R-08-82

Confidence assessment

Site descriptive modelling
SDM-Site Forsmark

Svensk Kärnbränslehantering AB

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Preface

The Swedish Nuclear Fuel and Waste Management Company (SKB) is undertaking site characterisation 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 characterisation 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 Forsmark site descriptive model, based on the information available at the completion of the surface-based investigations (SDM-Site Forsmark). 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 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 certain protocols and the associated workshops have proven to provide an excellent forum for overall cross-discipline integration and to provide insights to the modelling 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 confidence and uncertainty assessment and/or to the report:

- Johan Andersson and Kristina Skagius – managing the confidence assessment work.
- Michael Stephens, Assen Simeonov, Raymond Munier – geology.
- Rane Glamheden, Flavio Lanaro, Rolf Christiansson – rock mechanics.
- Jan Sunderg – thermal properties.
- Sven Follin – hydrogeology and hydrology.
- Marcus Laaksoharju, Ann-Chatrin Nilsson, John Smellie, Eva-Lena Tullborg – hydrogeochemistry.
- James Crawford – transport properties.
- Björn Söderbäck, Per-Olof Johansson and members of the SurfaceNet – the surface system.
- Kaj Ahlbom and the site investigation team at Forsmark.

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 the editor of this report.

In addition, I would like to thank all people working with quality assurance issues connected with databases which form a basis for uncertainty and confidence assessment. In particular, Göran Rydén, Allan Stråhle and Stefan Sehlstedt are acknowledged.

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

Anders Ström

Site Investigations – Analysis.

Summary

The objective of this report is to assess the confidence that can be placed in the Forsmark site descriptive model, based on the information available at the conclusion of the surface-based investigations (SDM-Site Forsmark). 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, see e.g. /SKB 2005a and 2006a/. They include assessment 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 Forsmark site descriptive model, based on the data available at the conclusion of the surface-based site investigations, have been assessed by exploring:

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

It is generally found that the key aspects of importance for safety assessment and repository engineering of the Forsmark site descriptive model are associated with a high degree of confidence. The geological model for Forsmark was primarily developed after the completion of the first 3 boreholes (KFM01A, 2A, 3A), suggesting that the geology of the site was relatively straight-forward and homogeneous. Because of the robust geological model that describes the site, the overall confidence in Forsmark site descriptive model is judged to be high. The overall reason for this confidence is 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. Most, but not all, of the low confidence aspects have little impact on repository engineering design or for long-term safety.

Generally, only few data have been omitted from the modelling, mainly because they are judged less relevant and reliable than the data taken into account. These omissions are judged to have little negative impact on confidence. However, in some cases inclusion of these less reliable data could have helped in justifying potentially less conservative values of stress.

Poor precision in the measured data are judged to have limited impact on uncertainties on the site descriptive model, with the exceptions of inaccuracy in determining the position of some boreholes at depth in 3-D space, as well as the poor precision of the orientation of BIPS images in some boreholes, and the poor precision of stress data determined by overcoring (OC) at the locations where the pre-existing deformations in the core exceeded the elasticity limit of the intact rock. These problems are identified and considered in the modelling, and affect uncertainty, but have a limited negative impact on confidence.

Overall there is limited measurement bias in the data and bias due to poor representativity is much reduced compared with earlier model versions. However, some degree of bias due to limited representativity remains in some areas. An important remaining bias relates to the fracture size data, since these have to be based on outcrops and not on data from the underground. However, the impact on uncertainty can be estimated and is accounted for in the modelling. Encountered biases are not judged a major concern for confidence in the model.

Some uncertainties remain in the Forsmark site descriptive model, but 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 uncertainties in the processes involved in groundwater evolution are sufficiently bounded in relation to conditions similar to those of the present day. However, the understanding of processes occurring during a glaciation is less good and uncertainties exist, especially in relation to buffering against infiltrating dilute groundwater.

Many of the alternative hypotheses formed in earlier iterations of the site descriptive modelling work have now been discarded or are handled by bounding assumptions. Nevertheless a few alternative hypotheses needed to be developed into alternative models, to be propagated to safety assessment or engineering. These alternative models concern: fracture size and intensity modelling in the geological DFN; geometry, connectivity and transmissivity of deformation zones in the regional domain; hydraulic properties and connectivity of the fracture network of a scale less than the deterministic deformation zone; alternative hypotheses as to groundwater composition and processes; processes for sulphate reduction; and effects of connectivity, complexity and channelling on distribution of flow.

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. Thus, the interdisciplinary feedbacks provide qualitative and independent data support to the different discipline specific descriptions and so enhance overall confidence.

Only data from underground investigations are judged to have the potential to further significantly reduce 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, i.e. from fracture mapping of tunnel walls etc. Specifically it will be necessary to carry out statistical modelling of fractures in a DFN study at depth during construction work on the access ramp and shafts.
- Uncertainties in stress magnitude will be reduced by observations and measurements of deformation with back analysis during the construction phase.
- Underground mapping data from deposition tunnels will allow fore a division of the fine-grained granitoid into different rock types. This will enable thermal optimisation of the repository.
- There is little point in carrying out hydraulic tests in additional surface-based boreholes (cf experiences with KFM08D). 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 excavations 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 mapping of flowing or potentially open fracture statistics in tunnels. 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 which will lead to more reliable models for transport from the repository volume, particularly close to deposition holes where the most important retention and retardation of any released radionuclides may occur in the rock barrier.
- More data on the near-surface rock, as well as on the depth and properties of the Quaternary deposits in the access area may be needed for detailed layout planning of the access.

Uncertainties outside the repository volume are larger, but are judged to be of less importance. More surface-based boreholes outside the local tectonic lens would only marginally decrease uncertainty.

Contents

1 Introduction

This report is a confidence assessment of the site descriptive model (SDM) for the Forsmark 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

The Forsmark site is located in northern Uppland within the municipality of Östhammar, about 120 km north of Stockholm. The candidate area for site investigation is located along the shoreline of Öregrundsgrepen. It extends from the Forsmark nuclear power plant and the access road to the SFR-facility in the northwest to Kallrigafjärden in the southeast Figure 1-1. It is approximately 6 km long and 2 km wide. The north-western part of the candidate area was selected as the target area for the complete site investigation work in 2005.

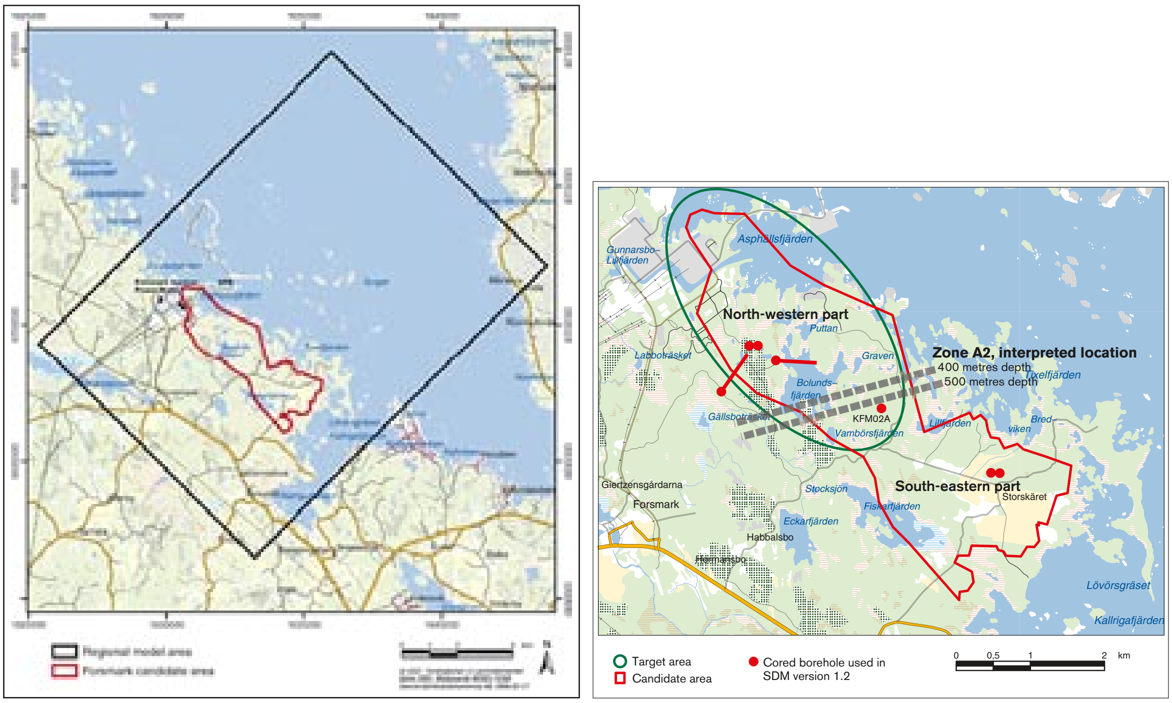


Figure 1-1. *The Forsmark candidate area (red) and the regional model area (black) in the preliminary site descriptive model /SKB 2005a/ (left). The north-western part of the candidate area was selected as the target area for the complete site investigation work (green in the right figure) (modified after Figure 2-15 in /SKB 2005b/).*

Investigations have been in progress in the Forsmark area since February 2002 and have provided data to two data freezes during the initial site characterisation phase and three during the complete site characterisation phase. The surface investigations undertaken comprise aerial photography, aerial and surface geophysical investigations, 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. The drilling activities that provide borehole data to the last data freeze comprise:

- Fourteen deep cored boreholes, 800 to 1,000 m long, both vertical and inclined and reaching vertical depths down to between c 600 and 1,000 m.
- Eleven shorter cored boreholes (100 to 600 m long), both vertical and inclined, reaching vertical depths down to between c 100 and 500 m.
- Thirty-eight percussion-drilled boreholes reaching vertical depths down to 200 m.
- More than 100 soil/rock boreholes through Quaternary deposits.

Information from the siting and construction of the three nuclear reactors at Forsmark and the pre-investigations and construction of the final repository for low- and intermediate-level reactor waste (SFR) is also stored in the SKB databases. These data are used in the site descriptive modelling, although noting that these “older” data is of lower quality than those collected during the current site investigation. Full references to the reports describing the data are given in the Forsmark SDM-Site /SKB 2008/.

The Forsmark area consists of a crystalline bedrock that formed between 1.89 and 1.85 billion years ago during the Svecokarelian orogeny and it has been affected by both ductile and brittle deformation. The ductile deformation has resulted in large-scale, ductile high-strain belts and more discrete high-strain zones, and the brittle deformation has given rise to large-scale fracture zones. Tectonic lenses, in which the bedrock is much less affected by ductile deformation, are enclosed between the ductile high strain belts. The candidate area is located in the northwesternmost part of one of these tectonic lenses.

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. 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 /Stephens et al. 2007/.

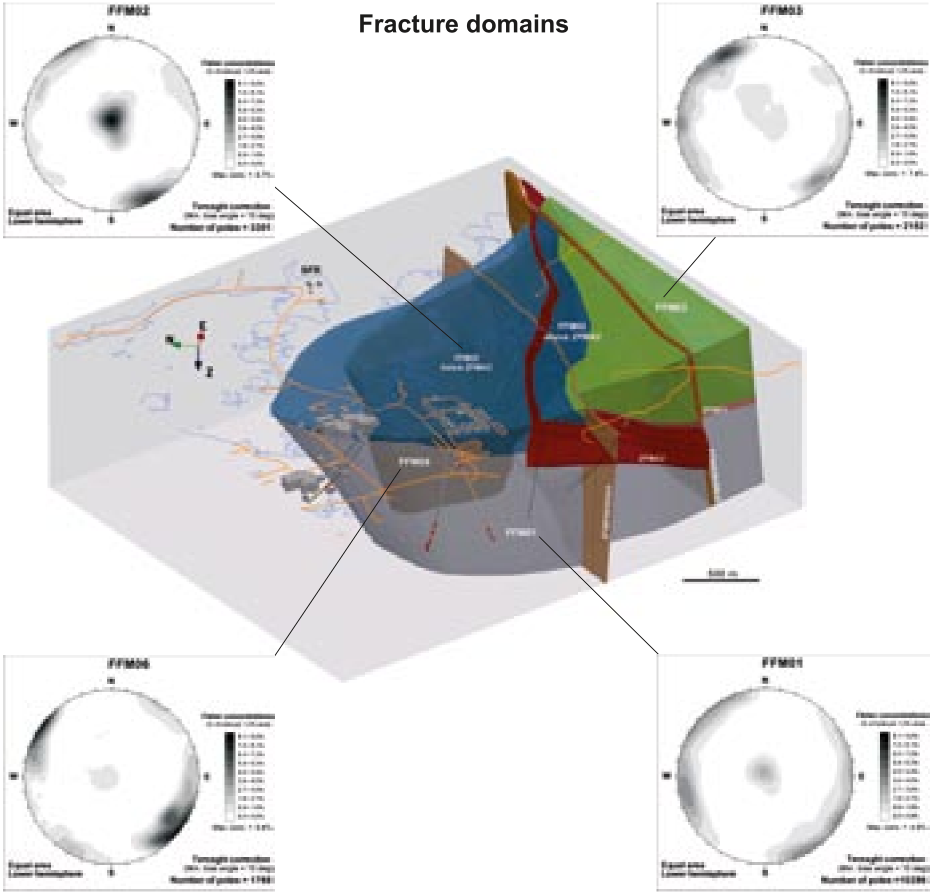
1.2 Need for uncertainty and confidence assessment

A site descriptive model will always contain uncertainties, but a complete understanding of the site is not required. The site characterisation 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 2005a and 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.

Fracture mineralogy
calcite-chlorite-laumontite-adularia-hematite-(clay minerals-pyrite-quartz-asphaltite-goethite) and "no mineral"

Fracture mineralogy
calcite-chlorite-(adularia-prehnite-hematite-laumontite-quartz-clay minerals-pyrite) and "no mineral"



Fracture mineralogy
chlorite-calcite-adularia-hematite-laumontite-quartz

Fracture mineralogy
calcite-chlorite-laumontite-adularia-hematite-quartz

Figure 1-2. *Three-dimensional model for fracture domains FFM01, FFM02, FFM03 and FFM06 in the north-western part of the Forsmark tectonic lens, viewed towards the ENE. The local model block is shown in pale grey. The gently dipping and sub-horizontal zones A2 and F1 as well as the steeply dipping deformation zones ENE0060A and ENE0062A are also shown (Figure 5-34 of SDM-Site Forsmark, /SKB 2008/).*

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 Forsmark site descriptive model based on the information available at the conclusion of the surface-based investigations (SDM-Site Forsmark). 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?

A site descriptive model will always contain uncertainties, but a complete understanding of the site is not 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. Even if the construction and detailed investigation phase does not imply potential radiological hazards, it would still be required that 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 the long-term safety. In summary, SKB's safety assessment SR-Can /SKB 2006b, 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 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. At Forsmark, the extent of the low permeable volume needs firmer confirmation. Within this volume it should be further assessed whether it can be described by a traditional DFN, or whether it is an extreme channelling system. The fracture size and transmissivity correlation also need to be studied. The remaining 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 *were collected and used as far possible in the biosphere models*.

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 /Brantberger 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, and on operational issues and safety assessment issues that impact construction and operations. The SER:

- 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.
- Assesses and presents conditions that may place constraints on the layout from the safety assessment point of view. Typically, this concerns respect distances to deformation zones, thermal dimensioning and application of avoidance criteria for deposition holes with respect to large fractures and unacceptable hydraulic conditions.
- Recommends ranges for the repository depth, based on feedback from SR-Can /see SKB 2006b, section 13.6.8/ and 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 licences application (Step D2), the geological constraints and engineering guidelines provided in SER cover the site adaptation of the final repository with respect to: (1) unsuitable deformation zones and rock mass conditions at depth, (2) parameters that affect the depth and areal size of the repository, and, (3) 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. 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.

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 characterisation data base, see chapter 2;
- Key remaining issues and their handling, see chapter 3;
- Handling of alternatives, see chapter 4;
- Consistency between disciplines and, see chapter 5;
- The main reasons for confidence and lack of confidence in the model, see chapter 6.

The protocols are based on the protocols 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.

- Uncertainty, confidence and consistency between disciplines have been a standard agenda item at the regular site descriptive modelling team meetings, held about every 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.
- At the end of the site modelling processes (i.e. in late September 2007) the assessment protocols, see above, 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 November 2007) 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 allows direct feedback from other disciplines and from the safety assessment and rock 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 for factual check and corrected when needed.

This means that the final answers to the protocol questions, as documented in this report, represent *the consensus view of the integrated 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 characterisation 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 for 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 Forsmark 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 Forsmark SDM-Site /SKB 2008/. Nevertheless, the users of the primary data, i.e. the site modellers, need to check their confidence in this data too, 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 it 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 are 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 strict 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:

- *Lineaments interpreted from topographic, bathymetric and airborne VLF data.* The significance of these data has been assessed and it has been found that the geological significance of lineaments at Forsmark based on these data sets is uncertain. Therefore, these data have not been used as a basis for the deformation zone modelling after model version 1.2. The modelling has instead focused on the magnetic data.
- *Scan-line mapping of fractures carried out in connection with the bedrock mapping programme*. Only fractures longer than 0.3–0.5 m are included in this mapping. The scan-line data could have provided information concerning the spatial variability of fracture intensity, pattern and orientation in the DFN modelling work.
- *Estimations of the dip of magnetic anomalies reported in /Bastani and Kero 2004/*. The geological significance of these data is uncertain. Measurements of tectonic foliation and rock contacts at the surface and along boreholes are judged to be more reliable.

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. The omissions should thus, if anything, enhance confidence.

2.2.2 Rock mechanics

The following rock mechanics data have not been used:

- *Information from percussion boreholes (however considered in the geological model).* These data were judged insufficient and irrelevant for determining rock mass mechanical properties. The empirical methods used to derive rock mass mechanical properties require frequency, orientation, aperture, roughness and infillings of the fracture that are not provided by percussion boreholes. The theoretical approach makes use of the geological DFN model. The DFN model does not consider percussion borehole information. Furthermore, the percussion boreholes reach only shallow depth (around 100 m) and are thus of minor interest.
- *Previous characterisations of the rock mass at SFR*. Previous characterisation at the operational waste facility SFR are at shallow depth and lie outside the candidate area. These data are hence of marginal relevance for the target volume.
- *Stress measurement data other than the overcoring data*. A stress model based entirely on data from the hydraulic (HF and HTPF) methods was excluded because the magnitudes obtained from these methods were not in agreement with the stress magnitudes obtained using other methods. This problem is well known for these hydraulic methods when both horizontal stresses exceed the vertical stress. While efforts were made during the complete site investigation stage (CSI) to overcome this issue, the testing procedure was assessed to be unsuccessful. In addition the predominance of open gently dipping fractures at Forsmark restricted the application of the HTPF method. The stress model developed for Forsmark is based on the measurements that indicated that both the maximum and minimum horizontal stresses are greater than the vertical stress. This stress model is in agreement with the general state of stress in the Fennoscandian shield as assembled in the Rock Stress Data Base /Stephansson et al. 1991/. Neglecting the low magnitudes from the HF and HPTF test methods leads to a conservative (i.e. higher) estimation of the *in situ* stresses.

Generally, only few data have been omitted from the rock mechanics modelling, mainly because they are judged less reliable than the data considered. Basing the stress modelling on the overcoring data leads to higher stress estimates than suggested by the omitted data. These omissions are judged to have little or no negative impact on confidence. It is also noted that high stress magnitudes are a potential issue for engineering and long term safety. Omitting the hydraulic fracturing data is conservative in this respect.

2.2.3 Thermal

The following thermal data have not been used:

- *Temperature loggings in KFM01D, 05A, 06A, 07A, 08A, 08D, 09A and 10A.* These borehole data have been rejected because of low quality. KFM09A was not used because it lies outside the candidate area. The impact of not considering these data is judged to be small.
- *Density loggings from boreholes KFM02A, KFM06C, KFM08C and KFM09A used to investigate spatial variability.* These data were not used because of very high noise levels (> 20 kg/m^3) or because the borehole lies outside the candidate area and was not considered relevant. The impact of not considering these data is judged small.
- *Heat capacity calculations from thermal conductivity and diffusivity measurements (TPS)*. These data are associated with bias because of the anisotropic character of the rock – due to foliation and lineation. Omission of these data has little impact, since direct measurements of heat capacity by the calorimetric method have also been performed.
- *Boremap data in some boreholes*. Not all boreholes were used as input for the geological spatial variability simulations because of limitations of the method. Including more borehole data and performing more geological simulations would have given more representative size distributions of subordinate rocks and, as regard proportions of thermal rock classes, better agreement with the geological rock domain model. The impact of not considering these data on the lower tail of the thermal conductivity distribution at canister scale is, however, judged to be small.

With the exception of boremap data, only few data have been omitted from the thermal modelling, mainly because they are judged less reliable than the data considered. The omissions are judged to have little negative impact on confidence.

2.2.4 Hydrogeological

The following hydrogeological data have not been used:

- *Hydraulic tests in boreholes drilled at SFR, Forsmark power plant and Finnsjön.* The measurements are of a low quality and it has been judged not meaningful to go into detail regarding the evaluations of these tests. The expected impact is probably minor, if any.

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

2.2.5 Hydrogeochemical

The following hydrogeochemical data have not been used:

- *Observations with representativity problems.* Many hydrogeochemical observations are excluded from the detailed modelling due to representativity problems. The data quality is partly dependent on the drilling water content and the potential for short-circuiting along the borehole. All the data are representativity checked and classified in 5 categories. The data used for detailed modelling are generally categorised as 1–3 and also the non-representative data provide qualitative information about the groundwater composition. However, samples strongly influenced by drilling fluid cannot be used.

Generally, the data omitted from the hydrogeochemical modelling are judged less reliable than the data considered. These omissions should thus, if anything, enhance confidence.

2.2.6 Transport

The following transport data have not been used:

- *Old Finnsjön data*. These data were excluded already in version 1.1, see /SKB 2004/, since they had incomplete geological or hydrogeochemical information and thus were not of a sufficient standard compared to the methods decided to be generally established for the site investigations. The data are too uncertain to be of real value.

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

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.
- *Chemistry data on hydrology and near-surface hydrogeology.* These data are used in the conceptual modelling, but not in the numerical modelling since the code MIKE SHE does not handle density driven flow. The impact on numerical modelling using MIKE SHE is analysed by comparison of results from the bedrock hydrogeological modelling in which density driven effects are considered.
- *Parts of time series data for some boreholes in the modelling of near-surface hydrology*. These data have not been used in some analyses due to disturbed conditions.

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.

- *Boremap data from percussion boreholes:* Assessment of rock type, identification of fractures, estimations of fracture frequency and identification of fracture minerals are all of low quality. This quality has not been quantified. However, it is important in the consideration of the quality of data generated from percussion boreholes and the single-hole interpretations of these boreholes.
- *Boremap data from cored boreholes*: Major errors in the core logging have probably been detected, but minor mistakes could go undetected. Some control on the reproducibility of core logging data, recorded in Boremap, has been made by letting the core logging teams from the two different sites (Laxemar and Forsmark) re-map cores already mapped by the other team /see Glamheden and Curtis 2006, Petersson et al. 2006, Carlsten et al. 2006/. Due to the poor

precision in data not visible in BIPS (Borehole Imaging Processing System), these data have been excluded from analyses of orientation.

- *Position of some boreholes at depth in 3-D space*: The range of uncertainty has been quantified /Munier and Stigsson 2007/ such that it can be propagated into the geological modelling work.
- *Orientation of BIPS images in some boreholes (e.g. KFM02A).* The range of uncertainty has been quantified /Munier and Stigsson 2007/ such that it can be propagated into the geological modelling work.

Only few of the used geological data are judged to have significantly poor precision. However, the quantified error ranges in determining the position of some boreholes at depth in 3-D space as well as the error ranges of the orientation of BIPS images in some boreholes (e.g. KFM02A) were both considered in the geological modelling work.

2.3.2 Rock mechanics

Precision is judged low for the following rock mechanics property data.

- *Tilt test results on fractures.* Tilts tests are used as a preliminary screening tool and because no confinement can be applied the shear strength obtained from such tests have limited application. Direct shear tests provide strength and deformation properties in the range of normal stress values expected. The results from direct shear results are used in repository design. The procedures for establishing the normal stiffness of the joints was modified during the CSI to account for the high stiffness values of the Forsmark intact rock. The results from the improved testing method were used in the theoretical rock mechanics model and are not considered to increase the uncertainty in the derived rock mass values.
- *Laboratory data on compressive and tensile strength.* Micro cracking due to release of stresses (sample disturbance) during coring may reduce the measured laboratory compressive and tensile strength values. The strength values from disturbed samples underestimate the actual *in situ* strength and therefore the derived strength values are conservative if microcracking occurs. The stress release process increases with depth. Measurements to assess the magnitude of this process with depth at Forsmark indicate that the effects of this process are minor at repository depth.

The uncertain precision of the rock mass quality impacts on the uncertainty of the mean value of the derived mechanical properties of the rock mass. Within the target volume these are quantified to ± 2–3% for the deformation modulus and to ± 3–7% for the uniaxial compressive strength. For other domains with less available data as well as for deformation zones, the uncertainty increases.

Precision is judged low for the following used stress data:

- *Stress data determined by overcoring (OC) at the locations where the measured strains are nonlinear and/or exceed the elastic limit*. At these locations the scatter in the stress magnitudes can be significant. But the mean value is judged to be precise.

The uncertainty in estimated *in situ* maximum horizontal stress is estimated to be within ± 15–20% in magnitude and within ± 15–20 degrees in trend. The estimation of the stresses by using indirect observation methods, see /Martin 2007/, has increased the confidence of the estimation of the *in situ* stresses.

2.3.3 Thermal

Precision is judged low for the following thermal data.

- *Large-scale field measurements in cored boreholes of anisotropy of thermal conductivity.* Individual temperature sensors in the boreholes have poor precision, but the data are more precise for the overall evaluation of anisotropy. This is supported by results of other field methods.

- *Thermal conductivity calculated from modal analyses (SCA).* These data are judged to be less precise than direct measurements.

These spread in 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

Precision is judged low for the following hydrogeological data.

- *Results from WireLine-tests and airlift-pumping*. These results generally have less precision than other hydraulic tests due to the prevailing low permeability conditions. No quantification of the precision is available.
- *The measurement threshold of the Posiva Flow Log (PFL) test*. It is found to be sensitive to high flow rates in the upper part of the cored boreholes. A quantification of the inaccuracy is available, see /Pöllänen and Sokolnicki 2004/.
- *The interpretation of pumping tests and flow logging in percussion-drilled boreholes.* It is highly sensitive to changes in the drill bit diameter due to wearing.
- *Transmissivity values for sediment-filled fractures.* This may influence transmissivity values in the upper c 50–100 m.

This is handled in the uncertainty assessment of the hydrogeological model, see /Follin 2008, section 8.5/. Poor precision in the data is judged to be a minor contributor to the overall uncertainty.

2.3.5 Hydrogeochemistry

The sample precision of major components and stable isotopes are judged to lie in the range (± 5–10%). The effect of these errors on the interpretation and uncertainty in the hydrogeochemical characteristics of the site are assessed by /Laaksoharju et al. 2008/, in their section on explorative analysis of these data. The concentrations of colloids, gases and microbes can have poor due to sampling difficulties, contamination effects or analytical problems. Many of these effects are well known and handled when judging the analytical results.

2.3.6 Transport

Precision is judged low for the following transport data.

- *Sorption data.* General uncertainties included in the evaluation of sorption coefficients and diffusivities are addressed and discussed by /Widestrand et al. 2003/.
- *In situ resistivity measurements.* The precision of these measurements depends on, among other things, the assumed water composition of the pore liquid. The overall impact of various uncertainties upon effective diffusivity is thought to be less than an order of magnitude within the target area /Crawford (ed) 2008/.
- *Diffusivity data.* There is a mismatch between laboratory and *in situ* measurements of diffusivity that is partly a result of stress release/core damage in samples measured in the lab. Effective diffusivities based upon laboratory data are consequently about an order of magnitude higher than corresponding values estimated from *in situ* data.

These findings are handled in the uncertainty assessment of the transport model, see /Crawford (ed) 2008/.

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.
- *Data for unsaturated zone parameters (pf-curves).* These data types have large impact on the estimates of run-off and discharge dynamics in the streams. The modelled discharge and water levels show good agreement with measurements, indicating that the assumptions made in the model are fairly good.
- *Depth of the overburden (Quaternary deposits) in terrestrial areas and also in outer marine areas.*
- *Production of biomass and standing stocks of biomass in the sea.*

The findings are handled in the uncertainty assessment of the near surface model, see /Lindborg (ed) 2008, section 6.3/.

2.4 Bias

Bias, i.e. to what extent the mean of the measured data deviate 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.

- *Data bearing on the size of fractures*. Data are only available from the surface and near-surface. This is of significance for fracture size-intensity analyses in DFN modelling for repository depth (c. 500 m). This bias can only be handled by data acquisition in connection with underground characterisation data.
- *Seismic reflection data.* Data are lacking in approximately 50% of the regional model area, outside the local model area (essentially north-east of the Singö deformation zone). This is of significance for the identification of gently dipping fracture zones and the hydrogeological modelling work at a regional scale. Only acquisition of new data can resolve this issue. Since this concerns a bias outside the local model area, the resulting uncertainty is not a problem for safety or engineering.

These biases are accounted for in the geological modelling, see /Stephens et al. 2007/. The bias in the fracture size data results in significant uncertainty in this important property.

2.4.2 Rock mechanics

There is judged to be some bias in the following rock mechanics property data.

- *Sampling for mechanical testing.* The sampling has prioritised the homogeneous sections (in rock type 101057) – as partly required by the testing method. However, this means that the measured spread in data is less than actual *in situ* spatial variation. There is also much less information from the rest of the candidate area, but this concerns volumes outside the potential repository area. The sampling approach is not considered to have any significant effect on the uncertainty in the rock mechanics model.

- *Laboratory data on the secondary rock types*. Data on secondary rock types in the candidate area (e.g. pegmatite, amphibolite, aplite) are limited.
- *Reproducibility of the laboratory results.* This has been checked by inter-laboratory comparisons. No significant differences between the laboratories' results were detected for the non-destructive tests. Differences in the laboratory results were observed for the destructive tests. The reasons for the differences could not be identified because the number of tests was very limited, i.e. the differences could be attributed to the natural variability in rock testing. The differences between the laboratories' results for the destructive tests were not judged to be significant.

However, even if though there are some potential biases in the rock mechanics property data, their impact on the uncertainty in the rock mechanics properties is judged low, since even considering the largest range of potential bias would only have insignificant impact on the properties.

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

- *Orientation of the instrument or fractures and temperature changes during reading cause scattering of the results.* These types of errors have been handled by improving the testing procedure.
- *Data on the minimum horizontal stress as estimated by the HF and HTPF methods.* These data have a large bias. Therefore these data have not been used when analysing *in situ* stresses.

The potential biases are thus accounted for in the stress modelling, see /Glamheden et al. 2007, 2008/.

2.4.3 Thermal

There is judged to be significant bias in the following thermal data and interpretations.

- *Using modal data in the SCA method.* SCA data have been compared with TPS data, but no corrections of SCA data have been made.
- *Representativity of modal analyses and TPS data*. For some subordinate rock types, representativity may be moderate to low due to few samples and possible biased sample selection.
- *Calculated heat capacity by the TPS method.* It may be biased due to the anisotropy within the rock. This has been dealt with by making direct determinations of heat capacity by the calorimetric method.

These biases are accounted for in the thermal modelling, see /Back et al. 2007/.

2.4.4 Hydrogeology

There is judged to be little bias in the hydrogeological data. Data from cored boreholes are sensitive to the trend and plunge of the fracturing relative to the orientations of the boreholes. However, there are several boreholes in different directions, which relaxes the problem significantly.

2.4.5 Hydrogeochemistry

There is judged to be significant bias arising in the following functions affecting the hydrogeochemical data.

- *Contamination from drilling fluids*. Contamination from drilling fluid affects representativity. Such biased data can be corrected by using back-calculations for conservative species such as Cl and ^{18}O, but representativity may still be questioned for less conservative species (e.g. Mg, SO_4).

- *Uneven data representation.* There are few data from low-angle transmissive single fractures and a lack of samples from depths greater than 700 m. This means that there is little information at depth although the information available from porewater chemistry can support process understanding, though not the quantitative process modelling.

These biases are accounted for in the hydrogeochemical modelling, see /Laaksoharju et al. 2008/. The uncertainty is partly handled by insight and process understanding from other sites (Laxemar; 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.

- *Sorption data for specific solutes and water types* may be biased by small sample sizes.
- *Sorption K_d values for redox sensitive solutes (U/Np)* may be underestimated (i.e. too low) for reducing conditions at repository depth due to the difficulty of maintaining appropriate redox conditions in laboratory measurements.
- *In situ resistivity measurements* used to estimate formation factors may be biased by EDL (electrical double layer) diffusion effects possibly giving overestimates of effective diffusivity *in situ.*

These biases are accounted for in the transport modelling, see /Crawford (ed) 2008/.

2.4.7 Near surface

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

- Precipitation data are biased for several reasons, mainly under-estimation due to wind losses. However, these biases are corrected using standard procedures.
- There are few measurements of hydraulic conductivity in the vertical direction. This bias is accounted for by use of generic data.
- There are few measurement of hydraulic conductivity of till.
- There are few measurements of hydraulic conductivities of sediments and peat. To ensure representative values, the database has been complemented with generic data.
- Most data on Quaternary deposit depth are from the central parts of the regional model area, which means that detailed knowledge about Quaternary deposit depth in the outer parts of the area is missing.
- Most limnic data are from Lake Eckarfjärden – corrections are not judged necessary (with some exceptions) since the lakes in the area are very similar.

These biases are accounted for in the near-surface modelling, see /Lindborg (ed) 2008/.
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 some 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 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. However, in some cases, inclusion of these less reliable data could have helped in justifying the use of less conservative values of stress.

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

- Poor precision in determining the position of some boreholes at depth in three-dimensional space as well as the poor precision of the orientation of BIPS images in some boreholes had to be considered in the geological modelling work. These factors mainly affect uncertainty in fracture orientation statistics, not, for example, the orientation of modelled deformation zones.
- The precision in stress data determined by overcoring (OC) at the locations where the pre-existing deformation in the core exceeded the elasticity limit of the intact rock is modest. However, estimation of the stresses by using indirect observational methods, see /Martin 2007/, has increased confidence in the estimation of the *in situ* stresses.

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

Some, potential biases in the data are identified.

- There is some measurement bias in chemical and transport (sorption data).
- Possibly, the most disturbing bias in the data concerns data on fracture sizes, which are only available from the ground surface, while there is reason to believe that the fracture size distribution may be different at depth, see /Stephens et al. 2007/. This necessitates considering a wide range of uncertainty in the geological DFN-model that could only be reduced by data obtained from the underground.
- There are also few chemical samples from low transmissive single fractures, and a lack of samples at depths greater than 700 m. This gives lower confidence in the deep groundwater descriptions and fracture domain hydrochemistry, although porewater information can partly be used to indicate the origin and fluxes of water types.

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 on defining the degree of confidence that can be placed in the model.

3 Key remaining issues and their handling

For confidence, it is essential to identify key 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 all key remaining uncertainties of importance and to address the following questions for each such issue:

- Why is the issue important? Does it affect key parameter for safety assessment or engineering? Is it essential for understanding (note that it must be of great importance to qualify as an issue)?
- What is the state of current knowledge and what is the cause for uncertainty?
- How is uncertainty quantified?
- How to handle in the safety case? Is 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 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 1.2 /SKB 2005a/. It was decided to substantially modify the uncertainty auditing protocol in order to ensure that the effort spent in addressing uncertainties concerns key issues – rather than details. Details and minor uncertainties should be discussed in the different discipline specific modelling reports supporting SDM-Site. 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 2006a/, 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 key uncertainties remain in the geological model. They are discussed in the following subsections.

3.2.1 Size of deterministicaly modelled gently dipping deformation zones

The size of deterministically modelled gently dipping deformation zones are important for other disciplines, in particular hydrogeology, rock mechanics (rock stresses) and repository design (respect distances), and consequently for safety assessment. However, the sizes are not an essential fact in developing the conceptual understanding of the site.

The estimated size is based on the modelling of surface seismic reflection data and intersections along boreholes, which are considerably more frequent in the target volume. Current knowledge is judged satisfactory where it concerns occurrence and properties, including orientation. Borehole intersections in the target volume provide some constraints on the along-strike and down-dip extension of these zones, but uncertainties remain in the geometric modelling work.

The gently dipping zones are extended to the nearest steeply dipping zone. In this manner, it is judged that the uncertainty is sufficiently bounded. Complementary seismic reflection data in a tighter network of two-dimensional profiles or in the form of three-dimensional data can reduce the uncertainty, but are judged unnecessary since the uncertainty is bounded.

3.2.2 Orientation and size of possible deformation zones

The orientation and size of structures denoted possible deformation zones in the single-hole interpretations, which have not been modelled deterministically, are uncertain. Some of these zones could be transmissive and connected and are thus of interest from a hydrogeological point of view. It is judged that these structures are either minor zones, see /Stephens et al. 2007/, or borehole intervals affected by an already modelled deformation zone. Furthermore, some minor zones may represent a branch from an already modelled deformation zone. Bearing in mind these comments, it is questionable whether this is a sufficiently important issue to warrant further investigation.

The occurrences of deformation zones in boreholes as well as some properties are known. Established properties include style of deformation, alteration, fracture frequency, fracture orientation and, in several cases, fracture mineralogy along the specific borehole intersections. Uncertainty concerns how to link the possible deformation zones with geophysical anomalies (e.g. a magnetic minimum), in order to establish their orientation and size. Such a link may simply not be possible using the geophysical data available at the ground surface.

These zones have been handled in the statistical DFN model using the assumption that they are minor zones. From the absence of geophysical anomalies it can be concluded that all these sections are less than 3 km in length, but it cannot be ruled out that some of them are longer than 1 km.

3.2.3 Gently dipping and sub-horizontal fractures in the upper part of the crystalline bedrock

There is considerable variation and uncertainty in the size and intensity of gently dipping and sub-horizontal fractures in the upper part of the crystalline bedrock inside the target volume. These structures are potentially highly conductive and may also affect rock mass stability. Thus, the variation and uncertainty affect assessment of stability and groundwater conditions (inflows and drawdown). For this reason, they are important considerations in the construction of the access ramp and shafts, and form part of the basis for a decision on the general location of the access. The recognition of their existence has also improved the geological understanding of the site and the understanding of the *in situ* rock stresses.

Current knowledge is based on a limited number of cored borehole sections in the upper part of the bedrock and the recognition of rock units and possible deformation zones in the single-hole interpretations with some property assignment, including an anomalously high frequency of gently dipping and sub-horizontal fractures. The uncertainty is handled and quantified by assigning the upper part of bedrock inside the target volume to a separate fracture domain (FFM02), within which fracture orientation, fracture size and fracture intensity have been statistically modelled in the DFN work separately from the fracture domains at repository depth (FFM01 and FFM06). The remaining uncertainties concern:

- The boundary between fracture domains FFM02 and FFM01, see Figure 1-2, in three-dimensional space,
- Whether or not and how fractures and possible deformation zones in the upper part of the bedrock can be linked from borehole to borehole.

It is judged that by the fracture domain approach, the uncertainty is sufficiently bounded at this modelling stage. At later stages, i.e. in case the site is selected and after the submission of a license application more data may be needed for the detailed design of the access construction.

Such data could be obtained by a core-drilling programme down to 200–250 m depth in connection with construction of the access ramp and shafts, drilling in the vicinity of these structures and possibly at other locations inside the target volume, and refined analysis of reflection seismic data in the near-surface realm.

3.2.4 Size distribution and size-intensity models for fractures at repository depth

The size distribution and size-intensity models for fractures at repository depth are uncertain. This is of major significance for the understanding of the site. It directly affects the hydrogeology and transport modelling, although the impact of the uncertainty is somewhat reduced by the consideration that these disciplines can also use independent hydraulic data. Since deposition holes need to avoid large fractures, the uncertainty is important for engineering (loss of deposition holes) and safety assessment (assessing impact of earthquakes).

The uncertainty results from the unavoidable bias of the completed statistical DFN modelling work, i.e. that it uses outcrop data to construct a size model for fractures, see also section 2.4.1. Fracture domains FFM01 and FFM06, which include the potential repository host volume, do not intersect the ground surface. For this reason, they lack outcrop data.

The uncertainty is bounded by use of alternative models with their inherent quantified uncertainties, see /Stephens et al. 2007, chapter 6/. These model alternatives cover a broad range of fracture configurations and are judged to bound the overall uncertainty. It is important to note, however, that the model alternatives yield different uncertainties in different size ranges. Therefore, the choice of alternative, or derivative thereof, must be steered by the intended use of the model. Ultimately, the uncertainty can only be further reduced by modelling data from underground tunnel and shaft mapping, obtained from relevant depths, i.e. in volumes where the repository will be placed.

3.2.5 Size and spatial distribution of subordinate rock types

The size and spatial distribution of subordinate rock types is uncertain, especially for anomalously thick amphibolite bodies in domain RFM045, see Figure 1-2. This is of major significance for thermal properties and rock mechanics and, for this reason, is also important for repository design.

Borehole data indicate that amphibolites greater than 5 m in thickness are an uncommon occurrence in domain RFM029, but are more plentiful in domain RFM045. The modelling scale has not permitted a deterministic approach. The uncertainty in the size and spatial distribution of amphibolite bodies in domain RFM045 is related to uncertainty in the representativeness of the bore-hole information, a direct result of the high degree of lithological heterogeneity present.

The simulations of the size and spatial distribution of subordinate rock bodies have been optimised for thermal modelling at the canister scale. For other scales, the uncertainties are greater, which means that the distributions of both larger and smaller bodies are less well described.

3.3 Rock mechanics and thermal

A few key uncertainties remain in the rock mechanics and thermal models. They are discussed in the following subsections.

3.3.1 Rock stresses

Rock stress magnitudes are uncertain even if upper bounds can be provided. There is much less uncertainty in stress orientation and it is judged known within quite narrow bounds. Understanding rock stresses is important for design of the repository in order to mitigate potential spalling and other stability problems and for the assessment of thermally induced spalling.

Current knowledge concerning stress magnitudes is based on both direct stress measurements and indirect methods. These are considered to be reliable /Martin 2007/. No significant stress-induced damage to cores or borehole walls (core disking or borehole breakouts) has been observed down to 1,000 m depth. There is more uncertainty in the stress measurement results for the upper part of the bedrock at Forsmark (FFM02) due to more heterogeneity, but given the relative low values in relation to the rock strength this has little impact on the design and construction of the access ramps or shafts.

The uncertainty is quantified by technical auditing of measurement results, statistical data analysis and numerical modelling. It is judged sufficiently well bounded for the current phase. The uncertainty in stress magnitudes cannot be removed using current surface based borehole exploration methods because of the limitations of the overcoring and HF and HPTF methods. Development of new stress measurements methods has not occurred in the past 20 years and therefore the appearance of new technology that would reduce the uncertainty is not expected. Repository design has evaluated the impact of under and over estimating the stress magnitudes. Uncertainties will be reduced by observations and measurements of deformation with back analysis during the construction phase. This input will later allow for revision of the detailed design, if needed.

3.3.2 Lower tail of thermal conductivity distribution

The thermal conductivity distributions, and especially their lower tails, are uncertain, see /Sundberg et al. 2008/. Since the repository is designed with a maximum temperature criterion for the bentonite buffer, this results in a larger designed repository if the rock is low conductive. In order to design the repository, the lower tail of the thermal conductivity distribution must be described adequately. If the modelled lower tail is less conductive than in reality this results in potentially unnecessarily large canister spacing in the design.

Thermal conductivity at Forsmark is in general high. However, in some parts of the rock domains there is a lower thermal conductivity and especially the occurrence of low conductivity amphibolite bodies in rock domain RFM045 has a large impact on the lower tail of the distribution. There are uncertainties in the typical length distributions for subordinate rocks and in the spatial heterogeneity for thermal conductivity.

The uncertainty is not quantified, but it is judged that the amphibolite body sizes are overestimated. This will overestimate the size and extent of the lower tail, i.e. there will be a tendency to estimate thermal conductivities lower than those actually present. Underground mapping data from deposition tunnels will allow for a division of the fine-grained granitoid into different rock types. This will enable further thermal optimisation of the repository layout with respect to thermal loading.

3.4 Hydrogeology

There is generally high confidence in the overall conceptual hydrogeological model, see /Follin 2008/. There are few major uncertainties inside the candidate area, whereas some remain outside this volume due to the lack of data outside the candidate area.

3.4.1 Hydraulic properties of the rock mass in the potential repository volume

There are remaining uncertainties in the spatial variation of hydraulic properties of the rock mass (e.g. hydrogeological DFN) in 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 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.

The uncertainties are much reduced compared with previous model versions, see /Follin et al. 2007ab/. A large number of PFL-tested boreholes show a consistent picture and confirms the existence and extent of the low permeability volumes at depths in FFM01 and 06. The PFL data are also largely consistent with the PSS-data and the differences are understood. The predicted high transmissivity frequency in the near-surface rock, but with PFL-anomalies only in locations of deformation zones at depth were also essentially confirmed by the later data from the borehole tests. The only deviations were insignificant differences in the locations of the intercepts between the borehole and the deformation zones. There were no hydraulic responses in the possible deformation zones. Interference tests suggest that the rock mass between the transmissive deformation zones is a very low permeable medium, but the interpretation is uncertain. Nevertheless, all responses found at depth are connected to the zones. Tests show very quick, large and stable responses in the connected system.

The existence of highly transmissive fractures near the surface is consistent with the assumed stress relaxation during deglaciation (horizontal sheet joints). There are hydrogeochemical evidences for tight rock at depth – see section 3.5. The very few gently dipping deformation zones NW of deformation zone A2, see Figure 1-2, makes the rock very competent. The absence of gently dipping deformation zones in this volume is in turn likely related to sheath fold resulting in the variation in orientation of the amphibolites that change from gently dipping in SE to more steeply dipping in NW.

A systematic analysis of the hydraulic and stress data have been carried out to explore possible relationships between the measured transmissivity values and the normal stress acting on the hydraulic feature, see /Follin et al. 2008/. The main findings from these analyses are listed below.

- No relationship was found between transmissivity and normal stress for the steeply dipping fractures. Since the normal stress ranged from 10 to 40 MPa this is to be expected since when the confining stress on laboratory samples exceeds 10 MPa, little or no decrease in transmissivity occurs.
- There is some evidence that the transmissivity of the gently dipping fractures decreases with depth. However, because both the frequency of open gently dipping fractures decreases with depth and the normal stress is also increasing with depth it is not possible to sort out cause and effect for these gently dipping features.
- Comparison of the fitted parameter values in the empirical equation that links stress and transmissivity shows that there is no agreement between the *in situ* values and the laboratory values.
- Comparison of the dilation and slip potential of the fractures and the measured transmissivity values shows that there is no increase in transmissivity as the slip and dilation potential increases or decreases.

There does not appear to be sufficient evidence from these analyses to support the notion that the magnitude of the flow along the fractures at Forsmark is solely controlled by the 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 uncertainty is described by the hydrogeological DFN model adapted to the different fracture domains and depth intervals. The model also predicts the intensity of currently non-connected open fractures. There is no alternative parameterisation – but the suggested model is informed by sensitivity analysis.

The Poisson process assumed for the hydrogeological DFN is not fully correct, but dividing the rock into fracture domains and different depth domains within the fracture domains mitigates this problem. The potential correlation between transmissivity and size is unknown, but there are indications suggesting semi-correlations. This uncertainty does not affect the local flow properties, but is of importance for migration.

It should also be noted that the essential characteristics of the hydraulic properties are captured by the PFL-anomalies, being the input to the DFN models. A PFL-anomaly represents an occurrence of groundwater flow discharging into a pumped borehole. Such flow could only occur for a transmissive fracture connected to the overall fracture network. The statistics on primary data thus provide a direct quantification of the variability of local flow, independent on any further assumption made in the DFN modelling. The DFN model is in fact calibrated to this flow variability.

The implications of the bounded uncertainty will be addressed in SR-Site. There is little point in obtaining information from additional surface-based boreholes. It is worth recognising that the prediction of hydraulic properties made prior to drilling borehole KFM08D largely coincided with the measured outcome after drilling, see /Follin et al. 2008/. This demonstrates that there is already a good coverage of boreholes all showing 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. The underground constructions will also provide possibilities for short range interference tests at relevant depth.

3.4.2 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 it is 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.

The hydraulic properties of HCDs, their spatial variability, anisotropy and scaling inside the target volume are uncertain. The HCD spatial distribution is strongly based on the deformation zone model. The geological deformation zone model is stable – and shows good correlation with hydraulic data, see /Follin et al. 2007b, 2008/. There are hydraulic data from all zones larger than 3 km inside the repository volume and from most deformation zones larger than 1 km. Several zones have two or more borehole intercepts. The available data show that there is both depth dependence and spatial variation within a deformation zone. Results of interference tests show that the HCDs form a well-connected system. The HCD model is calibrated to all these data. The data also show that the gently dipping and north-west zones are more transmissive than the north-east zones. This is qualitatively consistent with the orientation of the stress field.

The heterogeneity in the deformation zones is conceptually modelled as a discrete fracture network, of different character than the DFN in the rock mass between the zones. The most transmissive parts of the zones appear concentrated outside the zone core. However, in the numerical modelling, the zones are simplified to be represented as heterogeneous planes, where the spatial variability in the plane of the deformation zones is described as a non-correlated log-normal distribution. The spatial scale of variability is set to the size of the discretisation cells. The real scale of variability is not known.

Simulations show that particle paths inside the zones are strongly affected by the in-zone spatial variability, but their contribution to transport resistance is relatively small. It is possible to bound the impact – see further section 3.6.

3.4.3 Hydraulic properties outside rock domains RFM029 and RFM045

Hydraulic properties outside rock domains RFM029 and RFM04 are of limited importance for safety assessment and engineering at depth. Engineering have possibly additional needs, i.e. in potential locations for access ramp/shaft. Environmental impacts (on wells and wet areas) could also depend on near-surface hydraulic properties outside RFM029. In addition, the regional properties are important for understanding. More specifically, the hydraulic description in the regional scale 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 modelling is questioned.

Existing data from the bedrock south-west of the lens and extending to the Forsmark zone suggest that the fracture frequency increases in domains outside the lens. At depth, the transmissive fracture frequency and transmissivities are larger compared with inside the lens, and orientations differ. However, near the surface, the transmissivity is lower outside the lens by about a factor of 20. This is also consistent with the geological understanding.

Chemical sampling in transmissive deformation zones may be affected by up-coning during sampling, but indicate higher salinity south-west of the lens (cf discussion in section 3.5). Indications of saline water discharge into “Gällsboträsket” – could originate from the deep waters but alternatively instead originate from the stored marine water in the marchland. However, the latter hypothesis is contradicted by a mass balance assessment and possible indications of deeper water discharge, see /Johansson 2008/. Furthermore, groundwater simulations /Follin et al. 2007b/ show that the former hypothesis is consistent with the regional hydrogeological model where discharge could happen here due to the very low permeability of the lens. It should finally be noted that there is a regional groundwater divide between the lens and the Forsmark zone, and there is no need to consider volumes southwest of the Forsmark zone for overall hydrogeological understanding.

There are limited data from depth in the bedrock north-east of the Singö zone. SFR data extend down to about 150 m and they suggest relatively low frequency of transmissive fractures. Interference tests in HFM33 suggest no hydraulic responses across the Singö zone. However, other indications suggest that the Singö zone is not tight everywhere in its transverse direction, see /Follin et al. 2008/. The groundwater head below Lake Bolundsfjärden is about 0.5 m below sea level. This could be caused by the pumping of SFR (i.e. NE of the zone), or alternatively from pumping below the nuclear power plants (i.e. on the SW side of the zone). Before constructing the SFR facility, an overpressure was measured in deformation zone “H2” below the facility. This could indicate a transmissive hydraulic connection to the inland areas.

The upstream boundary conditions appear very robust (water divide). A relatively good understanding of the Eckarfjärden zone (two percussion drilled holes) appear to confirm the hypothesis, and data available from south-west of the lens suggest rock mass properties similar to more typical rock mass. A single parameterisation is given in the hydrogeological model. North-east of the lens there is potential for two alternative models (with and without hydraulic contact across the Singö zone.

Even if there are uncertainties in the conditions outside the lens, they have limited importance for long-term safety or engineering. The importance of these uncertainties were assessed by sensitivity analyses in the flow model and particle tracking already in version 1.2 of the site descriptive model /SKB 2005a, chapter 8/. These analyses are still relevant and show the relative unimportance of the uncertainties in conditions outside the lens for conditions inside the lens. The driving force for local groundwater flow inside the lens is sufficiently bounded by the well defined boundary conditions. Flow simulations of the past evolution suggest that the groundwater composition inside the lens essentially depends on the top-surface boundary and on the properties inside the lens. Thus, the current understanding is sufficient for the long-term evolution. The impact of an open repository is another matter – this may enhance connectivity and may also imply intrusion of groundwaters currently not existing at depth inside the lens. This needs to be assessed – but is most likely not affected by the details of the hydraulic properties outside the lens – but rather governed by the transmissive deformation zones and how the lens connects to these zones. The uncertainty in conditions outside the lens needs to be considered in safety assessment when assessing locations of discharge points. However, more surface-based boreholes outside the lens would only marginally decrease uncertainty and it is instead judged that the current uncertainty bounds are tight enough to make this issue non-important in SR-Site.

3.5 Hydrogeochemistry

Several uncertainties remain in the hydrogeochemical models. However, the only really significant ones of these concern the potential existence of a redox zone and whether the rock has sufficient capacity for buffering against intrusion of groundwater of low concentration of divalent cations.

3.5.1 Current distribution of water composition

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 fairly well known and characterised. There is a fair density of category 1–3 (mostly 2 and 3) water samples. There is a high density of samples from near surface and a fair from depth, but there is some bias in the availability of samples, see section 2.2.5. Data are anyway sufficient to significantly show differences both in major components and key isotopes between water in the gently dipping deformation zones, the relatively highly fractured near-surface rock of fracture domain FFM02, the connected transmissive fractures in fracture domain FFM01 down to about 350 m depth and in the very few connected transmissive fractures in fracture domain FFM01 below 350 m depth. These differences are most likely due to the differences in the transmissivity and connectivity of the water-conducting fractures in these different domains. There is only one sample taken outside the deformation zones in FFM03, which means that it is difficult to make any conclusions about the water composition outside the deformation zones in this fracture domain.

It is possible that some data are disturbed by up-coning caused by pumping during sampling. This is judged not to affect understanding, but could be a reason for not finding one-to-one matches between data and simulated salinity levels in groundwater flow models. Continued monitoring is a means to assess the importance of this.

Groundwater flow simulations of the past evolution since the Littorina Sea stage of the Baltic are now capable of representing the measured data, see /Follin et al. 2007b/ and could also consider the uncertainty introduced by potential up-coning. Some deviations still exists. In some simulated boreholes, the position of high salinity is less shallow than the measured ones. However, this is most likely an effect of the stochastic nature of the flow model, since locations with high salinity near the surface can be found close to, but not exactly in, the simulated boreholes. Analytical accuracy is well understood and quantified.

The uncertainties are judged sufficiently bounded. No further investigations are necessary, and underground investigations can be targeted to confirm the present understanding. Additional insight will be obtained from comparison with other sites (Laxemar; Olkiluoto) and time series data from the monitoring programme.

3.5.2 Overall understanding of groundwater evolution

Understanding the processes involved in groundwater evolution 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.

Present-day reactions are coupled to organic matter and microbiology. However, this near-surface buffering may be much less effective over long time periods, such as during glaciations, with less input of organic matter, than if the reactions were a result of processes of non-organic nature, i.e. weathering of the rock. Many reactions appear to occur at 0–200 m depth (fracture domain specific) with some evidence of oxidation/weathering in cores. The uncertainties are associated with a lack of understanding of the role of microbes and organic matter during a glaciation (e.g. microbial activity and sulphate reduction by methane originating from depth as electron donors). The depth to the redox zone may be very different along single fractures compared with fracture zones. Abundant existence of calcite suggests buffering against dilute groundwater – but the data suggest there are a few transmissive fractures at depth without any fracture minerals, although the latter observation is uncertain. A complementary study was in progress at the time of preparing this report. It aims to provide more detailed information bearing on the significance and origin of fractures that lack a mineral coating or filling and wall-rock alteration.

Modelling has increased understanding of the current dominant processes. Uncertainties are addressed and quantified by using coupled reactive transport modelling and coupling to hydrogeological modelling in an interactive approach /Gimeno et al. 2008, Molinero et al. 2008/.

- The existence of a near-surface reaction zone appears to be well established, but a problem is that the current redox zone is located already in the overburden and that there is no downward water flux. This means that it is hard to find evidence of the redox zone in the rock. The reason for not finding a typical redox front in the upper part of the bedrock is manifold (e.g. the channelled flow in mostly horizontal to gently dipping structures). Furthermore drill cores from the upper 100 m of the bedrock are relatively few so the amounts of samples are limited. However, the existence of goethite is limited to the upper 150 m in the gently dipping zones suggesting this is the maximum depth of oxidation in the past – but the question is whether channelling inside the zone may imply deeper penetration locally.
- Calcite is abundant, suggesting a buffering capacity against dilute groundwater. Quantification is ongoing and will be reported in a separate study.
- For the deeper system, the groundwater composition is a result of mixing, reactions (and also diffusion between fracture groundwater and matrix porewater), hence an integrated groundwater modelling approach is used to describe the effects from mixing and transport. The results can differ depending on how much weight is allocated on reactions versus mixing and hence, the results can differ depending on the selected model for transport. Present understanding achieved from interpretations of the chemistry and the isotope systems supports that both mixing and reactions determines the groundwater chemistry. This uncertainty is judged inconsequential for understanding the trends in future evolution.

The uncertainties in the processes involved in groundwater evolution are sufficiently well bounded for situations similar to that at present day. However, because of limited process understanding, the uncertainties during a glaciation can only be bounded within a quite large range, although the water composition is fairly well known for the glacial water. The uncertainties may be reduced by assessing results of underground monitoring (groundwater chemistry; fracture minerals etc) of the effects of drawdown and inflows during excavation, which will reflect dynamic conditions. Detailed seasonal microbial investigation programme in surface and shallow boreholes will indicate the role of the microbes (performed in e.g. Olkiluoto) during dynamic conditions. Laboratory tests at the Äspö hard rock laboratory may be utilised for addressing the role of the inorganic buffer capacity. Additional sampling of fracture minerals as part of the supplementary investigations may also reduce uncertainty.

3.5.3 Detailed current 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 safety assessment's evaluation of solubility and migration properties for current day conditions.

There is generally fair amount of data although there is a lack of data from low transmissive fractures and from depth.

Uncertainties are assessed as part of the coupled modelling of the system. Uncertainties are due to: i) the amount (%) of drilling water, ii) the hydrogeological complexity, iii) sampling problems (e.g. short circuiting).

The uncertainties are sufficiently bounded due to the strict criteria used in the sample categorisation. Further borehole investigations could support the spatial variability description of the site.

3.5.4 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.

Present meteoric water and current marine water are well defined. Littorina water is also rather well known, but not how it was altered after infiltration. There is also more uncertainty regarding the composition of brine, glacial and potential very old meteoric water. There is a lack of chemical/isotope information concerning highly saline groundwater and a lack of a suitable end member.

The cause for uncertainties may include unknown end-member compositions and ages (several meteoric/glacial waters with different ages). Littorina water affected by fast reactions, such as ion exchange, sulphate reduction, calcite precipitation, may have altered the HCO_3 and SO_4 content, which will affect the mixing calculations. Uncertainties associated with the effect from porewaters on the measured groundwater compositions are analysed. End-member selection is also tested in the hydrogeological modelling and the selection is compared with the selection used in hydrogeochemistry.

The uncertainties are bounded to the extent possible regarding postglacial and present day scenarios. With the exception of a deep borehole (i.e. > 1,500 m) where highly saline groundwater could better be described, further borehole investigations will not decrease the uncertainties. No complementary investigations are necessary.

3.5.5 Explanation of elevated uranium content in the groundwater

Some pegmatites in the Forsmark area contain elevated U contents in the groundwater (documented in the SDM version 1.2 report /SKB 2005a/ under "Geology", see for example

Figure 5-9). It is important to be able to exclude the occurrence of a nearby significant uranium source. However, it is probably even more important to be able to understand why these high values are found, since this affects process understanding, see section 3.5.2.

Different types of uranium mineralisations have been documented from the region, but not inside the target volume, though even there some fracture coatings (i.e. secondary mineralisation) have shown U-phases. Geochemical modelling has shown that the high U contents are limited to waters with mildly reducing conditions and bicarbonate contents over 50 mg/L. However, not all waters with these properties show high U contents, which is interpreted as evidence of an addition of U from an easily dissolvable phase unevenly distributed along the water path ways. U series isotopes measurements support redistribution of U during the last 100,000 years for some fracture coatings. Analyses have shown that the high U contents in the groundwaters cannot be explained by a colloid phase. Very few groundwater samples are available from fractures within fracture domain FFM01, but the indication is that U concentration is lower in groundwater from parts of the rock with low transmissive fractures.

It is clear that the U originated from the fracture minerals – but there are different hypotheses as to why it is so easily mobilised. The mineralisation is clearly connected to mildly reducing conditions – but could also be an indication of past oxidation. The highest U contents are found in groundwaters (associated with a Littorina component) from deformation zones ZFMF1, ZFMA2 and ZFMA4 at depths between 400 and 630 m, but also a possible deformation zone in borehole KFM08A at 546 m depth (devoid of a marked Littorina component) indicates the presence of easily mobilised U.

It is clearly established that the amount of U is small and not related to ore potential. The U phase is associated with the fracture system (not with the rock itself). This means that it has been brought into the fractures/deformation zones by fluid during some event/events in the past. It is probable that the U has been concentrated in the deformations zones, although some may have been transported from these zones into connected single fractures. Analyses of the fracture coatings show large variations. The fractures with the highest U contents and the groundwaters in corresponding sections indicate recent mobilisation of U. This U may at least partly be oxidised. However, the mineralisation is much older than the time of the most recent deglaciation, and should not be seen as an indication of potential for deep penetration of oxidising waters.

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

Some tracers (^{2}H and ^{18}O) that are assumed not to interact with their environment may in fact be reactive. These tracers are used in the hydrogeological simulations of the evolution the last 10,000 years and the uncertainty thus also affects hydrogeological understanding.

However, over the simulation time and conditions studied these tracers are non-reactive. Also trend analysis (^{18}O/Cl) would easily reveal possible deviations from conservative behaviour. Such deviations are not observed. Deviations caused by evaporation are observed for surface waters and Littorina type waters. Weak deviations caused by reactions are observed for the oldest groundwaters at the site.

The uncertainties are sufficiently bounded and quantified. However, they need to be considered in the hydrogeological simulations of the past evolution. Further borehole investigations would not decrease the uncertainties and no complementary investigations are necessary.

3.5.7 Porewater composition in the bedrock at depth

The porewater composition in the bedrock at depth is essentially important for overall understanding and coupling to hydrogeology and palaeo-events such as glaciations and interglaciations. It also affects the stability of engineered barriers and diffusion rates of solute transport. If shown to be consistent with the flowing groundwater composition, the porewater data are also important for demonstrating the existence of a connected matrix porosity.

There are several samples on the porewater composition in the bedrock. Uncertainties in sampling, e.g. unknown distances to the nearest water-conducting fracture if it is not intersecting the borehole and stress-release effects as well as uncertainties in the analytical data because of the small sample, are assessed and shown to be within the uncertainty bounds of the data. However, the question arises whether the data are properly understood. Can diffusion really explain why the matrix water is more dilute and why it appears to have such little spatial variability?

The present conceptualisation points to the existence of a very long period of brackish water (old meteoric ± old glacial + saline mixture) prior to the last glaciation dominating the water-conducting fractures in the Forsmark bedrock down to depths of around 1,000 m, below which there was a transition to more highly saline groundwaters. Within this 1,000 m interval there was a salinity gradient, with generally less saline groundwaters at shallower depths in the bedrock reflecting higher fracture frequency and transmissivity, i.e. more dynamic groundwater flow conditions.

Following the last deglaciation, very dilute glacial melt waters entered the bedrock, establishing diffusion concentration gradients between the porewaters and the, by now, more dilute fracture groundwaters. With the onset of the Littorina Sea stage, brackish waters of higher salinity than the groundwaters resident in the water-conducting fractures penetrated the bedrock, particularly to 500–600 m depth along the highly transmissive, gently dipping deformation zones in the hanging wall bedrock. The Littorina Sea stage was followed by the present meteoric water stage which is still on-going and has only influenced the upper bedrock levels where much of the Littorina has been flushed out during land rise following deglaciation. The data suggest the following.

- Steady-state conditions between porewater and fracture water appear to be confined to the upper 100–150 m where there is a high frequency of highly transmissive fractures in the bedrock.
- The present rock matrix porewaters at depths greater than about 300 m is much older than the dilute glacial melt waters, as indicated by the general lack of $\delta^{18}O$ correlation between porewater and fracture groundwaters, i.e. no indication of a cold climate recharge component from the last deglaciation and the lack of a marine component (i.e. Littorina Sea) in the porewaters, unless close to a water-conducting fracture presently characterised by Littorina Sea water.
- At depths greater than 600 m, steady-state conditions are mostly established between the brackish, non-marine nature of the porewaters and those in the fracture groundwaters; ^{36}Cl measurements have shown that these fracture groundwaters (e.g. KFM08A) are very old (> 1 Ma). There is every reason to suppose that the porewaters between 300–600 m depth are similar in age, but have less of a saline character as they represent the shallower part of the salinity gradient already established prior to the last deglaciation.

These findings are also generally consistent with the understanding of the rate of diffusion between fractures and pores. The difference in concentration between the porewater and the water in the fractures depend on the diffusivity in the rock matrix, the frequency and transmissivity of the water-conducting fractures and on the time available for equilibration.

A concentration/diffusion profile has been measured from deformation zone ZFMA2 down into the surrounding low transmissive host rock. It is possible to detect: a) the old matrix porewaters which dominate away from the major water-conducting fractures, 2) the pulse of the last deglaciation cold climate dilute water, c) the Littorina Sea pulse, and d) the present day meteoric waters closest to zone ZFMA2.

The uncertainties are sufficiently handled in the modelling. No further measurements are needed.

3.5.8 High sulphide content in monitoring data

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

New sulphide data from the monitoring programme indicates 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 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. Equilibrium calculations of these high sulphide waters with respect to ferrous iron monosulphides are described by /Laaksoharju et al. 2008/. A further assessment will be done in SR-Site.

3.6 Transport

Despite inherent difficulties in determining transport properties it appears that much of the uncertainties can be properly bounded by the hydraulic test data. The remaining uncertainties are discussed in the following subsections.

3.6.1 Effects of connectivity, complexity and channelling on distribution of flow

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

/Crawford (ed) 2008/ assumes fractures to be either open over their full extent or closed (annealed) over their full extent when estimations are made of the fracture intensity (total fracture area per volume of rock, P_{32o}) on the basis of fracture frequency (P_{10o}) measured in boreholes. This means that P_{32o} may be either underestimated or possibly even overestimated. Flow channels of limited extent have a low probability of borehole intersection meaning that the frequency of conductive features may be underestimated if open regions of fractures are not hydraulically well-connected. Fractures with flow 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 relevant repository depths.

Contact of surface asperities within individual fractures can lead to significant surface area fractions of open fractures being inaccessible for flow. If this contact area is sufficiently large, potentially conductive channels hosted within fracture planes may be below the percolation threshold. Furthermore, experience from tunnels, although not at Forsmark, does not suggest higher frequency of inflow points compared with what would be inferred based on all open fractures in boreholes. Also, the hydrogeological DFN model of Forsmark clearly suggests very long – but few connected fractures. Furthermore, if channels are very thin or even circular, diffusion into stagnant water means that matrix diffusion depths are larger than the transverse channel width.

There is also uncertainty in the location of fracture terminations. However, the impact of this on the flow related migration parameters is judged small, as long as the model correctly represents the connectivity of the rock mass.

/Crawford (ed) 2008/ handles the impact of some classes of channelling as well as alternative conceptualisations of the matrix diffusion geometry by simulations and scoping calculations (partly with generic data). Consequences of other uncertainties are assessed also by modelling of alternative cases. The impact of fractures with transmissivities less than 10^{-9} m^2/s is handled by scoping calculations of their impact on overall radionuclide release rates from a potential repository. These calculations indicate the following.

- 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 characterisation 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 fracture statistics in tunnels. 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 provide the largest part of the transport resistance /Crawford (ed) 2008/.

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.

3.6.2 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 a reasonably extensive sample from the “altered rock”, see /Stephens et al. 2007/ for an explanation of this word. Good site-specific sorption data are now available for most important classes of radionuclides. Remaining uncertainties relate to spatial variability and differences between the laboratory and *in situ* aqueous chemical environments.

There is now reasonably 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. 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 is quite large for many species. 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. Support for connected matrix properties may be obtained from porewater samples – see section 3.5.7.

The uncertainties are judged sufficiently well bounded and also straightforward to propagate into SR-Site. The impact of the uncertainties will be quantified by way of scoping calculations and sensitivity analyses within SR-Site. Some additional laboratory sorption measurements may be advisable during the construction phase to further reduce uncertainties.

3.6.3 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 (ed) 2008/, it is not possible to fully validate migration modelling of the repository volume. SWIW tests provide qualitative support for a quite high 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.

3.7 Near surface

A few key uncertainties remain in the near surface models. They are discussed in the following subsections.

3.7.1 Hydraulic properties of near-surface rock

The hydraulic properties of near-surface rock are key factors for the near-surface hydrological modelling. This modelling is also important for understanding near-surface chemistry. The hydraulic properties affect drawdown, inflow and grouting requirements in shafts and access tunnels and are thus of importance for engineering. The properties also affect the location of radionuclide migration end points.

The hydraulic description of the near-surface rock is part of the hydrogeological bedrock model and there is substantial support for the existence of a highly transmissive gently dipping fracture network, see section 3.4.1. Surface water balance data are of high quality, and this strongly constrains the near-surface hydrological model.

The uncertainty description of the near-surface rock is part of the bedrock hydrogeological model. Sensitivity analyses, including different boundary conditions, have been made using MIKE SHE modelling and the current description is judged sufficiently well bounded. However, more data may be needed for detailed layout planning of the repository access.

3.7.2 Impact of surface and near-surface hydrology and hydrochemistry on bedrock hydrogeology and hydrogeochemistry

The impact of surface and near-surface hydrology and hydrochemistry, e.g. composition of infiltrating waters, locations of recharge and discharge, geometry and properties of the overburden, on bedrock hydrogeology and hydrogeochemistry needs to be assessed to ensure that the descriptions in the bedrock models are sufficiently detailed for the purposes of these models. There is a need for a consistent conceptual description although details of modelling may differ.

Geometry and properties of till are well known, whereas there are less data on the interface between the Quaternary deposits and the bedrock and on the interface between groundwater and surface water. Uncertainties in temporal variation are handled by comparing the limited time series with longer time series from SMHI (Swedish Meteorological and Hydrological Institute), although these have less local applicability.

Sensitivity analyses using MIKE SHE provide uncertainties in recharge to be used as consistency checks in the bedrock hydrogeological modelling. These show that boundary conditions at depth are quite unimportant in determining recharge.

There will certainly be remaining uncertainties in the near surface hydrogeology. Sensitivity analyses are likely to show that these are unimportant with regard to overall performance – even if the uncertainty locally affects the position of release points or concentrations at them.

3.7.3 Depth of the overburden

The detailed depth of the overburden is important for engineering in assessing the implications of the access. However, details of this are not needed at the time of the license application.

Furthermore, for practical reasons the hydrogeology modelling is based on an earlier version of the depth model ("the 2.2 model"). This had many errors, since the airborne geophysics is uncertain and a new model has subsequently been produced for future use and for use by e.g. engineering. The impact of using the older model in the hydrogeological model is qualitatively assessed to be marginal.

3.8 Assessment

Some uncertainties remain in the Forsmark 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 uncertainties in the processes involved in groundwater evolution are sufficiently bounded in relation to conditions similar to those of the present day. However, the understanding of processes occurring during a glaciation is less good and uncertainties exist, especially in relation to buffering against infiltrating dilute groundwater down to repository depth. It appears that SR-Site will still have to handle the possibility of intrusion of dilute waters during ice-melting.

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 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 analysis during the construction phase.
- A more detailed subdivision of the rock type referred to as fine- to medium-grained metagranitoid (101051) in tunnels 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 fracture statistics in tunnels. 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. More surface-based boreholes outside the lens would only marginally decrease uncertainty. Potentially more data will be obtained from the investigations to be carried out for the potential expansion of the SFR repository.

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 remaining hypotheses needs to be developed into alternatives and propagated into engineering design and safety assessment.

4.1 Auditing protocol

SDM version 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. The table structure of version 1.2 is kept, with obvious revisions and covers:

- Potential "Primary" alternatives of the site descriptive model,
- When the hypothesis was raised and if the need for the alternative now is resolved in SDM-Site Forsmark,
- Impact on other discipline models (or aspects of these models),
- Implications for repository engineering in phase D2,
- Implications for SR-Site,
- Implications for investigations to "resolve" alternative,
- Handling in SDM-Site Forsmark.

It should be noted that these questions essentially are already covered by the questions asked on the remaining key uncertainties. However, the alternative table is retained, since it also keeps track of old hypotheses and because it summarises the alternative hypotheses and modelling handling. Furthermore, while the alternative 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 development of alternative models is an approach that can be used to handle uncertainty. 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 these earlier models. For overview and traceability Table 4-1 list both the currently considered alternatives as well as the previously considered ones. If an old alternative is now considered resolved this is stated in the table, with justification.

Table 4-1. Assessment of alternatives.

Potential "Primary" alternatives in SDM	When was the hypothesis raised and is the need for the alternative now resolved in SDM-Site Forsmark?	Impact on other discipline models (or aspects of these models)?	Implications for repository engineering in phase D2	Implications for SR-Site	Implications for investigations to "resolve" alternative	Handling in SDM-Site Forsmark and need for propagation into design and safety assessment
Surface and near surface description						
None.	Little conceptual uncertainty.					No alternatives developed.
Bedrock geology						
Rock domains – deterministic models at regional and local scales.	Little conceptual uncertainty.	Basis for thermal and rock mechanical modelling is judged sufficient with current geological model.	Indirectly affects thermal and rock mechanics design, but uncertainty judged to be sufficiently bounded.	Indirectly affects thermal and mechanical evolution, but uncertainty judged to be sufficiently bounded.	–	No alternative models developed. Only differences are in data resolution at the two model scales.
Deformation zones and fracture domains – deterministic models at regional and local scales.	The potential for alternative lineament interpretations was raised in model version 1.1, and alternative interpretations were carried out and assessed in model version 1.2. Alternative deformation zone models were also developed in model version 1.2 outside the areas where the data resolution was relatively high in this model version. Data acquisition after model version 1.2 and the focus on magnetic lineaments have radically reduced conceptual uncertainty, not least inside the target volume, and have removed the need for alternative deformation zone models. The remaining major uncertainty concerns the truncation of gently dipping zones.	Geometry of deformation zones is basic input to the hydrogeological model, and is also important for judging the uncertainty in the local stress field.	Layout is restricted by respect distances to deformation zones longer than 3 km. Frequency and location of minor deformation zones are important for the assessment of degree of utilisation, and are also potentially important for rock engineering considerations. However, minor deformation zones lie outside the scope of the deterministic modelling work.	Indirect importance due to their significance for groundwater flow and rock mechanics.	Deterministic location of minor deformation zones can only be resolved by underground data, e.g. tunnel mapping.	No alternative models developed. Only differences are in data resolution at the two model scales delivered. A conservative approach has been adopted in the truncation of the gently dipping zones (extended to the nearest steeply dipping zone). In this manner, it is judged that the uncertainty is sufficiently well bounded within the target volume.

Potential "Primary" alternatives in SDM	When was the hypothesis raised and is the need for the alternative now resolved in SDM-Site Forsmark?	Impact on other discipline models (or aspects of these models)?	Implications for repository engineering in phase D2	Implications for SR-Site	Implications for investigations to "resolve" alternative	Handling in SDM-Site Forsmark and need for propagation into design and safety assessment
Fracture size and intensity modelling in the geological DFN work.	Several alternative models of the size distribution and intensity, based on different approaches and assumptions for interpreting the field data. Some of these alternatives are less likely, but are conservatively retained to ensure bounding of the uncertainty.	Basis for hydrogeological DFN models and also for assessing rock mass mechanical properties. However, the listed uncertainties are relatively unimportant for these applications. The hydrogeological DFN depends much more on the hydraulic data and the rock mass properties are largely controlled by the intact rock properties.	The uncertainty affects degree of utilisation. The repository layout considers the space needed for the different alternatives.	The implications of the alternatives on the earthquake hazard needs to be assessed in SR-Site.	Issue could only be resolved by data from underground, e.g. tunnel mapping.	Alternatives clearly described for further assessment by repository engineering and SR-Site. Implications for hydrogeology and rock mechanics SDM are assessed to be small.
Rock mechanics						
Rock mechanics properties	Uncertainties are judged sufficiently well bounded.	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 analysis during the construction phase.	No alternative is presented since uncertainties are sufficiently well bounded.
Stress distribution.	The uncertainty is quantified and sufficiently well bounded by technical auditing of measurement results, statistical data analysis and numerical modelling.	Minor.	Stress – strength ratio is important for design of the repository and for assessment of thermally induced spalling.	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 analysis 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. However, the overall judgement is that the thermal modelling result is somewhat conservative.	Minor.	Affects spacing of canisters. Underestimating the thermal conductivity will lead to a conservative layout. The degree of utilisation can possibly be increased by discarding canister positions in rock types with low thermal conductivity (primarily amphibolitic dykes).	Necessary to assess whether buffer temperature criterion is met.	Uncertainties could only be reduced by observations and thermal experiments during the construction phase.	No alternative is presented since a conservative estimate is provided.

Potential "Primary" alternatives in SDM	When was the hypothesis raised and is the need for the alternative now resolved in SDM-Site Forsmark?	Impact on other discipline models (or aspects of these models)?	Implications for repository engineering in phase D2	Implications for SR-Site	Implications for investigations to "resolve" alternative	Handling in SDM-Site Forsmark and need for propagation into design and safety assessment
Hydrogeology						
Geometry, connectivity and transmissivity of deformation zones in the regional domain.	Raised in version 1.1, some alternatives assessed in version 1.2, but issue not fully resolved. Situation SW of the target volume is fairly well known as far as the Forsmark deformation zone. In between there is a regional groundwater divide. However, the situation NE of the target volume is less well established, this both concerns the significance of the Singö zone (is it a flow barrier) and properties of the rock mass NE of it.	Uncertainty in the upstream conditions affects the hydrogeochemical understanding, whereas the uncertainties downstream have relatively little importance for understanding.	Minor, would not affect inflow or grouting needs or degree-of-utilisation.	Minor impact on groundwater flow in repository and in transport resistance, since these depend on the conditions in the local domain. Large impact on how migration paths from a repository may extend outside the target volume. This uncertainty is increased by the very transmissive sheet joints overlain by a less permeable overburden forcing discharge outside the area above the target volume. May affect assessment of open repository, e.g. to what extent there is a possibility of sea-water intrusion into the rock mass.	More surface based boreholes outside the lens would only marginally decrease uncertainty. The interference tests already carried out is about as much that could be done by surface based investigations. Potentially more data will be obtained from the investigations to be carried out for the potential expansion of the SFR repository.	The upstream boundary condition is well established – and no alternative is needed. Downstream, the situation is more uncertain and two alternatives, with a tight or open Singö deformation zone have to be considered. In SR-Site this uncertainty in conditions outside the lens needs to be considered in safety assessment when assessing the locations of discharge points.
Hydraulic properties and connectivity of the fracture network at a scale less than the deterministic deformation zones.	Raised in version 1.1, some alternatives assessed in version 1.2, but issue then not fully resolved. In contrast to the situation after 1.2, there are now a multitude of data in support of the hydraulics description. It is based on the clearly identified fracture domains. The PFL-data used specifically captures the connected fractures, possibly apart from some very low transmissiive ones.	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 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 (cf experiences with KFM08D). 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.	Only remaining alternative concerns the potential correlation between fracture size and transmissivity. The alternative models of the degree of correlation need to be considered in SR-Site. Uncertainties regarding channelling inside the fractures are discussed under "transport", below.

Potential "Primary" alternatives in SDM	When was the hypothesis raised and is the need for the alternative now resolved in SDM-Site Forsmark?	Impact on other discipline models (or aspects of these models)?	Implications for repository engineering in phase D2	Implications for SR-Site	Implications for investigations to "resolve" alternative	Handling in SDM-Site Forsmark and need for propagation into design and safety assessment
	All deep PFL-tested boreholes show a consistent picture. Interference tests show that the rock mass between the transmissive deformation zones comprise a medium of very low permeability. However, it is not possible to resolve uncertainty in transmissivity versus size correlation.				They also provide possibilities for short range interference tests at the relevant depth.	
Hydrogeochemistry						
Alternative hypotheses as to groundwater composition and processes.	Raised in version 1.1. The following could be stated (see further section 3.5.2): There is a good understanding of the current spatial distribution of groundwater composition. The existence of a near-surface redox reaction zone appears to be well established, even though there are uncertainties in the data interpretation. Abundant existence of calcite suggests there is buffering capacity against dilute groundwater, but quantification is uncertain. For the deeper system, there are currently two alternative models i) basically a mixing model or ii) mixing + reactions.	Not directly, but would of course impact how to properly set up and execute the palaeohydrogeological simulations.	This has no direct impact. However, there could be an issue as to whether special action is needed to prevent infiltration during the construction and operational phase, as this could have a negative impact on groundwater composition.	Predictions of future groundwater composition have a large potential impact on the evolution of the EBS and also, to a lesser extent on the prediction of radionuclide migration, see section 3.5.2.	Investigation and monitoring from underground facilities (groundwater chemistry; fracture minerals etc). Additional data will be obtained from continued monitoring and long term experiments carried out at ÄHRL and Olkiluoto (ONKALO).	The uncertainties are sufficiently well bounded in terms of understanding of the present-day situation, whereas there are larger uncertainties as to the process understanding is sufficient for predicting the groundwater composition during a glaciation. SR-Site will have to handle the alternative possibility of intrusion of dilute waters during ice melting, even though current process understanding suggests that there is sufficient buffering for this situation not to occur.

Potential "Primary" alternatives in SDM	When was the hypothesis raised and is the need for the alternative now resolved in SDM-Site Forsmark?	Impact on other discipline models (or aspects of these models)?	Implications for repository engineering in phase D2	Implications for SR-Site	Implications for investigations to "resolve" alternative	Handling in SDM-Site Forsmark and need for propagation into design and safety assessment
Sulphate reduction.	New sulphide data from the monitoring programme indicates 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 SR-Can. 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. 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 SR-Site.
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 are judged small as long as the model represents connectivity of the rock mass, see further section 3.6.1. The SR-Can approach, dividing by 10 is thus very conservative.	During underground investigations the flowing fracture frequencies 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 SR-Site.

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

- *Fracture size and intensity modelling in the geological DFN*. 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 SR-Site 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.
- *Geometry, connectivity and transmissivity of deformation zones in the regional domain*. The volume south-west of the target volume is fairly well known out to the Forsmark deformation zone, and in between there is a regional groundwater divide. However, the volume north-east of the target volume is less well established. This concerns both whether the Singö zone is a flow barrier or not and the properties of the rock mass north-east of the Singö zone. The upstream boundary condition is well established and no alternative is needed. Downstream the situation is more uncertain and two alternatives, with a tight or an open Singö deformation zone have to be considered. Also, the uncertainty in conditions outside the lens needs to be considered in SR-Site when assessing location of discharge points.
- *Hydraulic properties and connectivity of the fracture network at a scale less than the deterministic deformation zones. Correlation between fracture size and transmissivity.* In contrast to the situation after SDM version 1.2, there are now a multitude of data in support of the hydraulics description. It is based on the clearly identified fracture domains. The PFL-data used specifically captures the connected fractures. All deep PFL-tested boreholes show a consistent picture. Interference tests show that the rock mass between the transmissive deformation zones comprises a very low permeable medium. The orientation of conductive fractures generally agrees with the orientation of the lowest principal stress. However, it is not possible to resolve uncertainty in the potential correlation between fracture size and transmissivity, and the three alternatives “full correlation”, “semi-correlation” and “no correlation” needs to be retained and propagated to SR-Site. The alternatives have no implications for engineering and need not be considered in the design work. (Uncertainties regarding channelling inside the fractures are discussed under “transport”, below.)
- *Alternative hypotheses as to groundwater composition and processes*. There is a good understanding of the current spatial distribution of groundwater composition and the existence of a near-surface redox reaction zone appears to be well established, even if there is uncertainty in the data interpretation. Abundant existence of calcite suggests that there is buffering capacity against dilute groundwater, but quantification is uncertain. The uncertainties are sufficiently bounded concerning the present-day understanding, whereas there are more uncertainties as to whether the process understanding is sufficient for predicting the groundwater composition during a glaciation. SR-Site will have to handle the alternative possibility of intrusion of dilute waters during ice melting, even if current process understanding suggests that there is sufficient buffering for this situation not to occur.
- *Sulphate reduction.* New sulphide data from the monitoring programme indicates 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 SR-Site.
- *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 bounding estimates of the influence of channelling assessed in SDM-Site will be propagated to SR-Site.

Remaining hypotheses and uncertainties are handled by bounding assumptions.

4.3 Assessment

Many of the previous hypotheses formed at earlier versions of the SDM work have now been possible to discard or to handle by bounding assumptions. Nevertheless, five hypotheses had to be retained with alternative models developed and propagated to engineering design and safety assessment.

- Alternative fracture size and intensity modelling in the geological discrete fracture network. Several alternative models on the size distribution and intensity are delivered, based on different approaches and assumptions for interpreting the field data. Some of these alternatives are less likely, but are conservatively retained to ensure bounding the uncertainty.
- Alternative geometry, connectivity and transmissivity of deformation zones in the regional domain. Downstream the target volume two alternatives have to be considered, with a transverse tight or open Singö deformation zone.
- Alternative hydraulic properties and connectivity of the fracture network. The remaining alternative concerns the potential correlation between fracture size and transmissivity.
- Alternative hypotheses as to groundwater composition and processes. These alternatives concern the possibility of intrusion of dilute waters during ice melting, even if current process understanding suggests that there is sufficient buffering for this situation not to occur.
- Alternative processes for 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 SR-Site.

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 answers to the first and second question, 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). In case the table suggests 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 bedrock geology model

Many disciplines are judged to provide important feedback 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. In the modelling work, aspects of the current stress regime (orientation, magnitude) have been used in the conceptual understanding of brittle structures at the site, in particular the interplay between the aperture of fractures, the current stress regime and hydrogeological properties. The results of the rock mechanical work have also provided support to the development of conceptual and geometric models for fracture domains.

Table 5-1. Summary of interactions judged to be important (yes in green), to what extent these where actually considered (black) or whether 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 modelling 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	**Hydrogeochemistry 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	**Hydrogeochemistry (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**

The thermal modelling provides feedback on the description of rock domains. It was essentially differences in thermal properties that motivated the division of rock domain RFM029 in a regional scale into RFM029 (local) and RFM045, and that placed some focus on the analysis of the thickness and orientation of the subordinate rock amphibolite. The mineralogy of different rock types has been presented with thermal properties in focus. Furthermore, stochastic simulation work of subordinate rock types made in connection with the thermal modelling work has provided further insights into the spatial distribution of these subordinate rock types.

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 results of interference tests have provided support to the geometric modelling of deformation zones. The results of the hydrological work have provided support to the build-up of conceptual and geometric models for fracture domains. Hydrogeological data have been used in the conceptual understanding of brittle structures at the site. The hydrogeological DFN model is based on the same basic assumptions as the "r_0-*fixed*" alternative geological DFN model, see /Stephens et al. 2007/. The fact that the hydrogeological DFN model manages to both reproduce the frequency of "open fractures" measured in boreholes and the frequency of connected transmissive fractures (obtained from the hydraulic PFL-data) lends strong support to the validity of the "r_0-*fixed*" geological DFN alternative.

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 results of the hydrogeochemical work have provided support to the build-up of conceptual and geometric models for fracture domains. The consistency between fracture mineralogy and current groundwater composition is assessed and provides input to the fracture mineralogical description (see e.g. section 3.5.5).

Characterisation of Quaternary deposits should indicate whether there is evidence for late- or post-glacial tectonic activity. Data on late- and post-glacial tectonics are used in the descriptive model. There is a high confidence that there are no regionally important, late- or post-glacial faults in the area.

5.2.2 Impacts on rock mechanics model

It is mainly the bedrock geology model that impacts the rock mechanics model through the rock domains, deformation zones and DFN model. Qualitative support for the stress model is also provided by the hydrogeological model. This input is used within the rock mechanics modelling.

The geological model is the basis for deriving relationship between mechanical properties and domains and deformation zones. Deformation zone geometry influences the stress field. Differences in fracture frequency with depth and between different fracture domains could possibly affect the stress field. Lithology and spatial variability in subordinate rock types directly affects the spatial distribution of mechanical properties of the intact rock. Mechanical properties have been evaluated on the basis of fracture domains, rock domains and deformation zones. Intensity, orientation and size distribution of open fractures have been used in the theoretical approach to calculate mechanical properties of the rock mass. Deformation zone geometry has been used in numerical modelling to evaluate the impact on relative stress magnitude and orientation. The regional modelling showed that only the gently dipping deformation zones affected the stress field. Since these do not occur at repository depth, variability in stress magnitudes and orientations is expected to be minor and bounded by the uncertainty estimates used in the repository design. The decrease in frequency of open fractures with depth has been used in numerical modelling to evaluate the stress gradient. Local variation in stress magnitude and orientation has been analysed by numerical modelling using data on open fractures in FFM01. Intact rock properties relate to rock types. Developing a detailed stochastic spatial model, based on similar approach as used in the thermal modelling /Back et al. 2007/, has been considered but found inappropriate.

Hydrogeology would impact the rock mechanics description, since water pressures reduce 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. The joint evaluation of the *in situ* stress and hydraulic data /Follin et al. 2008/ suggests that the coupling between normal stress and fracture transmissivity 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 basis for the relationship between thermal properties and rock types and their distribution in the rock domains, 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. Differences in the style of ductile deformation inside and along the margins of the tectonic lens have been taken account of in the stochastic simulation work.

Stress impacts on thermal properties are very small, at least 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 hydrogeology 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 further divided based on 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 not the same but consistent within the ranges of uncertainty.

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 Follin 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 tend 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 could not replace field data. Fracture shear stress/displacements affect fracture transmissivity in laboratory tests (as also shown by

/Ki-Bok Min 2004/). There is no evidence that shear displacements are occurring at Forsmark (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. These couplings are considered in the modelling work. Present-day salinity and water type distribution are "calibration targets" for simulation and the hydrogeological modelling considers density effects. In version 1.2 it was not always possible to match the hydrogeological model to the chemical data, and *vice versa*, but this comparison has now improved substantially and remaining deviations are judged to concern the current model's inability to resolve details of the local conditions at the sampling borehole (see section 3.5.1).

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.

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 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 palaeoeffects. Assessment of fracture minerals is a key input for the redox zone assessment, but the character of the available data makes the interpretation uncertain. 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 (generation of calcite and occurrence of asphaltite).

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 input in the chemical modelling.

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 hydrogeology and hydrogeochemical model.

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 transport model. Most migration modelling in support of the hydrogeochemical model is made within hydrogeology, i.e. only considering advection and matrix diffusion). Fully coupled, but simplified ("all" chemical processes) modelling is conducted for some aspects, e.g. oxygen consumption. CEC (cation exchange capacity) values determined within transport modelling are also used within the hydrogeochemical modelling. There is also a qualitative assessment of how sorption affects groundwater composition.

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 selection of water types and input to coupled modelling.

5.2.6 Impacts on transport model

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

The rock domains of the 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.

Stress changes will affect the fracture plane geometry and thus the degree of channelling. De-stressing of "intact" rock samples for laboratory measurements may also affect measured matrix porosity and formation factors. A scoping assessment of how stress changes affects channelling is part of the assessment of importance of channelling in general. Stress impacts on matrix properties have been considered, and judged not to be a major factor.

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 is used as input to the flow-related transport property assessment. Matrix and fracture properties are assessed for characteristics associated with connected transmissive fractures (PFL-anomalies).

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 high conductive fractures need to be consistent with rock matrix data used in transport model. Groundwater composition (identified water types) is used to set up laboratory tests and in parameterisation of the retardation model.

5.2.7 Near-surface

Many interactions take place among the different surface disciplines, which is why an integrated modelling approach is adopted for the surface system. It is also evident from the table 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 /Lindborg (ed) 2008, section 5 and 6/.

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 will be part of a preliminary safety case 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 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 aspects have the lowest 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.
- General statement of confidence.

6.2 Aspects of the site having high and low confidence

Key aspects of the Forsmark site descriptive model are judged to have high confidence. An overall reason for this confidence is the relative wealth of data from the target volume and the consistency between independent data from different disciplines. Some aspects have lower confidence. The lack of confidence is handled 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. Nevertheless, the final assessment on the importance will be made within the subsequent repository engineering and safety assessment activities, the judgement presented here is only indicative.

6.2.1 Geology

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

- Geometry and properties (rock types, homogeneity, ductile structures, mineralogy and petrophysics of dominant rock types) of rock domains RFM029 and RFM045 inside the target volume (part of the local model volume).
- Geometry and properties (length, thickness, orientation, alteration, fracture orientation, fracture frequency, fracture mineralogy, style of deformation, kinematics) of deformation zones with traces longer than 1,000 m inside the target volume (part of the local model volume).

The main reasons for this confidence are the consistency between model versions, wealth of data and support from other disciplines.

The following aspects are associated with the lowest confidence:

- Size of gently dipping fracture zones,
- Size distribution and size-intensity models for fractures at repository depth.

The lack of confidence is handled by providing bounding estimates of the sizes and a wide range of size distributions in the geological DFN model.

6.2.2 Rock mechanics

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

- Mechanical properties of the rock mass in rock domains RFM029 and RFM045.
- Orientation of *in situ* stresses.
- Magnitude of the vertical stress component.

The main reasons for this confidence in mechanical properties are the consistency between model versions, wealth of data and support from other disciplines. The main reason for confidence in the stress orientation is the consistent results between measuring methods and indirect observations at different scales (from borehole to tectonic plate). Confidence in vertical stress is provided by the consistency between measured values and theoretical values based on the weight of the rock cover. Overall confidence is provided by the mutual consistency between the understanding of geology and rock mechanics properties.

The following aspects are associated with the lowest confidence:

- Large-scale mechanical properties of fractures,
- Magnitude of horizontal stress components.

The lack of confidence in the horizontal stress is handled by providing bounding estimates. 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:

- Thermal properties of domain RFM029 with its higher degree of homogeneity in geology and thermal properties,
- Spatial statistical thermal models for most thermal rock classes.

The main reasons for this confidence is that the spatial statistical thermal models for most thermal rock classes are based on a satisfactory amount of data. Simulation allows upscaling to be performed in a theoretically robust way. Rock domain RFM029 has greater homogeneity in geology and thermal properties than domain RFM045. Overall confidence is provided by the mutual consistency between the geological and thermal properties description.

The following aspects are associated with the lowest confidence:

- The lower tail of the thermal conductivity distribution, particularly in domain RFM045. This limited confidence is related to uncertainties in the representativeness of the borehole data for domain RFM045, which in turn is a function of the higher degree of lithological heterogeneity in this domain.

The lack of confidence is handled by overestimating the extent of the lower tail in the distribution. This may result in excessively large designed distance between canisters, but the uncertainty is otherwise relatively unimportant.

6.2.4 Hydrogeology

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

- Distribution of conductive fracture frequency as a function of fracture domain and depth within the target volume.
- The anisotropy and heterogeneity in transmissivity inside the candidate area. It is pronounced but predictable.
- Overall conceptual model with highly transmissive sheet joints in the near surface rock, hydraulic structures (HCD) that coincide with the deformation zone model, overall transmissivity distribution between different types of deformation zones.
- The strong correlation between structural, mechanical, hydrogeological and hydrochemical data. The ductile deformation appears to govern the overall geometry of the brittle deformation zones, the anisotropy in transmissivity is largely consistent with the stress field, and differences in water composition can be explained by differences in deformation zone transmissivity and largely supports the existence of the very low frequency of connected transmissive fractures at depth between the deformation zones.
- Hydrogeological DFN properties of fracture domains FFM01–03 and FFM06. Overall representation of connectivity is robust and consistent with data as well as the resulting flow distribution in the near-field.
- Deformation zone properties in the target volume.
- Upstream boundary condition (regional groundwater divide).

The main reasons for this confidence are the wealth of hydraulic data in the target volume, the consistency with other disciplines and the few surprises as new data arrive.

The following aspects are associated with the lowest confidence:

- Details of the size distribution of the hydrogeological DFN as well as the transmissivity versus size correlation (although probably bounded by the model provided),
- Hydraulic properties outside the candidate area, as well as in fracture domains FFM04 and FFM05, because of limited data from these volumes,
- Details of the salinity distribution outside the candidate area,
- Hydraulic character and importance of the Singö deformation zone,
- Hydraulic properties downstream (north-east of) the Singö deformation zone.

The lack of confidence is handled 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 of most of the end members (meteoric, marine, glacial) and major processes (qualitative control concerning Eh and pH buffer capacity, major reactions) affecting the present water composition at the sampled locations,
- Predictability concerning expected groundwater compositions.

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 reactions modelling, interpretation of different isotope ratios (Sr, S, C), buffer capacity measurements (Eh, pH) and microbial data support the process understanding.

Reasons for the composition of matrix porewaters are fairly well established and correspond to the present conceptualisation of the Forsmark area.

The following aspects are associated with the lowest confidence:

- The redox front variations trough time,
- Mineral phases giving rise to the elevated uranium concentrations in the groundwater,
- The regional salinity distribution outside the target area,
- The *in situ* concentration of sulphide,
- The sources, production rate and transport mechanisms of geogas.

The implications of these uncertainties need to be assessed in SR-Site. The implications are potentially important.

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,
- The possibility to bound the impact of channelling.

The main reasons for this confidence are the confidence in the hydrogeological DFN in the target volume and a consistent improvement and convergence of measurement data. Previous problems with interpretation of sorption data have been largely resolved. The main uncertainties are known and can be approximately bounded by scoping calculations.

The following aspects are associated with the lowest confidence:

- Spatial variability of sorption K_d data.

The lack of confidence is handled by providing bounding estimates for SR-Site. The uncertainty is relatively unimportant.

6.2.7 Near-surface system

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

- The hydrochemistry of marine systems, lakes and shallow groundwater with regard to: nutrients, macro elements, characteristic levels, temporal variation and mass transport in drainage areas,
- 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 of the overburden (regolith) in the central area,
- Spatial distribution of different vegetation types,
- Flow pattern and migration paths resulting from e.g. MIKE SHE and GIS modelling.

The main reasons for this confidence are the relative wealth of data and the consistency with regional comparisons. Regarding the oceanography and hydrology confidence is obtained from local meteorological data which can be used together with regional data for extension of time series, the relative wealth of surface water and groundwater level data, surface discharge data, knowledge of hydraulic properties of till and the general good agreement between site-specific data and generic data. Numerical modelling results have successfully been compared with measured surface discharge and surface water and groundwater levels.

The following aspects are associated with the lowest confidence:

- Chemistry in biota and Quaternary deposits; limited amounts of data are available and spatial extrapolation is required,
- In spite of the fact that the general groundwater flow pattern is considered to be well-known, the exact location of discharge areas of deep groundwater is difficult to establish due to the complex geometry and varying hydraulic properties of the horizontal sheet joints obviously dominating groundwater flow in the near-surface bedrock,
- Depth distribution of the overburden (regolith) especially outside the central area,
- Process estimates (plant uptake, transpiration etc) – generally few measurements and short time series,
- Influence of chemical processes on the transport of elements.

These uncertainties are considered in the final uncertainty assessment of the near-surface model. They 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 Forsmark area are in a transient state although on very different time scales (diurnal, seasonal, annual, *etc*) /Söderbäck (ed) 2008/. For 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. 2008/. The site descriptive hydrogeological model /Follin 2008/ conclude that there are two processes that govern the development of the deep groundwater system in the Forsmark area: (i) the structural-hydraulic conditions in the bedrock, and (ii) the ongoing shore level displacement. Together, these processes govern the flushing of regolith and the bedrock and create a slowly changing hydrogeological-hydrochemical baseline in both model segments. An important result of this circumstance for the monitoring programme, which is the basis for the description and modelling, is that the recharge and discharge pattern of near-surface and deep groundwater varies in space and time, however at different rates, see the concluding sections of /Follin 2008/.

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 characterise 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 what is needed for the characterisation 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 environment, 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 /Lindborg (ed) 2008/.

When concluding the surface-based investigations at Forsmark, a good conceptual understanding of ongoing processes has been developed and while the deep groundwater system is transient, the changes are slow. For the near-surface environment, time series of up to six years now exists. 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. Arguments on long term changes need anyway to be derived from a mechanistic understanding of the processes, which may induce extreme values, combined with long-term measurements on reference sites.

Finally, the monitoring programme at the site continues. Data collected in these monitoring programmes 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 Forsmark site descriptive model has an overall high level of confidence. The geological model for Forsmark was primarily developed after the completion of the first three boreholes (KFM01A, 02A, 03A), suggesting that the geology of the site is relatively straight-forward and homogeneous. Because of the robust geological model that describes the site, the overall confidence in the Forsmark site descriptive model is judged to be high. The overall reason for this confidence is 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. Most, but not all, of the low confidence aspects have little impact on repository engineering design or long term safety.

7 Conclusions

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

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

It is generally found that key aspects of the Forsmark site descriptive model are associated with a high confidence. The geological model for Forsmark was primarily developed after the completion of the first three boreholes (KFM01A, 02A, 03A), suggesting that the geology of the site is relatively straight-forward and homogeneous. Because of the robust geological model that describes the site, the overall confidence in the Forsmark site descriptive model is judged to be high. The overall reason for this confidence is 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. 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 1.4.11.1, are now met in the completed site investigations, subject to levels of uncertainty that are viewed as acceptable.

Generally, only few 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 negative impact on confidence. However, in some cases inclusion of these less reliable data could have helped in justifying potentially less conservative values of stress.

Poor precision in the measured data are judged to have limited impact on uncertainties in the site descriptive model, with the exceptions of poor precision in determining the position of some boreholes at depth in 3-D space, as well as the poor precision of the orientation of BIPS images in some boreholes, and the poor precision of stress data determined by overcoring at the locations where the pre-existing deformation in the core exceeded the elasticity limit of the intact rock. These problems are identified and considered in the modelling. They affect uncertainty, but have only a limited negative impact on confidence.

Overall there is limited measurement bias in the data, and bias due to poor representativity is much reduced compared with earlier model versions but some remains. Important remaining biases are bias in the samples used for sorption data, bias in the fracture size data since they have to be based on outcrops and not on data from the underground. However, the impact on uncertainty can be estimated and is accounted for in the modelling. Bias is not judged a major concern for confidence in the model.

Some uncertainties remain in the Forsmark site descriptive model, but 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 uncertainties in the processes involved in groundwater evolution are sufficiently bounded in relation to conditions similar to those of the present day. However, the understanding of processes occurring during a glaciation is less good and uncertainties exist, especially in relation to buffering against infiltrating dilute groundwater.

Many hypotheses formed at earlier versions of the site descriptive modelling are now discarded or handled by bounding assumptions. Nevertheless, six 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 obtained from underground excavations. There it will be necessary to carry out statistical modelling of fractures in a DFN study at depth during construction work on the access ramp and shafts.
- Uncertainties in stress magnitude will be reduced by observations and measurements of deformation with back analysis during the construction phase.
- More detailed division of the fine-grained granitoid (101051) in tunnels will enable thermal optimisation of the repository.
- There would be 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 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 mapping of flowing or potentially open fracture statistics in tunnels. 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 radionuclide 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.
- More data on the near-surface rock, as well as on the depth of the Quaternary deposits in the access area may be needed for detailed layout planning of the access.

Uncertainties outside the repository volume are larger, but are judged to be of less importance. More surface-based boreholes outside the lens would only marginally decrease uncertainty. More data will anyway be obtained from the investigations to be carried out for the potential expansion of the SFR repository.

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