics assessment of rock mass properties.

Details of the geological DFN model are provided by /La Pointe et al. 2008/. The size of large fractures and MDZ is constrained by the lineaments based on interpretation of high-resolution ground magnetic and LIDAR data. Strike orientation of these features (for classification of size by set) is fairly certain, but information on the dip orientation of MDZ-scale structures is weak, since data are only really available from MDZ intercepts in cored boreholes. The current knowledge of the size and shape of sub-horizontal fractures is weak. The only available data come from surface outcrops;

the abundance of borehole data is not helpful in this particular case. There is missing information on sizes in the range 10 m to ~ 100 m. Lineament maps only cover down to ~ 100 m in length (LIDAR/ Ground Magnetics) and outcrops are too small. The resolution in geophysics is not sufficient to address this.

Size is the single largest uncertainty in the geological DFN model, whereas orientation, intensity, and the spatial model are all well-treated and well-constrained. The size of sub-horizontal fractures is most uncertain. The uncertainty in size is quantified through uncertainty analysis, which produces ratios of P_{32} for various size-intensity model alternatives to the established based case model, and by a verification case ranking of alternative models. Uncertainty in fracture shape or morphology is not addressed by the geological DFN model.

Analysis of tunnel and excavation data during construction may add to the understanding of the fracture size. Additional studies could be useful (larger-scale surface mapping, vertical excavation trenches), but these are very expensive and time consuming. Therefore the initial site construction would be the best opportunity to address this issue. At the current stage the uncertainty is judged sufficiently bounded by the range of alternative models presented.

3.3 Rock mechanics

A few major uncertainties remain in the rock mechanics model /Hakami et al. 2008/. They are discussed in the following subsections.

3.3.1 *In situ* state of stress

Understanding rock stresses is important for design of the repository in order to mitigate potential spalling and other stability problems and for the long term safety assessment of THM related issues, such as thermally induced spalling.

There is a good understanding of major horizontal stress orientation, being NW-SE, whereas the stress magnitudes, which are expected to be fairly low compared to typical situations in the Fennoscandian shield, are more uncertain. The main reason for uncertainty is the low spatial coverage from direct measurements. One component of uncertainty also stems from the evaluation of the primary data (spread and potential bias in the data). However, no indirect observations in the deep boreholes indicate high stress conditions and there are comparative data and experience at depth from Äspö HRL. This means that there is very high confidence in the upper stress limit.

The uncertainty is quantified by assessing the quality of the data and by stress modelling. It is given as a span for the mean stress. Additional measurements underground (in shorter boreholes) are expected to decrease the uncertainty in the results. The uncertainty in the stress magnitude will also be reduced when the construction starts and there is a possibility to measure deformations and back analyse the stresses.

3.3.2 Intact rock mechanical properties

The intact rock mechanical properties are important for design of the repository and for assessment of thermally induced spalling in the deposition hole.

The intact rock strength depends on the rock type and there is also a fairly large expected variation in strength, due to mineralogical variation/grain size distribution, within each rock type. The uncertainty in the proportions of different rock types in the rock domains RSM01A and RSM01M is fairly large, and thus the total expected strength distribution, on rock domain basis, is also fairly uncertain.

A model for intact rock properties is given for each rock type, but not for each domain. The uncertainty in each parameter is described by a span in the value of the mean of the distribution.

The uncertainty can be dealt with statistically and is bounded.. The uncertainty in the detailed distribution of rock types is expected to be reduced during construction.

3.4 Thermal model

A few major uncertainties remain in the thermal model /Sundberg et al. 2008/. They are discussed in the following subsections.

3.4.1 Spatial variability of rock of low conductivity

Apart from the uncertainties in the lower tails of the thermal conductivity distributions, there are of course uncertainties related to the overall distribution of thermal conductivity for each rock domain, but these are much less critical for repository design. A maximum temperature criterion on the bentonite means that a larger repository is required if the rock is of low conductivity. This means that in order to design the repository, the lower tail of the thermal conductivity distribution must be described adequately. Thermal conductivity at Laxemar is generally low. Small uncertainties in the lower tail of the thermal conductivity distributions will have a significant impact on canister spacing. The more certain the model, the more efficient the design can be.

There are uncertainties in the lower percentiles of the modelled thermal conductivity distributions for rock domains RSMA01, RSMM01 and RSMD01 for the following reasons. There is uncertainty in the thermal conductivity models for different thermal rock classes (TRC) both as regards the distribution models and the spatial correlation models. For example, it is not clear whether the spatial correlation models used are applicable to the whole thermal conductivity distribution. There are also uncertainties in the reproduction of typical size distributions and anisotropy for the bodies of subordinate rock types in the geological simulations, which is related to the present ability to model heterogeneity. This may be mainly significant for the lower tail of the thermal conductivity distribution for TRC 102 in domain RSMD01. The reason is that the critical rock types in domain RSMD01 are present in relatively small proportions and as relatively small bodies. However, the influence on the lower tail at the 5 m scale in rock domain RSMD01 is limited due to upscaling effects. The potential anisotropy in the geometry of subordinate rocks in domains RSMA01 and RSMM01 has not been modelled due to lack of information but this anisotropy is relatively small.

There are also limitations in the ability to reproduce variability in rock type proportions in the geological simulations. There are uncertainties in the estimated rock type (TRC) proportions in each rock domain. The impact of this on low percentiles is however small although some impact on domain RSMD01 can be inferred. Finally, the simulation scale (2 m) used in the lithological simulations causes discretization errors for rock types that occur at sizes smaller than the simulation scale. This has an impact on the thermal model for domain RSMD01 only, due to the presence of small bodies of fine-grained diorite-gabbro. However, the impact at larger scales is small.

The overall uncertainties resulting from these different sources or error have not been quantified. However, uncertainties related to TRC proportions have been quantified and are small.

The thermal TRC models are judged to slightly underestimate the lower tail of the thermal conductivity distribution. An improved understanding of the distribution, correlation and anisotropy of different TRCs, would be better resolved from underground investigations.

3.4.2 Geometrical bounds on different thermal subdomains

Clear geometrical bounds on subdomains with different thermal properties, would enhance the current the ability to further optimize canister spacing in different subdomains in domain RSMM01 and RSMA01. Without geometrical boundaries this only can be made using conservatively low values of the thermal conductivity, resulting in an unnecessarily high designed distance between deposition holes.

Thermal subdomains are identified and modelled, but are not geometrically bounded. Volumes for the different subdomains are estimated from occurrences in the boreholes. The occurrences of thermal subdomains will be better characterized and bounded from underground investigations.

3.4.3 Anisotropy in thermal conductivity

Anisotropy in thermal conductivity, as indicated by field measurements, affects the thermal design, but the effect is small.

It is clearly established that thermal anisotropy exists and that it is linked to foliation. The mean in anisotropy factor is judged to be quite reliable, but the spatial variability of the anisotropy is uncertain, mainly due to sparse data. The current knowledge of the orientation of the foliation and judgement of the anisotropy factor already now allows proper handling in the design of the repository.

3.4.4 *In situ* temperature

In situ temperature also affects the thermal design.

The quality approved borehole logging data indicate only small variations in temperature at repository depth, but this conclusion is based on limited data from four boreholes.

The uncertainty is judged bounded, and the confidence strengthened by comparison with PFL temperature data in packed-off sections in the temperature-logged boreholes.

3.5 Hydrogeology

Some major uncertainties remain in the hydrogeological model, see /Rhén et al. 2008/ and /Rhén et al. 2009/. They are discussed in the following subsections.

3.5.1 Hydraulic properties of the rock mass (HRD) inside the potential repository volume

The spatial variability of hydraulic properties affects the distribution of flow and, together with the objectives of the specific application, the appropriate approach to upscaling. This affects the modelling of the processes affecting groundwater chemistry. The properties need also to be consistent with the geological and rock mechanics understanding. For safety assessment, this directly affects flow-related retention properties both in the near and far-field as well as buffer and canister stability. The hydraulic properties need also be considered for creating a safe repository design. Furthermore, these properties affect grouting needs and strategies.

There is a fair amount of data from rock domains and the fracture domains FSM_N, FSM_EW007, FSM_NE005, FSM_C and FSM_W), /Rhén et al. 2008/. The investigations have been extensive but also covered a large area (volume) including both the Laxemar local model area and the Simevarp subarea, cf. Chapter 1. As a consequence there are fairly large distances between boreholes even within the focused area and there are limited data to assess spatial distributions of hydraulic properties and to define subvolumes in the form of hydraulic rock domains (HRDs) with different hydraulic properties as well as depth dependencies. One should therefore expect that there can be a considerable variation of the properties within the HRDs in the focused volume. Especially below elevation –650 m the data of the conductive fractures are sparse and the hydrogeological DFN models below that elevation should be considered uncertain.

Outside the local model area there are only a few hydraulic tests east of the Laxemar local model area relevant for calibrating the hydrogeological DFN models. The assessed hydrogeological DFN properties within the regional volume outside the Laxemar local model volume are highly uncertain.

There is a clear depth dependency, shown by the results from different hydraulic tests. There is also a basis for separating the data into different HRDs, but the spatial variation within any rock domain and depth interval is rather high. The division of HRDs based on fracture domains shows a slightly larger separation of properties than using rock domains, as judged from the basic fracture statistics and PFL-f statistics. The sample size for describing the different HRDs is anyway judged adequate. Using the PFL-s (5 m sections) generally the hydraulic rock domain mean hydraulic conductivity for rock outside the deterministic deformation zones for different depth intervals can be considered different at the 95% confidence level. The PFL-f statistics become more uncertain at greater depth as there are few boreholes within a domain and not all of them are drilled to greater depths. An important factor is also that the frequency of PFL-f intercepts becomes low at the greatest depths, which together with limited available borehole lengths at great depths causes great uncertainties in intensities and especially in the deepest of the depth zones used (> –150 m, –150 to –400 m, –400 to –650 m, < –650 m).

There are several interference tests available but generally with very few observation sections. In a few interference tests, there have been a substantial number of observation sections but limited pumping time. Unfortunately there exists no interference tests with longer duration and with more or less all boreholes monitored within the influence radius of the test, causing great uncertainties in some areas concerning possibly connections between deformation zones and hydraulic responses in what is considered as possibly “good rock”.

The uncertainty is quantified by statistical analysis of the data and by numerical modelling using the hydrogeological DFN /Rhén et al. 2008/. Hydrogeological DFN models with three different types of transmissivity distributions have been developed, but only the transmissivity model that is considered to be the conceptually most reasonable based on all open fractures has been tested in the regional groundwater flow modelling /Rhen et al. 2009/. The current hydrogeological DFN model is judged reasonable since it is calibrated against all available data.

The developed hydrogeological DFN models show anisotropic conditions that vary mainly by depth (horizontal and WNW conductive fractures dominate near surface and by depth the intensity of the horizontal set decreases). The magnitude of the ratio between maximum and minimum permeability estimated from block modelling of the hydrogeological DFN models is considerably less than observed in the nearby Äspö HRL and possibly suggests that the anisotropy within the Laxemar local model volume is underestimated. Still, the main directions for maximum and minimum permeability in the horizontal plane are consistent, and give appropriate indications of how the anisotropy changes with depth.

The calibration of the hydrogeological DFN model considers the connected conductive fractures on a large scale, since it is based on the PFL logging results established from long-duration pumping. The hydraulic field tests of different types indicate that there probably exists local conductive fracture networks (compartmentalised network) that are not, or at least badly, connected to the “global hydraulically connected fracture system” tested by PFL logging. The role of compartmentalised networks, if any, needs to be addressed in the safety assessment.

It is judged that the uncertainties are bounded. Estimates of porous medium conductivties in the 20 to 100 m scale, down to potential repository depth and based on simulations with the current hydrogeological DFN model, are judged to be within a factor of 2–3 of the real values, but details of the upscaling are still uncertain /Rhen et al. 2009/. It is noted that the true inflow distribution can only be fully known during construction and as assessed by pilot holes and probe holes during tunnel excavation.

3.5.2 Hydraulic properties of HCDs, their spatial variability, anisotropy and scaling inside the target volume

The hydraulic properties of hydraulic conductor domains HCDs (the HCDs essentially coincide with the deterministically modelled deformation zones), their spatial variability, anisotropy and scaling inside the target volume affect the site-scale groundwater flow modelling. The properties are of some importance for engineering, since they affect the extent of grouting needed and also affect the drawdown. The properties are of little importance for safety assessment, since the transport resistance in large deformation zones is anyway considered to be very low. However, the hydraulics of the deformation zones is potentially important for the evolution of groundwater composition.

Within the focused volume several of the deformation zones (HCD) are intersected by one or more boreholes /see Rhén et al. 2008, 2009/. It was observed that there is a large variability of hydraulic properties within some of the deformation zones, indicating that heterogeneity is likely to be large within the HCDs. As a consequence, most assessments of hydraulic properties for an individual HCD in the present model must be considered very uncertain, though the general depth trends of mean transmissivity seem to be justified by the tests made with the regional groundwater flow model. The assessed heterogeneity of the transmissivity used in the modelling (as a large-scale variation) has support in data but must still be considered uncertain. One should also observe that below –150 m elevation the numbers of borehole intercepts with deformation zones are more limited compared with above and, particularly within the Laxemar local model volume with a more limited data set, the assessment of trend functions of the transmissivity with depth for the HCDs is uncertain (but the uncertainty is quantified).

Outside the local model area there are only hydraulic tests available east thereof that provide data for estimating properties of HCDs. The assessed properties within the regional volume outside the Laxemar local model volume are obviously highly uncertain.

The existence of dolerite dykes and their possible function as hydraulic barriers has been proven. However, it is not known if the most obvious example; ZSMNS001, acts as a barrier along its whole extent. The other dolerite dykes proven to exist seem to be possible hydraulic barriers, but it is considered very uncertain if they are barriers over longer distances. The thicknesses observed in boreholes are limited and may indicate that one should not expect a barrier effect of similar characters as ZSMNS001. The geological description also indicate that possibly other dolerite dykes than observed in boreholes may exist, but these are likely to be relatively thin and possibly just acts as local hydraulic barriers.

The importance for safety assessment has been assessed in the SDM. Tests carried out suggest that with our current conceptualisation, regardless on how we model the zones they will contribute very little to radionuclide retention. In simulating groundwater chemistry, it is believed that the general characteristics of the HCDs are relevant since the water samples generally represent the highly transmissive zones. However, for the detailed design of the access there may be need for more data from the zones that may be traversed.

3.5.3 Hydraulic boundary conditions at the regional scale

The regional hydraulic description is important for the modelling and integration with hydrogeochemistry and to provide reasonable boundary conditions for the flow within the repository volume. However, for safety assessment bounding assumptions could always be made if the adequacy of the regional modelling is in doubt.

Flow modelling at a very large scale /Holmén 2008/ indicates that applying no flow boundary conditions for the vertical and bottom boundaries in a reduced regional model, compared to a larger regional model extending to the western boundary of the catchment, overestimates the length of flow paths by a factor of 1.1–1.2, overestimates breakthrough time of flow paths by a factor of 1.3–2.5 and underestimates the specific flow by a factor of 0.7–0.9 in the repository volume. The simulation with the large model also demonstrates that the weakly developed surface water divide is not a groundwater divide for the groundwater flow at large depths. None of these differences are of any importance. The uncertainties are small compared with other uncertainties and will not affect the groundwater flow regimes of importance in the safety assessment.

3.5.4 Consistency between stress magnitudes, stress orientations and observed anisotropy of hydraulic conductivity

Assessing consistency between stress magnitudes, stress orientations and the observed anisotropy of hydraulic conductivity would enhance understanding. Current observations from Laxemar suggest that more transmissive fractures are more common parallel to the main principal stress (i.e. in NW). There is also a very weak trend between increasing normal stress and decreasing fracture transmissivity, but the scatter is large. In summary, there does not appear to be sufficient evidence from analyses between transmissivity and stress, to support the notion that the magnitude of the flow along the fractures at Laxemar is solely controlled by the current normal stress acting on the fracture. This should not be surprising because the majority of the fractures formed more than 1 billion years ago and the current stress state has only been active for the past 12 million years. It is more likely that the transmissivity values are controlled by fracture roughness, open channels within the fracture and fracture infilling material. The lack of a quantified correlation is of no concern. Given the large scatter of transmissivity data it is necessary to build the hydrogeological model on the observed hydraulic data rather than on weak trends and hypotheses.

3.6 Hydrogeochemistry

There are still remaining uncertainties in the hydrogeochemical models, see /Laaksoharju et al. 2009/. These are discussed in the following subsections.

3.6.1 Current distribution of water composition

Knowledge of the current distribution of water composition is essential for site understanding and conceptual modelling since it indicates the age and origin of the groundwater. The composition (e.g. Eh, pH, TDS etc) is of key importance to safety assessment since it affects the stability of the buffer and the canister as well as the migration properties of radionuclides.

The water composition and the water types are well known and characterized. There is an adequate density of category 2–4 water samples, although most of them are category 3. This implies that the major water types, e.g. meteoric (including cold and temperate origins), deep saline and brackish marine waters of Littorina types can be identified. The marine water component is much less evident at Laxemar than at Simpevarp. However, the precise location of the different waters is more uncertain, especially inside hydraulic rock domain HRD_EW007, where it appears that the sampling has caused mixing of waters from different locations, usually near surface waters. This is in agreement with the hydrogeological understanding. Present understanding suggests that past hypotheses of deep penetration of recent meteoric water are not valid.

Analytical errors are understood and of minor importance for major elements and stable isotopes. The categorisation is judged to be robust. In hydraulic domain HRD_C the uncertainties are judged moderate, but in more conductive hydraulic domains, e.g. HRD_EW007, samples may not fully represent the depth interval from where they were obtained. This also implies a need for caution when calibrating the hydrogeological model to these data. There are few data north of deformation zone EW007.

The system is fairly well understood and the observations of mixing can be well explained by the hydrogeology. At least from this perspective the uncertainties are sufficiently bounded. No further surface based investigations are judged necessary, but would of course always add more insight. Underground investigations can confirm the present understanding. Additional insight will be obtained from comparison with other sites (Forsmark; Olkiluoto) and monitoring/time series programme data.

Generally, the upper 150 to 200 m of bedrock include a mixture of young recharging groundwaters that are fairly well characterized with corresponding low uncertainties. At greater depths (particularly to about 500 m depth) the main uncertainties are associated with low quality hydrochemical data (e.g. short-circuiting problems) and a lack of spatially distributed hydrochemical data, both laterally (particularly in the case of the porewater), and at depths greater than 700 m (particularly in the case of the fracture groundwater), such that a large degree of expert judgement has been used to extrapolate the hydrochemistry. However, these uncertainties were reduced with the realisation that at depths greater than 700 m, the fracture groundwater and porewater chemistries increase fairly uniformly in salinity and laterally appear to be quite homogeneous.

3.6.2 Overall understanding of groundwater evolution

Understanding the processes involved in groundwater evolution (e.g. palaeo aspects, transport and water rock interactions) is essential for predicting the future evolution of groundwater composition, for safety assessment key aspects include Eh, pH and salinity at repository depth. The redox and alkalinity buffering capacity of the bedrock is shown in SR-Can to be of key importance for groundwater composition and future changes due to e.g. potential intrusion of oxygenated water. The concentration of divalent cations is critical for buffer stability and sulphide for canister stability.

As further discussed by /Laaksoharju et al. 2009/ the main processes determining the overall geochemical evolution of the Laxemar- Simpevarp area groundwater systems are mixing and reaction processes. Mixing has taken place between different types of waters (end members) over time, making the discrimination of the main influences complex. In addition to mixing processes and the effects of their superimposition, different chemical reactions have taken place in the system due to the interaction between groundwaters, minerals and/or microbial activity (e.g. aluminosilicate and carbonate dissolution/precipitation, cation exchange, gypsum dissolution, main redox reactions, etc). Some elements and stable isotopes (Cl or $\delta^{18}O$) behave conservatively in groundwater whereas others are affected by chemical reactions to differing degrees, especially the redox-sensitive elements.

The overburden (near surface/shallow system down to 250 m depth) is dominated by water-rock interactions between the recharging meteoric water and the soil, till sediments and bedrock. Weathering and potential calcite dissolution under acidic conditions in infiltrating water in the near-surface bedrock environment is promoted and controlled by biogenic input of carbon dioxide. This gives rise to pH values usually above 7, calcium concentrations mostly between 50 and 200 mg/L, and bicarbonate concentrations up to 600 mg/L in the near surface waters (down to about 20 m depth). Concentrations then decrease to very low values at great depths. However, bicarbonate locally reaches values up to 100 to 200 mg/L in some of the brackish glacial groundwaters hosted in the upper approximately 500 m.

In the intermediate to deep bedrock system (250–1,200 m depth), groundwater mixing processes usually dominate and the effects of reactions between the groundwaters and the minerals in the fracture fillings are superimposed on mixing signatures. There are traces of downward advective movement of groundwater to maximum depths of about 1,200 m. Below this depth, low flow and stagnant conditions prevail and solute transport is increasingly diffusion controlled.

It is envisaged that prior to the last glaciation there existed a concentration profile extending from dilute meteoric waters in the near surface of the bedrock to highly saline, brine-type compositions at about 1,000 m depth and deeper. These highly saline groundwaters, as today, indicate high contents of chloride, calcium, sodium, potassium and sulphate, low values of magnesium and bicarbonate, a more or less constant Ca/Sr ratio, and enriched $\delta^{18}O$ signatures. Then, with the onset of the last glaciation/deglaciation, the input of dilute waters (meteoric or glacial meltwaters) over time, modifies the pre-existing concentration profile from the surface to depth. The cold climate signature will deplete the $\delta^{18}O$ signature and waters with low pCO_2 and high pH values will enter the system. These different mixtures will promote calcite precipitation and cation exchange due to dilution, i.e. lead to a decrease of calcium and increase of sodium in the groundwaters.

The next major event is the input of a marine component (Littorina Sea) into the bedrock following several diagenetic processes during its passage through marine sediments. This water will then pass into the bedrock down to different depths depending on the coastal proximity (more in Simpevarp and Äspö than in Laxemar), on the rock hydraulic properties, and on the salinity of the pre-existing groundwaters (i.e. glacial to brackish glacial waters with depleted $\delta^{18}O$ signatures). Eventually, the higher density of these Littorina waters will displace the previous dilute waters and the result will be groundwaters more enriched in $\delta^{18}O$, magnesium, sulphate, bicarbonate and silica. Calcite will precipitate and the cation exchange will produce the decrease of sodium and the increase of calcium in the waters. Finally, the continuous input of meteoric waters will produce a superimposed dilution profile which will be more marked in the recharge areas such as in Laxemar. Modelled groundwater mineral equilibrium features are supported by mineralogical and microbial observations. The pH buffering capacity in Laxemar at depths greater than 100 m appears to be controlled by the carbonate system, and modelling indicates that this water is in equilibrium with calcite.

According to data analyses and modelling of the redox system, reducing conditions currently prevail at depths greater than about 20 m. Most of the Eh values determined in the Laxemar subarea are in the brackish glacial groundwaters at depths between 100 and 700 m. The iron and the sulphur systems are very important for the control of redox processes in the Laxemar-Simpevarp area groundwaters. Iron (II) and (III) minerals are widely distributed in the studied systems and the presence of iron reducing bacteria (IRB) has been documented. However, the bioenergetic calculations and the redox modelling approach performed from a partial equilibrium assumption for iron reduction and sulphate reduction processes indicate that sulphate reduction is the thermodynamically favoured process. All the data indicate that the system has retained a significant reducing capacity to the present day. The key role played by sulphate reducing bacteria (SRB) in the stabilisation of these reducing conditions is supported by several lines of evidence, including the microbially influenced $\delta^{34}S$ values found in pyrites from the Laxemar-Simpevarp area at shallow to intermediate depths, and the low $\delta^{13}C$ values found in calcites from fracture fillings from the same area. The importance of the SRB at great depths (> 700 m) in the Laxemar subarea remains unclear.

3.6.3 Detailed groundwater composition at repository depth

Detailed and accurate data on the current groundwater composition at repository depth are needed as input to geochemical models e.g. equilibrium codes that in turn provide input to the evaluation in the safety assessment of solubility and migration properties for current day conditions.

There were too few samples from depth available for the version 1.2 Laxemar site descriptive model. Now there are better quality samples from repository depth. This means that the uncertainties are relatively well bounded, but coupled modelling and time series data may further improve the description of the spatial variability. The monitoring programme has already provided such additional information.

The uncertainties are sufficiently well bounded due to the strict criteria used in the sample categorisation. The additional borehole investigations after version Laxemar1.2, have improved the possibilities for better sample quality from the repository depth and support the spatial variability description of the site.

3.6.4 Selection of end-member groundwater chemistries

Uncertainty in selection of end-member groundwater chemistries (including intact rock matrix porewater chemistry) affects the understanding of groundwater mixing processes and thereby the integration with hydrogeology.

Mixing models based on water conservative elements have reduced the uncertainties in the mixing modelling. A statistical approach is used where a large number of end-member compositions are varied within an interval and tested as to how well they describe the measured composition /Gimeno et al. 2008/. The causes of uncertainties may include unknown end-member compositions and ages (several meteoric/glacial waters with different ages). Littorina waters influenced by fast reactions may affect the mixing calculations. Uncertainties are also associated with effects from porewater on the measured groundwater compositions.

The uncertainty is given as a probability range. The end-member selection is also tested in the hydrogeological modelling and the selection is compared with the selection used in hydrogeochemistry.

The uncertainties are sufficiently bounded to the postglacial and present day scenarios. No complementary investigations are considered necessary.

3.6.5 High sulphide content in monitoring data

Sulphide content is a key issue in safety assessment. Roughly, sulphide contents above 10^{-5} M can have potential detrimental impacts on canister corrosion if combined with buffer density losses.

Old data from Äspö and KLX01 may be incorrect due to analytical uncertainties, but more likely from pumping effects (new sulphide data are available) and sampling difficulties. Analytical uncertainties are assessed by using different laboratories for comparisons. It may be possible in the future to argue for an upper boundary on current sulphide content.

The sulphide concentration in the groundwater is controlled by ferrous iron and the saturation index for amorphous FeS. The future evolution is still uncertain – i.e. what is the impact of sulphate reducing bacteria together with methane concentrations. Equilibrium calculations of these high sulphide waters with respect to ferrous iron monosulphides are described by /Gimeno et al. 2008/. Further borehole investigation would increase the possibilities for more sulphide data from repository depth together with gas sampling. Time series from the ongoing monitoring programme are judged likely to allow a final assessment of what is the undisturbed sulphide concentration as well as how the sulphide content may change due to future intrusion of marine water.

3.6.6 Conservatism of assumed conservative tracers (^{2}H and ^{18}O)

Some conservative tracers (^{2}H and ^{18}O) that are considered to remain unchanged by their environment, may in fact be reactive over a long time period due to, e.g. water-rock interactions. However, over the simulation time (usually in the order of 10,000 years) and conditions studied at Laxemar, these tracers are non-reactive and such deviations are not observed. Therefore ^{2}H and ^{18}O are considered reliable and are used for the hydrogeological modelling of the post-glacial groundwater.

The uncertainties are sufficiently well bounded and quantified. However, they need to be considered as a potential reason for deviations between observed groundwater compositions and results from the hydrogeological simulations of the past evolution. Further borehole investigations would not decrease the uncertainties and no complementary investigations are necessary.

3.6.7 Porewater composition in the bedrock at depth

The porewater composition in the bedrock at depth is important for overall understanding and coupling to hydrogeology including an understanding of the effects of palaeo-events such as glaciations and interglaciations. It acts as an archive of past fracture groundwater compositions and therefore of the palaeohydrogelogical evolution of a site. It also affects the stability of engineered barriers, may influence the diffusion rates of solute transport and, in relation to the evolution of the flowing groundwater composition, demonstrates the existence of a connected matrix porosity

There are 57 porewater samples from three boreholes (KLX03, KLX08 and KLX17A) and this provides adequate coverage of the vertical distribution of porewater composition at the site, but not laterally. Porewater is of dilute $Na\text{-}HCO_3$ chemical type with Cl contents of less than 1,000 mg/kg down to about 430 m depth. In one borehole, KLX08, such conditions extend to 650 m depth. In this upper part of the bedrock the isotope signature ranges from present day infiltration to old meteoric water representing cool to temperate past climatic conditions. Dilute porewaters with depleted oxygen-18 signatures ($\delta^{18}O < -13‰$) clearly indicating cold- climate (possibly glacial) infiltration are found at depths of about 300–500 m. At about repository depth, the salinity increases to about 5,000–7,600 mg/L Cl and the chemical type changes to a $Na\text{-}Ca\text{-}SO_4$ porewater with enhanced sulphate concentrations. In borehole KLX08 this change occurs at 660–750 m depth and displays a larger variability in Cl contents from 2,700–6,000 mg/kg. Towards greater depth, the isotope signatures for the deep and saline waters are generally enriched, although some variations can be observed, for example, Na-Ca-Cl type of porewater with a salinity of 5,100 and 8,200 mg/kg is found at the greatest depths in boreholes KLX03 and KLX08 respectively, and the isotopes are still enriched.

The porewaters are generally in equilibrium with fracture water down to about 360 m depth. In boreholes KLX03 and KLX17A, between 360 m and 430 m, porewater and fracture groundwater have almost identical depleted $\delta^{18}O$ values and suggest a steady-state situation, whereas the Cl content of the porewater is only half that of the fracture groundwater indicating a transient state. In borehole KLX08, a similar situation is established down to at least 500 m. Towards greater depth, fracture groundwater data are limited to one single analysis in borehole KLX03 at about 920 m depth where a transient state exists between porewater and fracture groundwater.

Several uncertainties may affect the interpretation. Changes in the fracture groundwater can, by diffusion, change the isotope composition in the porewater but may leave the porewater chloride content unchanged, as indicated for the depth interval between 360–430 m. Changing climate events will superimpose their respective signatures on each other. It is impossible to know, but can be assessed by modelling, whether there is a flowing fracture or not intersecting the borehole, close to a given sampling point. The data set for both porewater and fracture groundwater is limited. Ranges of uncertainty are provided considering these different sources of uncertainty.

The uncertainties are sufficiently managed in the modelling. The observed profiles and differences between porewater and fracture groundwaters are understandable given the distribution of water conductive features and our understanding of the past evolution of groundwater composition. Further measurements (e.g. more fracture profiles) and especially more high-quality fracture groundwater analyses would, however, considerably improve our understanding of the Holocene and Pleistocene evolution of the site, but such improved understanding is not judged needed at this stage of the programme.

3.7 Transport

Despite inherent difficulties in determining transport properties it appears that many of the uncertainties can be appropriately bounded by the hydraulic test data. The remaining uncertainties are discussed by /Crawford and Sidborn 2009/ and in the following subsections.

3.7.1 Effects of connectivity, complexity and channelling on the distribution of flow

In SDM-Site Laxemar the hydrogeological DFN model produced by hydrogeology is used as a basis for transport calculations and subsequent safety assessment. Transport from the repository to the biosphere will occur along strongly channelized flowpaths. Understanding of their properties is essential for the interpretation of measurement data and the correct parameterisation of flow and transport models. Current DFN models do not capture all relevant channelling effects potentially important for radionuclide migration. (Additionally, modelling programmes are not currently capable of modelling all relevant types of channelling).

In deriving the hydrogeological DFN, fractures are implicitly assumed to be either open over their full extent or closed (sealed) over their full extent when DFN models are conditioned on borehole data. This could have the consequence that flow channel frequencies may be underestimated. On the other hand, in a forward modelling perspective this assumption also means that hydrogeological DFN models will exhibit greater hydraulic connectivity and higher flow rates than might be realistic for the site. Flow channels of limited extent have a low probability of borehole intersection meaning that the frequency of conductive features is likely to be underestimated in the hydrogeological DFN modelling. The impact of this depends upon the relative permeability of the fracture pore space surrounding the main flow channels residing in a fracture. For moderate amounts of fracture normal compression, neglecting the impact of fracture filling materials, it is thought the fracture pore space will be sufficiently well connected hydraulically that most flow channels hosting non-negligible flows should be identifiable even if not directly intersected. Furthermore, experience from tunnels does not suggest a higher frequency of inflow points compared with what would be inferred based on all open fractures in boreholes.

Another potential concern is that fractures with transmissivity less than about 10^{-9} m^2/s are censored from the PFL data. This may also lead to underestimation of the flow channel frequency at repository depth.

/Crawford and Sidborn 2009/ handle the impact of some classes of channelling as well as alternative conceptualisations of the matrix diffusion geometry by simulations and scoping calculations. Consequences of other uncertainties are assessed by modelling of alternative cases. The impact of fractures with transmissivities less than 10^{-9} m^2/s is managed by scoping calculations of their impact on overall radionuclide release rates from a potential repository. These calculations indicate give rise to the following conclusions:

- The existence of strongly conductive fracture intersections should not have a significant detrimental influence on the transport resistance (F-factor, see SR-Can /SKB 2006b, Section 9.3.5/) of typical flow paths, provided that the fracture intersections do not form a continuous flow path through the rock volume. Observation of tunnel inflows may give some evidence for or against the existence of such features within the repository volume.
- Uncertainty concerning hydrogeological DFN parameters and the role of channelling phenomena may lead to underestimation of flow channel frequency in the repository volume. However, provided that the fracture transmissivity model is reasonable (approximately correct order of magnitude), the overall F-factors for typical flow paths through the repository volume should not be greatly different.

Overall, this means that the uncertainties in flow related migration properties can be bounded. In order to narrow the bounds, underground characterization data would be needed. The hydrogeological DFN fitting parameters for fractures within the repository volume can only be properly constrained by mapping of flowing or potentially open fractures in tunnels and associated statistics. Surface outcrop statistics are not relevant for properties at repository depth. During underground investigations, the frequencies of flowing fracture in tunnels and investigations of couplings between rock mechanics properties and fracture transmissivities may give clues as to the extent of in-plane flow channelling. This will lead to more reliable models for transport from the repository volume, particularly over the first 5–15 m from canister positions, which may provide the largest part of the transport resistance.

Additional physical mechanisms enhancing solute uptake such as radial diffusion from channels of limited extent and diffusion into stagnant zones with concomitant matrix diffusion may enhance transport retardation substantially. Flow channelling may, therefore possibly have an overall beneficial effect.

Alternative models incorporating these physical processes are studied in SDM-Site. *In situ* data from SWIW (Single Well Injection Withdrawal) tracer tests lend strong qualitative support to the existence of enhanced solute uptake mechanisms of this kind.

3.7.2 Migration properties of the rock matrix

Migration properties of the rock matrix and their scaling to larger areas/volumes are directly important for radionuclide migration. They are also important for understanding groundwater chemistry and for enhancing confidence in the hydrogeological model.

There is currently very good data support for rock matrix formation factors and their spatial variability in the matrix rock from *in situ* resistivity measurements. There is some residual uncertainty concerning the reasons for differences between laboratory and *in situ* studies, although this is small and will not have great impact upon transport. There is no apparent and consistent correlation between formation factor and stress at Laxemar. There are very few data concerning the effective diffusivities of altered rock close to fracture surfaces.

Relatively good site-specific sorption data are now available for most important classes of radionuclides. Remaining uncertainties relate to methodological considerations, small sample numbers, and possible differences between laboratory and *in situ* aqueous chemical environment. Spatial variability is likely to play a subordinate role compared to the overall uncertainty in sorptive properties.

There is now very good consistency between measurements of BET (Brunauer Emmet Teller) surface areas of intact rock and surface areas estimated by extrapolation of data for crushed rock and surface areas measured on large monolithic pieces. Measurement data suggest that there is a less good correlation between BET surface area, CEC (Cation Exchange Capacity), and sorption K_d than hoped for (at least when comparing different rock types). This causes some uncertainty when using BET or CEC as a proxy for upscaling K_d values and evaluating spatial variability.

Generally, there is a low and quantified uncertainty in diffusivity. Sorption uncertainty is quantified – but quite large for many species, partly due to uncertainty in water chemistry and non-equilibrium in the conducted tests. U and Np values for highly reducing conditions are likely underestimated due to difficulties in keeping redox low in the laboratory. There is a possible uncertainty in the distribution of altered rock. However, the importance of this depends on the difference in migration properties between altered and unaltered rock. Data suggest that altered rock implies increased retention – so this uncertainty can be conservatively bounded.

The existence of diffusive exchange over many tens of metres and very long time scales is strongly supported by the signatures of paleohydrogeochemical markers found in the porewater of the rock matrix at the Laxemar site, see Section 3.6.7. Specifically, the fact that sampled matrix porewater many tens of metres distant from the nearest identifiable flowing fracture contains relict groundwater signatures is a strong indication of an essentially unlimited matrix penetration depth. This should be considered to be a separate issue to the actual rate of diffusive exchange, which is less well illuminated by the porewater studies. The matrix porewater studies do not indicate depths of penetration that are inconsistent with the estimated transport properties of the rock.

The uncertainties are judged sufficiently well bounded and also straightforward to propagate into safety assessment. The *in situ* formation factors are likely to underestimate the true values. In order to reduce uncertainty in sorption values, Safety Assessment may need to consider additional experimental data, even if these were not conducted on samples from the site. Furthermore, uncertainty in future water chemistry is handled in Safety Assessment, and is not a direct SDM matter. Additional laboratory sorption measurements may be advisable during the construction phase to further reduce uncertainties. Generally, altered rock exhibits enhanced retention characteristics relative to unaltered rock so that neglecting this will not detrimentally impact radionuclide transport predictions.

3.7.3 Validation of flow-related transport properties

For understanding and confidence it is important to aim at field tests validating the flow-related transport properties. However, as explained by /Crawford and Sidborn 2009/, it is not possible to fully validate migration modelling in the repository volume. SWIW tests provide qualitative support for a quite large diffusive component, although not necessarily in the matrix. Overall, the findings are consistent with the migration conceptual model but are not proof of the validity of that model.

3.8 Near-surface

A few uncertainties remain in the near-surface models /Söderbäck and Lindborg 2009/. They are discussed in the following.

3.8.1 Limited data to support the model of Quaternary deposits

The properties and geometry of the Quaternary deposits are bases for flow and transport models. However, there is only information from a few points in the deeper layers and the spatial extrapolations are hence uncertain. No quantification is made, mean values are used, but it is judged that uncertainties will have limited to high impact on models using these data.

Furthermore, the field investigations of the Quaternary deposits are limited to the central part of investigation area. This lack of data is managed by using remote sensing studies and/or extrapolation. The uncertainties are not quantified, but discussed and the basis for the model is described.

3.8.2 Few or imprecise data for the hydrology and near-surface hydrogeology models

There is poor precision in surface discharge data from stations with natural cross-sections. These data are used in the calibration of flow models, essential for ecosystem and chemical mass balance modelling. The data error is on the order of 25% because of poor measurements. The uncertainty is addressed by comparison with other stations. Data judged to have large errors are excluded.

Wind speeds from the meteorological stations appear to be underestimated. This needs to be considered when using these data for calculation of potential evapotranspiration and descriptions of meteorological conditions.

There are few groundwater monitoring wells in high-altitude areas. This affects the conceptual model of infiltration and groundwater recharge processes since the data are used as input, or to constrain, the numerical flow models and hydrochemical modelling. This leads to relatively poor knowledge of hydraulic and hydrochemical conditions in high-altitude areas. The model is calibrated against discharge and groundwater heads in low-altitude areas.

There is also a lack of information on the hydraulic properties of the near-surface rock. This is a key parameter for hydrological modelling as it affects drawdown, predictions of inflow and grouting requirements in shafts and the access tunnel, and affects the modelled locations of discharge areas of deep groundwater. The available data are mainly from outcrops, excavations and soil-tube drilling. No rock cores are available from upper the part of the bedrock and there are no specific hydraulic test data from the upper part of percussion boreholes. The uncertainty is not quantified, but managed by sensitivity analysis in the MIKE SHE modelling considering the effects on water balances and water flows between the soil and the superficial rock.

3.8.3 Water chemistry in Quaternary deposits and near-surface bedrock below lakes and sea bays

There are only limited data on water chemistry in Quaternary deposits and near-surface bedrock below lakes and sea bays. This affects the conceptual model of flow patterns, especially chemical evolution and discharge from the more deep-seated bedrock. Data are available from two monitoring wells.

3.8.4 Present anthropogenic impact

Present anthropogenic impact, e.g. land use, industry, infrastructure and site investigations, affects the natural system and interpretations of data. Some information has been compiled, but there is only a limited description. The impacts have generally not been quantified, but disturbed data are disregarded. Supplementary investigations guided by modelling could be undertaken to resolve this issue.

3.9 Assessment

Some uncertainties remain in the Laxemar site descriptive model. Most of them are quantified or at least bounded by alternative models or assumptions. The impacts of the quantified or bounded uncertainties are to be assessed in the design and safety assessment. It is judged that the confidence in the Laxemar site descriptive model has reached such a level that the body of data and understanding is sufficient for the purposes of safety assessment and repository engineering at this stage. Consequently, none of the remaining issues are of key importance relative to the needs at this stage.

It is judged that only new data from underground investigations can significantly reduce the following uncertainties within the potential repository volume:

- The range of size distribution and size-intensity models for fractures at repository depth can only be reduced by data from underground excavations. Mapping fractures in the underground openings will allow statistical modelling of fractures in a DFN study at depth allowing test of current alternative hypotheses on the fracture size distribution.
- Uncertainties in stress magnitude will be reduced by observations and measurements of deformation and subsequent back analysis during the construction phase. Complementary direct measurements using short boreholes in different directions may also be performed from underground.
- A more detailed description the rock and the thermal conductivity distributions from underground investigations will enable thermal optimisation of the repository, if this is judged needed.
- There is little point in carrying out hydraulic tests in additional surface-based boreholes. The next step in confidence building would be to predict conditions and impacts from underground tunnels. Tunnel (and pilot hole) data will provide information about the fracture size distribution at the relevant depths. Underground investigations will also provide possibilities for short-range interference tests at relevant depth.
- Uncertainties in understanding chemical processes may be reduced by assessing results from underground monitoring (groundwater chemistry; fracture minerals etc) of the effects of drawdown and inflows during excavation.
- The hydrogeological DFN fitting parameters for fractures within the repository volume can only be properly constrained by the mapping of flowing or potentially open fractures in tunnels and associated statistics. Surface outcrop statistics are not relevant for properties at repository depth. During underground investigations, the flowing fracture frequencies in tunnels and investigations of couplings between rock mechanical properties and fracture transmissivities may give clues to the extent of in-plane flow channelling. This will lead to more reliable models for transport from the repository volume, particularly over the first 5–15 m from canister positions, which may have the greatest impact on overall radionuclide release rates.

Uncertainties in the regional area are larger, but are judged to be of less importance.

4 Handling of alternatives

Alternative model generation should be seen as an aspect of model development in general and as a mean of exploring confidence. At least in early stages, when there is little information, it is evident that there will be several different possible interpretations of the data, but this may not necessitate that all possible alternatives are propagated through the entire analysis chain including safety assessment. Combining all potential alternatives in all their permutations leads to an exponential growth of calculation cases – variant explosion – and a structured and justified approach for omitting alternatives at early stages is therefore a necessity. At later stages, such as at the completion of the surface-based site investigations the number of hypotheses should be reduced, since they are constrained by the available information. However, the implications of the remaining hypotheses need to be developed into alternatives and propagated into engineering design and safety assessment.

4.1 Auditing protocol

SDM version Laxemar 1.2 kept track of alternative hypotheses and what alternatives to be propagated to further analyses. This record keeping is maintained also in SDM-Site Laxemar. The table structure of version 1.2 is kept, with obvious revisions and covers:

- Potential "Primary" alternatives of the site descriptive model?
- Reason for the alternative hypotheses?
- Impact on other discipline models (or aspects of these models)?
- Implications for repository engineering in phase D2?
- Implications for safety assessment?
- Implications for investigations to "resolve" alternative?
- Handling in SDM-Site Laxemar?

It should be noted that these questions essentially are already covered by the questions asked on the remaining uncertainties. However, the alternative table is retained, since it also keeps track of old hypotheses and because it summarises the alternative hypotheses and handling in different models. Furthermore, while the alternatives hypotheses usually arise at the level of the discipline-specific models, they need to be considered in combination across the site descriptive model as a whole.

4.2 Summary of alternatives and their handling

The situations where alternative models are now considered have been addressed in Chapter 3. Furthermore, previous site descriptive model reports have listed alternative hypotheses valid at the time of presenting those earlier models. For overview and traceability Table 4-1 list both the currently considered alternatives and the previously considered ones. If an old alternative is now considered resolved, this is stated in the table, with justification.

Only a few of the original alternative hypotheses are developed into alternatives to be propagated to safety assessment or engineering. These are summarised below:

- *Alternative geological DFN-models.* The absence of fracture trace data from underground makes it necessary to formulate several alternative models of the size distribution and intensity. Some of these alternatives are less likely, but are conservatively retained to ensure bounding the uncertainty. The alternatives are propagated to repository design and to safety assessment. They will impact degree of utilisation in the design and the safety assessment of earthquake hazards. Implications for hydrogeology and rock mechanics in the SDM work are judged to be small and do not need to be propagated further.

- *Hydraulic properties ("transmissivity" and connectivity) of deformation zones in the Laxemar subarea.* These properties are uncertain. Some different cases of the transmissivity distribution are explored in the regional flow modelling /Rhén et al. 2009/. They have little impact and it is not justified to propagate these to safety assessment.
- *Hydrogeological DFN. Upscaling and correlation between fracture size and transmissivity.* In contrast to the situation after version Laxemar 1.2, there are now a multitude of data in support of the hydraulics description. However, it is not possible to resolve uncertainty in the transmissivity versus size correlation. There is also an issue as to how uniquely the current model captures the upscaling of PFL-data into large block values. The remaining alternative relates to the potential correlation between fracture size and transmissivity. The alternative models of the degree of correlation need to be considered in safety assessment.
- *Sulphate reduction.* New sulphide data from the monitoring programme indicate increasing sulphide values. The reason is unknown, initial drilling and pumping may have disturbed the system or may have facilitated sulphate reduction. Time series from the ongoing monitoring programme are judged to allow a final assessment of what is the undisturbed sulphide concentration as well as of how the sulphide content may change due to future intrusion of marine water. This assessment will have to be done in the safety assessment.
- *Effects of connectivity, complexity and channelling on the distribution of flow (F-factor)*. Details of the flow field on the fracture plane are uncertain. In SR-Can, channelling was handled by dividing the transport resistance obtained from the hydrogeological DFN model by a factor of 10, whereas SDM-Site explores a multitude of channelling hypotheses. The bounding estimates of the influence of channelling assessed in SDM-Site Laxemar will be propagated to safety assessment.

Remaining hypotheses and uncertainties are managed by bounding assumptions.

Table 4-1. Assessment of alternatives.

Potential "Primary" alternatives in SDM	Reason for the alternative hypotheses	Impact on other discipline models (or aspects of these models)?	Implications for repository engineering in phase D2	Implications for safety assessment	Implications for investigations to "resolve" alternative	Handling in SDM-Site Laxemar and need for propagation into design and safety assessment
Surface and near surface description						
None (little conceptual uncertainty)	Little conceptual uncertainty.					No alternatives developed.
Bedrock geology						
Geometry of Rock Domains in the Laxemar subarea.	No need or basis for an alternative rock domain model in the Laxemar local model volume. The rock domain model has been updated in the SDM-Site Laxemar model version.	None, since no alternative model has been constructed.	None	None	None	No need to propagate an alternative model. The interpretation of existing data is straight forward.
Alternative lineament interpretation.	An independent lineament interpretation was performed.	The lineament interpretation is input to the deformation zone modelling.	None	None	No	An alternative lineament interpretation exists. However, it is judged that the alternative model was not different enough to justify an alternative deformation zone model development.
Changes of existence or geometry of deformation zones (extent and directions) in Laxemar subarea.	Earlier alternative interpretations of individual DZs have been resolved as part of the ongoing modelling work.	Geometries of deformation zones are basic input to the hydrogeological model, and are also important for judging the uncertainty in the local stress field.	DZ geometrical uncertainties should be taken account of in sensitivity layout studies etc.	No	No	No alternative versions have been propagated. However, uncertainties including the geometrical properties strike, dip and particularly length of DZs only identified by single borehole intercepts remain and clearly impact layout studies etc.
Character and properties – also of the well established zones.	Character and properties – also of the well established zones are uncertain.	The character and properties of deformation zones affect the stress and hydrogeological models.	Deformation zone properties, for zones that could be intersected by the tunnels, are of importance for the detailed design and layout	Of no importance since safety assessment only considers the size of the zones being important for the earthquake hazards		No alternatives have been developed. Uncertainties are described by confidence classes and likely spans in assigned properties.

Potential "Primary" alternatives in SDM	Reason for the alternative hypotheses	Impact on other discipline models (or aspects of these models)?	Implications for repository engineering in phase D2	Implications for safety assessment	Implications for investigations to "resolve" alternative	Handling in SDM-Site Laxemar and need for propagation into design and safety assessment
Alternative geological DFN-models.	Alternative size-intensity models are carried through full DFN analysis. Recommended model presented. Alternative models ranked in terms of performance on verification tests. Alternative models are presented in the Geological DFN report and are therefore available to other model teams for sensitivity and uncertainty studies in their models.	Rock Mass Mechanics, Hydrogeology, Transport	May affect space and degree of utilisation. (Amount of key blocks may be affected by alternative DFN-models.)	Yes, new set of calculations for RN-transport. Affects probability of deposition holes being intersected by fractures long enough to be a potential hazard during a large earthquake.	Issue could only be resolved by data from underground, e.g. tunnel mapping, potentially combined with additional surface mapping and surface based geophysics	Implications on probability of canister intersection for the different alternatives presented need to be assessed within safety assessment.
Thickness of minor deformation zones in the DFN-model.	This issue was raised in earlier versions of the Laxemar SDM, but is now deleted from the list of alternatives, since this uncertainty is directly handled in the geological model. Statistics of observed MDZ thickness are presented in the Geology summary report /Wahlgren et al. 2008/.					
Rock mechanics						
Rock Mechanics Properties – due to alternative geological DFN-models	This issue was raised in previous version of the Laxemar SDM, since the DFN-model is input to the "theoretical approach" and there are alternative DFN-models.	Minor.	Strength – stress ratio is important for design of the repository and for assessment of thermally induced spalling.	Distribution of rock mass (large scale) deformation properties are important for assessment of THM-processes around the repository. No – or minor impact expected.	Uncertainties could only be reduced by observations of stability and measurements of deformation with back analyses during the construction phase.	No alternative is presented since uncertainties are sufficiently well bounded.

Potential "Primary" alternatives in SDM	Reason for the alternative hypotheses	Impact on other discipline models (or aspects of these models)?	Implications for repository engineering in phase D2	Implications for safety assessment	Implications for investigations to "resolve" alternative	Handling in SDM-Site Laxemar and need for propagation into design and safety assessment
Alternative Stress Model	This issue was raised in a previous version of the Laxemar SDM	No (but stress modelling may provide feedback to deformation zone model and possibly hydrogeology).	Affects risk that spalling will occur, which may need to be handled by adjusting tunnel orientations.	Important for rock mechanics evolution – including assessment of thermally induced spalling.	Uncertainties could only be reduced by observations of stability and measurements of deformation with back analyses during the construction phase.	No alternative is presented since uncertainties are assessed to be sufficiently well bounded.
Thermal model						
Spatial distribution of thermal properties	There are uncertainties in the distribution of thermal conductivities – especially in the lower tail of the distribution.	Minor.	Affects spacing of canisters. Underestimating the thermal conductivity will lead to a conservative layout. The number of canisters per area can possibly be increased by optimising the canister distance according to the local thermal conductivity or changing the distance between disposal tunnels.	Necessary to assess whether buffer temperature criterion is met.	Uncertainties could only be reduced by observations, conditional modelling and thermal experiments during the construction phase.	No alternative is presented since a bounding estimate is provided.
Hydrogeology						
Alternative in the geological model of geometry of deformation zones and their connectivity.	Issue raised in earlier versions of the Laxemar SDM. However, since the confidence is much better in the current deformation zone model there is no further need to consider this alternative.					

Potential "Primary" alternatives in SDM	Reason for the alternative hypotheses	Impact on other discipline models (or aspects of these models)?	Implications for repository engineering in phase D2	Implications for safety assessment	Implications for investigations to "resolve" alternative	Handling in SDM-Site Laxemar and need for propagation into design and safety assessment
Change of hydraulic properties ("transmissivity" and connectivity) of deformation zones in Laxemar subarea. (Depth dependence, T correlation to orientation.)	Issue raised in earlier versions of the Laxemar SDM.	New regional hydrogeologic model – affects palaeohydrogeological model.	Possibly minor – would affect construction consequence analysis and impact of "open repository".	Possibly minor for radionuclide migration (little transport resistance in zone). Impact of "open repository". Potentially important for evolution of groundwater chemistry and thus for retardation properties and parameters.		The need to further resolve this issue essentially depends on how it affects the understanding of regional groundwater flow and the evolution of water composition. Some different cases of the transmissivity distribution are explored in the regional flow modelling, /Rhén et al. 2009/. They have little impact and it is not justified to propagate these to safety assessment.
Alternative hydrogeological DFN, including alternative T vs. size correlation. Depth dependence, correlation to rock domain, T correlation to orientation and upscaling	Alternative has been kept since version Simpevarp 1.1 and is still not fully resolved. In contrast to the situation after Laxemar 1.2, there are now multitudes of data in support of the hydraulics description. However, it is not possible to resolve uncertainty in transmissivity versus size correlation. There is also an issue as to how uniquely the current model captures the upscaling of PFL-data into large block values.	The uncertainty may affect large-scale transport and thus could affect the palaeohydrogeology calibration efforts.	Inflow to deposition holes is a key parameter affecting degree of utilisation. However, since the model is calibrated on the PFL-data, i.e. on flow data at a scale rather similar to flow into a deposition hole, it is judged that the model is sufficiently robust for this aspect.	The hydrogeological DFN-model is a key input to safety assessment. It affects both near-field evolution and far-field migration. Regarding the former it is judged that the current hydrogeological DFN is sufficiently robust, whereas the remaining transmissivity versus size uncertainty will certainly affect retention in the rock mass.	There is little point in carrying out additional surface-based boreholes. There is already a good coverage of boreholes and all show the same picture. The next step in confidence building would be to predict conditions and impacts from underground tunnels. Tunnel (and pilot hole) data will provide information about the fracture size distribution at the relevant depths. They also provide possibilities for short range interference tests at the relevant depth.	The remaining alternative concerns the potential correlation between fracture size and transmissivity. The alternative models of the degree of correlation need to be considered in Safety assessment. Uncertainties regarding channelling inside the fractures are discussed under "transport", below.

Potential "Primary" alternatives in SDM	Reason for the alternative hypotheses	Impact on other discipline models (or aspects of these models)?	Implications for repository engineering in phase D2	Implications for safety assessment	Implications for investigations to "resolve" alternative	Handling in SDM-Site Laxemar and need for propagation into design and safety assessment
Hydrogeochemistry						
Spatial variability in 3D at depth.	Issue was raised in previous versions of the Laxemar SDM. The issue is now essentially resolved, since there is an adequate understanding of the current distribution of groundwater composition, see Section 3.6.1.					
Sulphate reduction	New sulphide data from the monitoring programme indicate increasing sulphide concentrations. The reason is unknown, initial drilling and pumping may have disturbed the system or may have facilitated sulphate reduction.	No	No	A key issue in safety assessment. Sulphide content above 10^{-5} M would have a potential detrimental impact on canister corrosion if combined with buffer density losses.	Longer time series from the monitoring programme. The monitoring programme continues and contributes with further data for an increased understanding. Infiltration tests during construction of the repository.	Time series from the ongoing monitoring programme are judged to allow a final assessment of the undisturbed sulphide concentration as well as how the sulphide content may change due to future intrusion of marine water. This assessment will have to be done in Safety assessment.
Transport						
Effects of connectivity, complexity and channelling on distribution of flow (F-factor).	Details of the flow field on the fracture plane are uncertain. In SR-Can channelling was handled by dividing the transport resistance obtained from the hydrogeological DFN model by a factor of 10, whereas SDM-Site explores a multitude of channelling hypotheses	The palaeohydrogeological modelling carried out as part of the hydrogeological assessment uses these migration data as input.	No	Channelling is usually suggested to have a large impact on retention along migration paths. However, the impact the uncertainty has on the flow related migration parameters is judged small as long as the model represents connectivity of the rock mass, see further Section 3.7.1. The SR-Can approach, dividing by 10 is thus very conservative.	During underground investigations the frequencies of flowing fractures in tunnels and investigations of couplings between rock mechanical properties and fracture transmissivities may give additional clues to the extent of in-plane flow channelling which will lead to more reliable models for transport from the repository volume, particularly over the first 5–15 m from canister positions, which may have the greatest impact on overall radionuclide release rates.	The bounding estimates of the influence of channelling assessed in SDM-Site will be propagated to Safety assessment.

5 Consistency between discplines

Another prerequisite for confidence is consistency (or at least no conflicts) between the different discipline model interpretations. Furthermore, confidence is enhanced if aspects of the model are supported by independent evidence from different disciplines.

5.1 Auditing protocol

Assessing consistency between disciplines has been made using the already established table structure, i.e:

- Which aspects of the "source" discipline would it be valuable to consider in developing the "target" discipline?
- Which aspects of the "source" discipline have actually been used when developing the "target" SDM?
- Are there any discrepancies between the answers to the first and second questions, and if so why?

Discrepancies between what it would be valuable to consider and what actually has been considered affects confidence in the model. However, it is primarily for the users to determine whether these discrepancies are acceptable.

5.2 Important and actually considered interactions

Table 5-1 shows a summary of the results of the assessment of inter-discipline interactions. In addressing the questions, the effort is spent primarily on issues judged to be important and not in explaining why unimportant interactions indeed are so. Answers are presented as an "interaction matrix" where interactions from a diagonal element are shown on the row and interaction on an element are shown on the column. Furthermore, the table both shows what interactions are judged to be important (in green) and to what extent these were actually considered (in black). If the table suggests that there is an interaction (noted by "yes" in the table), its character and handling in the SDM are addressed in the following subsections.

5.2.1 Impacts on the bedrock geology model

Many disciplines are judged to provide important feedbacks to the geological modelling, although essentially in a qualitative manner. Such feedback has now been considered. However, it should also be noted that an essential part of the modelling philosophy is to base the geometrical framework on geological information and reasoning and not to "fit" the geological model to the other models.

Feedback from rock mechanics on stress orientations in relation to fracture sets could give additional confidence in the deformation zone and DFN model. Feedback to geology from rock mechanics concerning *in situ* stress measurements obtained in southeast Laxemar has led to changes in the modelled extent of zones and ensured consistency between the two disciplines. The analysis suggests that division into rock domains (together with the additional fracturing domains) is appropriate for the rock mechanics modelling needs.

The thermal modelling provides feedback to the description of rock domains. Further refinement of the lithological distribution within rock domains is provided by a geostatistical approach applied in thermal modelling. There has been input from the thermal modelling in the definition of the density threshold for subdivision of the Ävrö granite in Ävrö quartz monzodiorite and Ävrö granodiorite. In the thermal modelling the uncertainties in the TRC proportions have been estimated.

Table 5-1 Summary of interactions judged to be important (yes in green), to what extent these where actually considered (black) or whether the interaction was not judged important for the SDM. For details, see discussion in Section 5.2. (Note, there is a clock-wise interaction convention in the matrix, e.g. influence of geology on rock mechanics is located in box (1,2), whereas the influence of rock mechanics on geology is located in box (2,1)).

Bedrock geology	Yes/Yes	Yes/Yes	Yes/ Yes	Yes/ Yes	Yes/Yes	Yes/Yes	Not important for SDM	Yes/Yes	Not important for SDM.
Yes/Yes	**Rock mechanics (in the bedrock)**	Not important for SDM.	Yes/Yes	Yes/Yes	Yes/Yes	Not important for SDM.	Not important for SDM.	Not important for SDM.	Not important for SDM.
Yes/Yes	Not important for SDM	**Thermal (in the bedrock)**	Not important for SDM.	Yes/Yes	Yes/Acceptable to neglect this impact.	Not important for SDM.	Not important for SDM.	Not important for SDM.	Not important for SDM.
Yes/Yes	Yes/Yes	Yes/Yes	**Hydrogeology in the bedrock**	Yes/Yes	Yes/Yes	Yes/No such model-ling has been done.	Yes/Yes	Not important for SDM.	Not important for SDM.
Yes/Yes	Not important for SDM	Not important for SDM.	Yes/Yes	**Hydrogeo-chemis-try in the bedrock**	Yes/Yes	Yes/Yes	Not important for SDM.	Not important for SDM.	Not important for SDM.
Not important for SDM.	Not important for SDM.	Not important for SDM.	Yes/Yes	Yes/Yes	**Bedrock Transport Properties**	Not important for SDM.	Not important for SDM.	Not important for SDM.	Not important for SDM.
Not important for SDM.	Not important for SDM.	Not important for SDM.	Not important for SDM.	Yes/Yes	Not important for SDM.	**Hydrogeo-chemistry (surface and near surface)**	Yes/Yes	Yes/Yes	Yes/Yes
Not important for SDM.	Not important for SDM.	Not important for SDM.	Yes/Yes	Yes/Yes.	Not important for SDM.	Yes/Yes	**Surface and near surface hydrology**	Yes/Yes	Yes/Yes
Yes/Yes	Not important for SDM.	Not important for SDM.	Yes/Yes	Yes/Yes	Not important for SDM.	Yes/Yes	Yes/Yes	**Quaternary Deposits**	Yes/Yes
Not important for SDM.	Not important for SDM.	Not important for SDM.	Not important for SDM.	Yes/Processes identified, but not quantified.	Not important for SDM.	Yes/Yes	Yes/Yes	Yes/Yes	**Biota**

Hydrogeology could provide confirmation of and indications of the properties of deformation zones and can also provide a feedback to the conceptual thinking in the deterministic deformation zone and stochastic DFN modelling work. These feedbacks are considered. The significance of differences between rock domains as well as between fracture domains is assessed. Fracture domains are used as basis for HRD. This provides support for the division into fracture domains. Hydraulic differences between rock types are also assessed. The hydrogeological data interpretation has also influenced judgements on deformation zone orientation and extension. There has been interaction on fracture set definition such that it is consistent between the hydrogeological DFN and the geological DFN. The "k_r-scaled" assumption applied the hydrogeological DFN was also considered for the geological DFN.

Hydrogeochemical data should be considered for division of parts of rock domains outside deformation zones into fracture domains. It should be checked whether the fracture mineralogy is consistent with current groundwater composition. The consistency between fracture mineralogy and current groundwater composition is assessed and provides input to the fracture mineralogical description (see e.g. Section 3.6.2).

Characterization of Quaternary deposits should indicate whether there is evidence for late- or post-glacial tectonic activity. The digitial elevation model (DEM) is used as input for identifying topographical lineaments. Data on late- and post-glacial tectonics are used in the descriptive model. No regionally important, late- or post-glacial faults are found in the area.

5.2.2 Impacts on the rock mechanics model

It is mainly the bedrock geology model that impacts on the rock mechanics model through the rock domains, deformation zones and DFN-model. This input is used within the rock mechanics modelling.

The geological model is the basis for deriving a relationships between mechanical properties, rock domains and deformation zones. Rock domains (lithology) are the basis for the spatial distribution of intact rock mechanical properties. The geological DFN model is used to infer rock mass mechanical properties in the theoretical approach.

Deformation zone geometry influences the stress field. Deformation zone geometry is used as input to the numerical stress modelling by /Hakami et al. 2008/.

Differences in fracture frequency with depth and between different fracture domains could possibly affect the stress field. The variation in rock domain mechanical stiffness in the Laxemar subarea is judged too low to be of importance.

Hydrogeological conditions would impact the rock mechanical behaviour since water pressure reduces the rock stress to effective stress. However, this coupling has little effect on the parameters predicted, but is of course considered by repository engineering. Furthermore, the coupling is relatively trivial to take into account, since water pressures are close to hydrostatic, i.e. no special hydraulic modelling is needed.

Stress magnitudes and orientations should be consistent with the anisotropy of hydraulic conductivity. A joint evaluation of the *in situ* stress and hydraulic data suggests that the coupling between *in situ* stress and hydraulic properties is weak. The hydrogeology data show that the structural/fracture geology is a much more important factor to consider than the current stress field.

It should also be noted that thermal expansion analysis is not part of the SDM, but is indeed considered in repository engineering and safety assessment.

5.2.3 Impacts on the thermal model

It is mainly the bedrock geology model that impacts the thermal model through the rock type descriptions of the rock domains. This input is used within the thermal modelling.

The geological model provides the geometrical framework for the rock domains used in thermal modelling, the rock type distribution and the relationship between anisotropy in thermal properties *and ductile structures.* Thermal properties have been evaluated on the basis of rock types and rock domains. Modal analyses have been used as (one) input. The orientation of ductile structures has been used in the analysis of anisotropy in thermal properties.

Stress impacts on thermal properties are very small, as long as the rock is water saturated /Walsh and Decker 1966/. This coupling is neglected.

Thermal convection and other groundwater flows affect uncertainty in measurement of in situ temperature. These effects are considered when assessing uncertainty in *in situ* temperature values.

5.2.4 Impacts on the hydrogeological model

Many disciplines can inform the hydrogeological modelling and most of this input is considered.

Bedrock geology provides the geometrical framework in terms of rock domains, deformation zones, fracture domains and DFN-geometry for the hydrogeological models. The deformation zone geometry is used as input to HCD definition and the fracture domains are used for defining HRD, but these are then both combined and divided into depth zones based on the hydraulic data. There is only a weak link between the geological DFN and the hydrogeological DFN, since they concern somewhat different aspects of the fracturing of the rock (i.e. only the open conductive fractures are part of the hydrogeological DFN). Set definitions are the same. Assessment of differences in size distribution between the models also suggests that that the models are more similar in their characteristics of the larger size fractures, see /Rhén et al. 2008/. The significance of differences between rock domains as well as between fracture domains is assessed and shown to be a good basis for dividing the rock into HRDs. The descriptions of deformation zones are not fully used in the property assignment, but ensembles of zones with similar characteristics (orientation properties) are used to define statistical samples for describing the variability within the different class zones.

Stress orientation, i.e. a rock mechanics input, is expected to affect hydraulic anisotropy and past deformations (normal and shear) affect the fracture transmissivity. The hydraulic model is based on the hydraulic data rather than on theoretical considerations. However, assessment of hydraulic data in relation to the stress field is a key component in developing confidence in the hydrogeological model, /see Rhén et al. 2008/. The orientation of transmissive fractures and deformation zones shows some consistency with stress orientation – but not a 1:1 relation. Transmissivity of individual fractures tends to decrease with increased normal stress (and depth), but there is a wide spread over several orders of magnitude. Empirical relations between stress and transmissivity are not generally applicable – and can not replace field data. Fracture shear stress/displacements affect fracture transmissivity in laboratory tests (as also shown by /Min et al. 2004/). There is no evidence that shear displacements are occurring at Laxemar (e.g. lack of seismic evidence). *In situ* geometric factors such as channelling and fracture intersections are more likely to affect fracture transmissivity than shear stress/displacements.

Temperature affects water density and viscosity. This impact is considered and judged unimportant.

There is a strong coupling between hydrogeology and hydrogeochemistry, since it is suggested that mixing is the main process for groundwater evolution. Furthermore, density differences, created by varying salinity, affect the flow regime. Present day salinity as well as O-18 and Br/Cl and some other components are "calibration targets" for simulation. The hydrogeological models consider density effects. The present day redox front is found at relatively shallow depth.

Modelling of salt migration should be consistent with assessed migration properties. The transport model could also provide feedback on what aspects of the hydrogeological DFN are of importance for the transport resistance estimates. Consistency checks as regards porosities and mass transfer parameters used in palaeo-hydrogeology simulations are made /Rhén et al. 2009/ and show reasonable to good agreement.

There are also interactions with the surface system. The identification of water types and boundary conditions in the near-surface hydrogeochemistry provides input to the surface water type considered in the modelling. Also, surface hydrology and near-surface hydrogeology as well as topography and the description of the Quaternary deposits provide input to the formulation of the top boundary conditions. All these interactions are considered in the modelling, although simplifications are made.

5.2.5 Impacts on the hydrogeochemistry model

Many disciplines are judged to provide important feedbacks to the hydrogeochemical modelling and most of this input is considered.

Fracture mineralogy and the chemical composition of the bedrock, as provided by the geological model, require consideration. Geological evolution impacts on the palaeohydrogeological understanding. Fracture mineralogy and volumes are considered and the chemical composition is used in the modelling of the palaeohydrogeology. Assessment of fracture minerals is a key input for the redox zone assessment. Bedrock geochemistry and mineralogy are used in deriving the matrix porewater composition. An indirect influence that is also considered is that different deformation zones and fracture domains correlate to the groundwater composition, since they have different hydraulic properties. The geological evolution is considered when describing the palaeohydrogeological evolution.

Stress release of cores could affect the interpretation of matrix porewater composition. These impacts have been considered, and shown not to be of significance. The impact of stress release lies within the envelope of uncertainty in the matrix porewater composition.

Temperature affects reactions and precipitation and dissolution of minerals. Current temperature is used as an input in the chemical modelling. Formation temperature of the infiltrating waters affects the water composition ($\delta^{18}O$). This is used as a clue for determining ages and origins of waters found today.

Groundwater flow (advective mixing and matrix diffusion) is considered a main mechanism for distribution and evolution of groundwater composition. Simulation of past salinity and some specific species allows comparison with groundwater compositions provided by hydrogeochemistry. These comparisons generally enhance confidence both in the hydrogeological and hydrogeochemical model. The simulated position of the fresh water and the occurrence of Littorina water (including "pockets" of glacial waters in low conductive parts, surrounded by more modern water) agrees reasonably well with measured data, although there are uncertainties, see /Rhén et al. 2009/. The flow model is used as input for reactive transport simulations, focusing on Ca, Na, Mg migration. Old numerical simulations of the sampling procedure made for the TRUE project at Äspö HRL, show that disturbances caused by mixing during sampling is a probable explanation for the variability and potential bias in groundwater samples. No such quantitative assessments were made at Laxemar, but in the hydrogeological calibrations there is an awareness that the location of "point samples" is uncertain.

Migration processes (advection, matrix diffusion and sorption) are part of the overall complex of processes affecting groundwater composition. Differences in water composition between the rock matrix and high conductive fractures need to be consistent with rock matrix data used in the transport model. Diffusivities needed to explain disequilibrium between matrix and fracture waters are more or less consistent with diffusivities assessed from the rock samples. The transport model implications of the matrix porewater data are currently not fully assessed, but the apparent penetration depths observed are not inconsistent with the understanding of matrix diffusion, although lack of knowledge concerning initial and boundary conditions makes it very difficult to make any strong quantitative conclusions. CEC values determined within transport modelling are also used within chemical modelling. However, the CEC data appear to be unreliable, since the method used is suited to soils with much higher CEC values. The data for crushed rock samples are therefore highly uncertain. There has been a qualitative assessment of how sorption affects groundwater composition /Crawford and Sidborn 2009/. There are no direct effects relevant to radionuclides, since they are present at very low concentrations. For major components, such as Ca, Mg, Na, K, the ion exchange properties of the rock can in principle be used to predict groundwater evolution due to ion exchange processes.

There are also interactions from the surface system. Surface and near-surface hydrogeochemistry and hydrology and hydrogeology influence the waters in the bedrock. Some data are used in a simplified coupled/integrated model and the measured near-surface data are used to define a reference water in mixing calculations. Also, the description of the Quaternary deposits provides input to the selection of water types and input to coupled modelling. Microbial processes in surface and near-surface waters affect near surface water composition. This coupling is already considered in the coupling between near-surface chemistry and "bedrock rock chemistry".

5.2.6 Impacts on the transport model

Many disciplines are judged to provide important feedback to the transport modelling and most of this input is considered.

The rock domains defined by bedrock geology provide the main tool for extrapolating the transport property data into three dimensions. This coupling is considered to the extent possible. The spatial distribution of rock matrix properties (e.g. diffusivity, sorption) is based on rock domains (identified rock types in the rock domain model), fracture domains (different fracture types) and deformation zones. Fracture mineralogy and hydrothermal alteration are considered. Even though there is variable coverage between rock domains, the differences in properties between domains are small. Geology also qualitatively informs as to where there could be reason for channelling, e.g. in rock type boundaries.

The structure of fractures as well as stress will affect the fracture plane geometry and thus the degree of channelized flow. De-stressing of "intact" rock samples for laboratory measurements may also affect measured matrix porosity and formation factors. Scoping assessment of the importance of channelized flow generated by considering different degrees of fracture contact area, using typical fracture aperture distributions are made. There is no direct assessment of stress, and the aperture distributions is judged more important than stress for the potential of creating channelling. Stress impacts on matrix properties have been considered, and judged not to be a major factor. Nevertheless, *in situ* values, determined by electrical resistivity logs are used.

Temperature generally affects viscosity and thus diffusivity. Since thermal effects are very small, it is acceptable to neglect this impact and this is also the position that has been adopted.

There is an obvious correlation between transport and hydrogeological parameters. Hydrogeology could also identify potential flow paths for which a transport description is needed. The hydrogeological DFN, as well as PFL-data, are used as input to the flow-related transport property assessment. Matrix and fracture properties are assessed for core sections associated with connected transmissive fractures (PFL-anomalies). There is also a division between samples from HRDs and HCDs.

Groundwater composition affects diffusion and sorption parameters and is a necessary input to process-based retention modelling. Differences in water composition between the rock matrix and highly conductive fractures need to be consistent with rock matrix data used in the transport model. Groundwater composition (identified water types) is used to set up laboratory tests and in the parameterisation of the retardation model. Diffusivities needed to explain disequilibria between matrix and fracture waters are more or less consistent with diffusivities assessed from the rock samples. Groundwater composition is needed and used for determining the *in situ* formation factor data.

5.2.7 Impacts on the near-surface model

Many interactions take place among the different surface disciplines, which is why an integrated modelling approach is adopted for the surface system.

- *Surface and near surface hydrogeochemistry* obtains data on mineralogy and geochemistry from the geological model, is part of coupled hydrogeological/hydrogeochemical conceptual modelling, uses rock hydrogeochemistry data, uses the flow pattern and discharge data from the near surface hydrology as input to mass balance and mass transport modelling, uses the model of Quaternary deposits as a basis for the conceptual model and uses data on primary production and respiration.
- *Surface hydrology, near surface hydrogeology* and oceanography is part of the coupled hydrogeological/hydrogeochemical conceptual modelling, uses the bedrock hydrogeology model for comparisons of heads, fluxes and flow paths in rock, consider density differences for head corrections, considers surface and near surface hydrogeochemistry for supporting analyses and the evaluation of chemical data to identify discharge areas of deep groundwater, uses the Quaternary deposits model as a basis for the conceptual and numerical model and considers the vegetation map, LAI, root mass distribution and root depth as input data to water balance modelling.

- *The model on Quaternary deposits and transport properties in QD, topography and bathymetry* uses data on fracture zones, mineralogy and geochemistry to study whether the till is local or transported (during glaciation), uses data on chemical characteristics of Quaternary deposits as supporting data for evaluation of transport properties, considers flow field and evapotranspiration components and uses bioturbation and accumulation process descriptions as well as vegetation data.
- *The description of biota in the surface system* uses the chemical composition of soil, waters and biota in modelling and validation of flow of matter in ecosystem descriptions, considers discharge rates, volumes of surface waters and groundwater, groundwater levels, water balances, geometrical data on surface waters, modelled discharges of groundwater and transpiration data, and also considers the spatial distribution of Quaternary deposits, their accumulation and historical descriptions.

It is evident that many feedbacks are required, and also made, in order to produce consistent, integrated models within the disciplines where modelling is performed for both the surface system and the deep rock. For more detail, see /Söderbäck and Lindborg 2009/.

5.3 Assessment

Essentially all identified interactions are also considered in the site descriptive modelling work. Furthermore, the interdisciplinary feedbacks provide qualitative and independent data support to the different discipline specific descriptions and thus enhance overall confidence.

6 Confidence statement

Since SDM-Site Laxemar may be part of a safety assessment in support of a license application, it is essential to establish the level of confidence in the site descriptive model based on the available data. Subsequent analyses within repository engineering and long term safety assessment will then address whether this confidence is sufficient to warrant the programme to continue to its underground phase. A related issue is whether the only outstanding issues are those that are best resolved underground.

6.1 Auditing protocol

For this reason a new set of questions are addressed within each discipline:

- What aspects of the model (properties, specific volumes) have the highest confidence?
- What are the main reasons for confidence in the model? e.g. wealth of data, consistency with other disciplines, consistency with past evolution, stability over time (i.e. few surprises as new data arrive), other.
- What aspects of the model have the lowest confidence and how this is managed in the uncertainty assessment?
- General statement of confidence.

Highlighting the aspects having the highest and the lowest confidence respectively, is a qualitative approach of bracketing the whole range of confidence.

6.2 Aspects of the site having high and low confidence

Key aspects of the Laxemar site descriptive model are judged to have high confidence, even if details of the spatial variability are left unknown. An overall reason for this confidence is the relative wealth of data and the consistency between independent data from different disciplines. Some aspects have lower confidence. The lack of confidence is managed by providing wide uncertainty ranges, bounding estimates or alternative models. Most, but not all, of the low confidence aspects are judged to be of relatively little importance for repository engineering design or for long-term safety, considering the feedback from these activities as listed in Section 1.4. While, the final assessment on the importance will be made within the subsequent repository engineering and safety assessment activities, it is nevertheless possible to provide indicative judgments on the importance, based on this feedback.

6.2.1 Geology

The following aspects of the geological model are associated with the highest confidence:

- Properties and character of the dominant rock type in the rock domains in the focused area. While the precise geometry of the rock domains may still be adjusted in details, the character of the rock types that characterize the domains is very well established.
- The geometrical framework of the major deformation zones bordering and within the local model area is considered well established, with their outcrop positions and extents at the ground surface having the highest confidence.
- The fracture network properties (orientation, size and overall intensity), covered by the range of alternative models, of the rock mass north of ZSMNW042A and outside of ZSMEW007A, i.e. in all fracture domains except FSM_S, have high confidence. The spatial variability of fractures, especially intensity and orientation, is very well quantified and parameterized down to 9–15 m scales. Fracture intensity data from the surface can be extrapolated to depth (i.e. fracturing at the surface is generally not different from fracturing at planned repository level).

The main reasons for this confidence are:

- Wealth of data from rock domains, with a fairly good consistency between predictions and outcome when new boreholes are drilled and consistency with data from other boreholes.
- Consistent supporting data and interpretation for the major critical deformation zones and confirmatory independent interpretation of lineaments.
- New fracture data from the rock mass (i.e. not affected by DZ) consistent with existing data in the Ävrö granite and quartz monzodiorite.
- The fracture domain model that couples DFN and deformation zones together to produce a more complete description of brittle deformation at Laxemar.
- Abundant new data from Lidar and high resolution ground geophysical surveys and from boreholes drilled at many different orientations to principal fracture set directions.

The following aspects are associated with the lowest confidence:

- The spatial distribution, including the Ävrö granodiorite and diorite/gabbro component, in rock domain RSMM01, and to a certain degree also the orientation of subordinate rock types.
- The distribution of altered rock outside deformation zones.
- The size distribution of rock bodies from geological simulations.
- The brittle kinematic history of the deformation zones.
- Orientation, thickness and frequency of deformation zones not coupled to lineaments.
- Properties of individual deformation zones away from borehole intercept positions.
- Size and size-intensity relationship of sub-horizontal fractures.
- Size, spatial variability and length/thickness correlation of MDZ-sized structures.
- Orientation, size and overall intensity of fractures in fracture domain FSM_S.

The lack of confidence is mainly managed in safety assessment and engineering by providing bounding estimates of the sizes of different rock bodies and a wide range of size distributions in the geological DFN-model. Only the uncertainty in the DFN-model has any importance for long term safety.

6.2.2 Rock mechanics

The following aspects of the rock mechanics model are associated with the highest confidence:

- Mechanical properties of intact rock for the dominant rock types.
- Mechanical properties of the rock mass, between deterministic deformation zones.
- Overall stress orientation and magnitudes.

The main reasons for this confidence in mechanical properties are the consistency between model versions, wealth of data from well established laboratory and evaluation methods and support from other disciplines. Confidence in rock mass properties is also supported by the fact that the empirical and the theoretical approaches give similar results. Confidence in the stress model is provided by the fact that there are no surprises compared with previously existing data in the region and by the consistency between the fairly few direct measurements and indirect observations.

The aspect associated with the lowest confidence is the:

- Large-scale mechanical properties of deformation zones.

However, the large-scale mechanical properties of fractures are, within the estimated bounds, of limited importance for both engineering and long-term safety.

6.2.3 Thermal properties

The following aspects of the thermal model are associated with the highest confidence:

- The three-dimensional spatial statistical thermal models for the major thermal rock classes.
- The overall spatial distribution of thermal conductivity for rock domain RSMD01 with its higher degree of homogeneity in geological and thermal properties.
- The lower percentiles of the thermal conductivity distributions for rock domains RSMA01 and RSMM01.

The main reasons for this confidence are the satisfactory amount of data for the spatial statistical thermal models for some thermal rock classes, the greater homogeneity of rock domain RSMD01 compared with domains RSMA01 and RSMM01 and that the lower percentiles of thermal conductivity for domains RSMA01 and RSMM01 are not very sensitive to the uncertainties in the geological simulations.

The following aspects are associated with the lowest confidence:

- Spatial statistical thermal models for some thermal rock classes (TRC 33A, 33B, 102).
- The overall spatial distribution of thermal conductivity for Domain RSMA01 and RSMM01 because of their higher degree of heterogeneity in geology and thermal properties.
- Difficulties in modelling heterogeneity of the geology present in domain RSMA01 and, in particular, for domain RSMM01.

The lack of confidence is managed by slightly conservative thermal models that influence the lower tail of the domain distributions. This may result in somewhat larger designed distances between canisters than needed, but otherwise the uncertainty is relatively unimportant.

6.2.4 Hydrogeology

The following aspects of the hydrogeological model are associated with the highest confidence:

- The general trend of decreasing hydraulic conductivity with depth.
- Existence of HCDs with little evidence of missed large deformation zones in the repository volume.
- Statistical distribution of PFL inflow points is well established at least down to 500 m depth, but the upscaling is less certain.
- Presence of anisotropy (but probably underestimated as to its magnitude).
- Differences in hydraulic properties between different HRDs, especially HRD_N, HRD_EW007, HRD_C and HRD_W, within the local model volume. The boundaries between other HRDs in other regions are uncertain.
- Differences in hydraulic properties between the main rock types.

The main reasons for this confidence are:

- The wealth of data in main domains HRD_N , HRD_EW007, HRD_C and HRD_W within the local model volume, as well as fair stability over time of those domain properties, in terms of hydraulic conductivity.
- Consistency with other disciplines and especially that some geologically defined deformation zones have been confirmed by interference tests and that the anisotropic hydraulic conditions seem to follow what is to be expected from rock stress variation with depth.
- Key components of the present day groundwater chemical composition seem possible to simulate with the assessed hydraulic properties as well as reasonable assessments of boundary conditions for the last 10,000 years and a possible range of hydrogeochemical initial conditions.

The following aspects are associated with the lowest confidence:

- The spatial variability and anisotropy within HCD, but its importance is bounded by numerical sensitivity analyses.
- The confidence of assessed properties of HCDs with no or just one hydraulic observation.
- Spatial variability and anisotropy within MDZ. It is probably present and can affect the hydrogeological DFN model characteristics and effective hydraulic block hydraulic conductivity.
- Hydrogeochemical initial conditions used in the groundwater flow modelling of the evolution since the past deglaciation. However, there is an evolving understanding of the hydrogeochemical evolution, which would improve the description, see /Rhén et al. 2009/.

The lack of confidence is managed by providing bounding estimates or alternative models, as described previously. The implications of these uncertainties are relatively unimportant for safety assessment or engineering.

6.2.5 Hydrogeochemistry

The following aspects of the hydrogeochemical model are associated with the highest confidence:

- The origin, major end members and major processes affecting the present water composition at the sampled locations.
- The current spatial distribution of groundwater types, even though the spatial resolution is relatively coarse.
- Existence of a redox transition zone detected from the fracture minerals.

The main reasons for this confidence are the many consistent time and spatial data to support the description concerning the origin, most of the major end members and major processes. Integration with hydrogeology supports the palaeohydrogeological description of the site. Various considerations such as reactive modelling, interpretation of different isotope ratios (Sr, S, C) buffer capacity measurements (Eh, pH) and microbial data support the process understanding.

The following aspects are associated with the lowest confidence:

- Understanding of measured levels of sulphide and ability to predict sulphide production.
- Undisturbed detailed groundwater composition at repository depth.
- Buffer capacity regarding Ca and Mg content applicable to dynamic flow conditions.
- Detailed spatial variability and groundwater types associated with different rock domains. The results indicate poor correlation, possibly due to few samples. The description is focussing on divisions into groundwater types.

The implications of these uncertainties, especially on sulphide and dilute groundwaters, need to be assessed in subsequent safety analysis. The implications are potentially important for safety assessment but not for engineering.

6.2.6 Transport properties

The following aspects of the transport model are associated with the highest confidence:

- Formation factor data for intact rock and its spatial variability, at least within an order of magnitude.
- Average sorption properties of the rock matrix considering the four major representative water types and a set of radionuclides judged to be representative of several different kinds of sorption chemistry.
- Lower bounds on the transport resistance F can be established.

The main reasons for this confidence are as follows:

- A consistent improvement and convergence of measurement data. Previous problems with interpretation of sorption data have been partially resolved. Uncertainty in sorption data is still very high (in spite of an ambitious laboratory programme)
- Paleohydrogeochemical signatures from matrix porewater studies indicate the existence of connected matrix porosity over significant distances (tens of metres).
- The confidence in the lower bounds on transport resistance F is based on the confidence in the wealth of PFL-data and in the supporting evidence from dilution tests as well as the sensitivity analyses on the importance of channelling etc.

The following aspects are associated with the lowest confidence:

- The power law exponent, k_r for fracture size variation in the hydrogeological DFN and its relation to channelling effects, size-transmissivity relations for flow and frequencies of conductive features. Many aspects of this are not possible to internalise in the data analysis at present without introducing additional (and poorly constrained) correction factors for model fitting.
- Spatial variability of K_d data and its relation to groundwater composition.

The lack of confidence is managed by providing bounding estimates for safety assessment. The uncertainty is relatively unimportant for safety assessment, and not important for engineering.

6.2.7 Near-surface system

The following aspects of the near-surface system are associated with the highest confidence:

- Nutrient and macro element concentrations in surface waters.
- Catchment areas of surface water and near-surface groundwater.
- Overall water balance. Surface-water and groundwater levels.
- General groundwater flow pattern.
- Hydraulic properties of till.
- Horizontal distribution and stratigraphy (conceptually) of Quaternary deposits in the central area.
- Terrestrial vegetation.
- The conceptual ecosystem models.

The main reasons for this confidence are the relative wealth of data and the consistency with regional and global comparisons, the well-defined domains of Quaternary deposits and consistency of typical stratigraphy and that the surface is well exposed in many areas. Alternative numerical models supported by site data provide support to the model of biota.

The following aspects are associated with the lowest confidence:

- Hydrochemistry in the deep Quaternary deposits and near-surface bedrock.
- Some discharge measurements.
- Hydraulic properties of deep Quaternary deposits along valleys.
- Hydraulic properties of near-surface rock.
- Depth of Quaternary deposits, especially outside the central area.
- Description of Quaternary deposits in areas not covered by detailed field investigations.
- Process estimates (plant uptake, transpiration etc) and the characterization of microbiological processes.

These uncertainties are considered in the final uncertainty assessment of the near-surface model. Their implications for long-term safety or engineering are judged to be of relatively little importance for long-term safety or engineering.

6.3 Temporal variation and baseline

The hydrological and near-surface hydrogeological conditions in the Laxemar-Simpevarp area are in a transient state although on very different time scales (diurnal, seasonal, annual, etc) /Söderbäck 2008/. For an example, the long-term changes in the climate, from the time of the latest deglaciation and before, still show imprints on the composition of the deep groundwater system /Laaksoharju et al. 2009/. The site descriptive hydrogeological model /Rhén et al. 2008, 2009/ concludes that there are two processes that govern the development of the deep groundwater system in the Laxemar-Simpevarp area: (i) the structural-hydraulic conditions in the bedrock, and (ii) the ongoing shore-level displacement.

Site investigations should include the collection of time series data for the parameters showing significant temporal variation, i.e. those for which a single snapshot will not be enough to characterize undisturbed conditions or processes. For conditions strongly affected by seasonal variation, the within year variation will be much larger than the longer-term variation. This means that the detection and description of any longer term variation requires considerably more effort than is needed for the characterization of within year variation. It is instead judged that the best approach for the site investigations is to focus on obtaining a mechanistic understanding of ongoing processes. To capture longer trends in the near-surface an additional approach has been to carefully capture the within-year variation during initial, "undisturbed" conditions for a few years and then relate these measurements to good reference data for a description of the between-year variation /Söderbäck and Lindborg 2009/.

By the conclusion of the surface based investigations in Laxemar a good conceptual understanding on ongoing processes has been developed and while the deep groundwater system is transient, the changes are slow. For the near-surface, time series of up to 6 years now exist. These time series are judged sufficiently long to capture typical within year variation. Some additional years of baseline monitoring would not provide significantly more information on longer-term changes and extremes. In any case arguments on long term changes need to be derived from a mechanistic understanding of the processes that may result in extreme conditions, combined with long-term measurements on reference sites.

Finally, the monitoring programme at the site continues. Data collected in this monitoring programme will, together with the initially collected baseline data, form the reference against which any changes caused by repository construction can be recognised and distinguished from natural and other man-made temporal and spatial variations in the repository environment.

6.4 Overall assessment

Generally, it is judged that the Laxemar site descriptive model has an overall high level of confidence and has reached such a level that the body of data and understanding is sufficient for the purposes of safety assessment and repository engineering. Details of the spatial variability are left unknown. The overall reason for this confidence is the wide spatial distribution of the data and the consistency between independent data from different disciplines. While some aspects have lower confidence, this lack of confidence is managed by providing wider uncertainty ranges, bounding estimates and/or alternative models. Most, but not all, of the low confidence aspects have little impact on repository engineering design or for long term safety.

7 Conclusions

The confidence in the Laxemar site descriptive model, based on the data available at the conclusion of the surface based site investigations, has been assessed by exploring:

- Confidence in the site characterization data base.
- Remaining issues and their handling.
- Handling of alternatives.
- Consistency between disciplines.
- Main reasons for confidence and, if applicable, the main reasons for less confidence in some aspects of the model.

Generally, the site investigation database is of high quality, as assured by the quality procedures applied. It is judged that the Laxemar site descriptive model has an overall high level of confidence. Because of the relatively robust geological model that describes the site, the overall confidence in the Laxemar site descriptive model is judged to be high, even though details of the spatial variability are left unknown. The overall reason for this confidence is the wide spatial distribution of the data and the consistency between independent data from different disciplines. While some aspects have lower confidence, this lack of confidence is managed by providing wider uncertainty ranges, bounding estimates and/or alternative models. Most, but not all, of the low confidence aspects have little impact on repository engineering design or for long term safety. It may also be noted that the feedback requirements from SR-Can to the site modelling, see Section 1.4.1, are now met in the completed site investigations, subject to levels of uncertainty that are viewed as acceptable. Furthermore, the key characteristics of the undisturbed site are adequately understood prior to introducing any major disturbance of excavation.Only a few data points and a few types of data have been omitted from the modelling, mainly because they are judged less relevant and reliable than the data considered. These omissions are judged to have little or no negative impact on confidence in the site descriptive model of Laxemar. In fact, identification of unreliable data and their elimination should have a positive effect on confidence.

Poor precision in the measured data is judged to have limited impact on uncertainties in the site descriptive model, with the exceptions of interpretation and combination of borehole and outcrop fracture data and general uncertainties in sorption data.

Some, potential biases in the data are identified.

- There is non-uniform distribution of borehole data across the local model volume. In particular there are few boreholes in southern Laxemar. Also drilling activities have focused on the interpreted major lineaments and not all possible local major deformation zones have been investigated by drilling.
- Possibly, the most important bias in the data concerns fracture sizes at potential repository depth, especially for the gently dipping ones, since there are no data om such fractures from the surface. This necessitates considering a range of uncertainty in the geological DFN-model that could only be reduced by data obtained from underground.
- There are few water chemistry samples from the low transmissive parts of the fractures and minor zones, even if more data are now available from rock matrix studies in some boreholes. Furthermore, a potential source of bias includes contamination from drilling fluid. Such biased data have been corrected by using corrective back calculations, but the representativity may be still questioned.
- There is some measurement bias in transport, especially sorption, data.

Overall, there is only little measurement bias in the data and it does not affect confidence. Bias due to poor representativity is much reduced compared with earlier model versions, but some still remains. The impact on uncertainty can be estimated and is accounted for in the modelling. The limited remaining identified bias is thus not judged to be a major factor in defining the degree of confidence that can be placed in the model.

Some uncertainties remain in the Laxemar site descriptive model, but they are generally quantified, bounded by alternative models or assumptions or judged to be of little importance. The impacts of the quantified or bounded uncertainties are to be assessed in the design and safety assessment.

The block conductivities resulting from the current hydrogeological DFN are judged to be within a factor 2–3 of the real values, but details of the upscaling are still uncertain. Also the need for grouting is likely to be considerably variable because of the idiosyncrasies of the fracture network. It must be noted that the true inflow distribution and the need for grouting in the underground constructions can only be fully known during construction, as assessed by pilot holes and probe holes during tunnel excavation.

The presence of a reaction zone in the rock can probably be used to argue for stable redox conditions also during future glacial episodes. It appears that the deepest penetration of the redox front during the Quaternary is limited to about 50–100 m. There is less confidence in the potential for buffering against dilute groundwaters. Today relatively dilute glacial waters (Ca concentrations below 100 mg/L) are found also at depth, i.e. down to 400 m, but current concentrations do not drop below 40 Mg/L. Current understanding is not sufficient to dismiss the possibility of deep penetration of dilute waters during a glaciation.

Many hypotheses formed at earlier versions of the site descriptive modelling are now discarded or handled by bounding assumptions. Nevertheless, five hypotheses have had to be retained with alternative models developed and propagated to engineering design and safety assessment.

Another prerequisite for confidence is consistency, or at least no conflicts, between the different discipline model interpretations. Furthermore, confidence is enhanced if aspects of the model are supported by independent evidence from different disciplines. Essentially all identified interactions are considered in the site descriptive modelling work. Furthermore, the interdisciplinary feedbacks provide qualitative and independent data support to the different discipline specific descriptions and thus enhance overall confidence.

Only data obtained from underground excavations are judged to have the potential to further significantly reduce uncertainties within the potential repository volume. Specifically, the following aspects are highlighted:

- The range of size distribution and size-intensity models for fractures at repository depth can only be reduced by data from underground excavations. Mapping fractures from the underground openings will allow statistical modelling of fractures in a DFN study at depth and testing current alternative hypotheses on the length distribution.
- Uncertainties in stress magnitude will be reduced by observations and measurements of deformation with back analyses during the construction phase. Complementary direct measurements using short boreholes in different directions may also be performed from underground.
- A more detailed description of the rock and the thermal conductivity distributions from underground investigations will enable thermal optimisation of the repository.
- There is little point in carrying out hydraulic tests in additional surface-based boreholes. The next step in confidence building would be to predict conditions and impacts from underground tunnels. Tunnel (and pilot hole) data will provide information about the fracture size distribution at the relevant depths. The underground investigations will also provide possibilities for short-range interference tests at relevant depth.
- Uncertainties in understanding chemical processes may be reduced by assessing results of underground monitoring (groundwater chemistry; fracture minerals etc) of the effects of drawdown and inflows during excavation.
- The hydrogeological DFN fitting parameters for fractures within the repository volume can only be properly constrained by the mapping of flowing or potentially open fractures in tunnels and associated statistics. Surface outcrop statistics are not relevant for properties at repository depth. During underground investigations, the frequencies of flowing fractures in tunnels and investigations of couplings between rock mechanical properties and fracture transmissivities may give clues to the extent of in-plane flow channelling. This will lead to more reliable models for transport from the repository volume, particularly over the first 5–15 m from canister positions, which may have the greatest impact on overall radionuclide release rates.

Uncertainties outside the repository volume are larger, but are judged to be of less importance.

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