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ORIGINAL ARTICLE

Site-descriptive modelling for a final repository for spent nuclear fuel in Sweden

**Johan Andersson · Kristina Skagius ·
Anders Winberg · Tobias Lindborg ·
Anders Ström**

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Abstract The handling and safe disposal of spent fuel from nuclear power plants has been an issue since the 1950s when the first suggested method, geological storage in salt formations, was proposed in the US. Since then a number of methods have been developed for different types of bedrocks and waste types. One common need applicable to all these methods is to describe features and processes essential in repository design and demonstrations of long-term safety. So far, most methods have not described, nor emphasized, the importance of site-specific understanding of key parameters related to a specific repository design. Furthermore, the need of interdisciplinary research and the benefits gained when handling the site as a unified connected and mutually interrelated system (from bedrock to surface) have not been fully discussed. During a 30-year period, research has been performed in Sweden to demonstrate feasibility and long-term safety of underground geological disposal of spent nuclear fuel. In this paper, the overall strategy and discipline-specific modelling methods used in the site description of a final repository in Sweden are described, as exemplified by the Forsmark site. The resulting site description covers understanding of the historical evolution of the site, site data describing the current situation as well as spatially variable models needed to design the repository and evaluate long-term safety after closure. Finally, lessons learnt from this work are summarized, which are important when employing this method in the future.

Keywords Integrated · Site description · Site investigation · Spent fuel · Uncertainty · Safety assessment

Introduction

Nuclear energy is destined to play an important role in the societal transition towards a low-carbon, low-CO_2-emitting energy production for a foreseeable future. One of the critical issues for further development and new implementation of nuclear energy is demonstration of methods for safe disposal of associated wastes. Disposal of high-level and/or long-lived radioactive waste in engineered facilities (repositories) located underground in suitable geological formations has been widely investigated worldwide during the last three decades. The role of the geological formation is to provide stable mechanical conditions, favourable hydrogeochemical conditions, low groundwater turnover and effective retention of radionuclides, if released from the disposal site. As early as the 1950s, the US National Academy of Sciences recommended deep disposal of long-lived radioactive wastes in geologically stable formations, such as deep salt beds. In 1998, the US Environmental Protection Agency (EPA) certified the Waste Isolation Pilot Plant (WIPP), hosted in bedded salt near Carlsbad, NM, USA for safe long-term disposal of HLW radioactive wastes (research and military origin). An integrated description of the geology and hydrogeology of the WIPP site is found in Swift and Corbet (2000). The welded tuff of Yucca Mountain, NV, USA has also been proposed for disposal of spent nuclear reactor fuel and HLW wastes (civil origin). An integrated

J. Andersson · K. Skagius · T. Lindborg · A. Ström
Swedish Nuclear Fuel and Waste Management Company (SKB),
PO Box 250, 101 24 Stockholm, Sweden

A. Winberg (✉)
Conterra AB, Ögärdesvägen 4, 433 30 Partille, Sweden
e-mail: anders.winberg@conterra.se

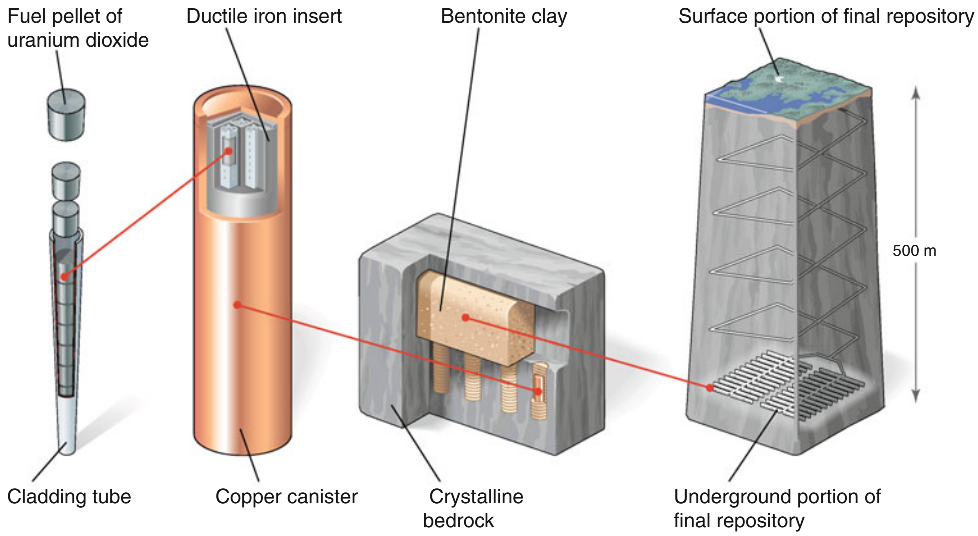

Fig. 1 The KBS-3 concept for disposal of spent nuclear fuel (SKB 2011)

description of the hydrology and hydrogeochemistry of the proposed disposal at Yucca Mountain is given by Stuckless (2012). The Canadian Bruce site (NWMO 2011; Intera 2011) is planned to host a repository for low-level/intermediate level waste in an argillaceous limestone. Corresponding work is also underway in Europe addressing deep disposal of HLW wastes in volcanic rock in the UK (Michie 1996; Bath et al. 1996), in clay in France and Switzerland (Gautschi et al. 2004) and crystalline bedrock in Finland (Posiva 2009), Switzerland (Thury et al. 1993) and Sweden.

One of the principal challenges of the ensuing safety analysis of a repository is to make credible that conceptual models describing the present situation of the geological system, as described in the site-descriptive model, also are valid for the long-term perspective (Nordstrom 2012; Bredehoeft 2003, 2005). Studies of natural analogues to the disposal system (Miller et al. 2000), making use of observable historic records of past performance of natural systems of similar time scales as the performance assessment, or even longer, may lend additional support for long-term projections of repository performance. In recent years, collective international efforts have emphasized the role and importance of the integrated geoscientific understanding in building and obtaining acceptance for safety cases related to geological disposal of nuclear wastes (OECD-NEA 2009, 2010).

The Swedish Nuclear Fuel and Waste Management Company (SKB) is responsible for management and safe final disposal of radioactive waste from the Swedish nuclear power plants. More than 30 years of research and development has led SKB to put forward the KBS-3 method for the final disposal of spent nuclear fuel. This method is based on three protective barriers. The spent nuclear fuel is encapsulated in copper canisters with cast iron inserts containing the spent nuclear fuel rods. Embedded in a bentonite clay buffer, the canisters are subsequently placed in deposition holes in crystalline bedrock at a depth of about 500 m (Fig. 1). The deposition tunnels are backfilled with bentonite and sealed with a concrete plug. Rock caverns, transport and main tunnels are backfilled and a top sealing is put in place after the disposal is completed.

This paper describes the methods used, results and lessons learned from the site investigations and site-descriptive modelling performed at Forsmark and Simpevarp/Laxemar in Sweden, as exemplified by results from the Forsmark site.

Repository siting and site investigations

The Swedish siting process was initiated some 20 years ago, including regional studies and pre-studies in selected municipalities, with the objective of locating candidate sites for a repository for the final disposal of spent nuclear fuel (Johansson 2006). Following a successive screening and pre-studies in eight municipalities, where bedrock conditions were considered favourable and public acceptance was granted, the Swedish government in late 2001 decided to allow proceeding with site investigations according to plans presented by SKB. During 2002, site investigations commenced at Forsmark and Simpevarp/Laxemar (Fig. 2).

Site-descriptive modelling in a context

The earlier Swedish experience included safety analyses that were based on site investigations and modelling, but lacked an integrated site modelling of the studied potential sites, see e.g. SKB (1999). In the planning for the site investigations at Forsmark and Laxemar, the need of a holistic view and integrated models was emphasised (SKB 2000). Experiences from the OECD/NEA International

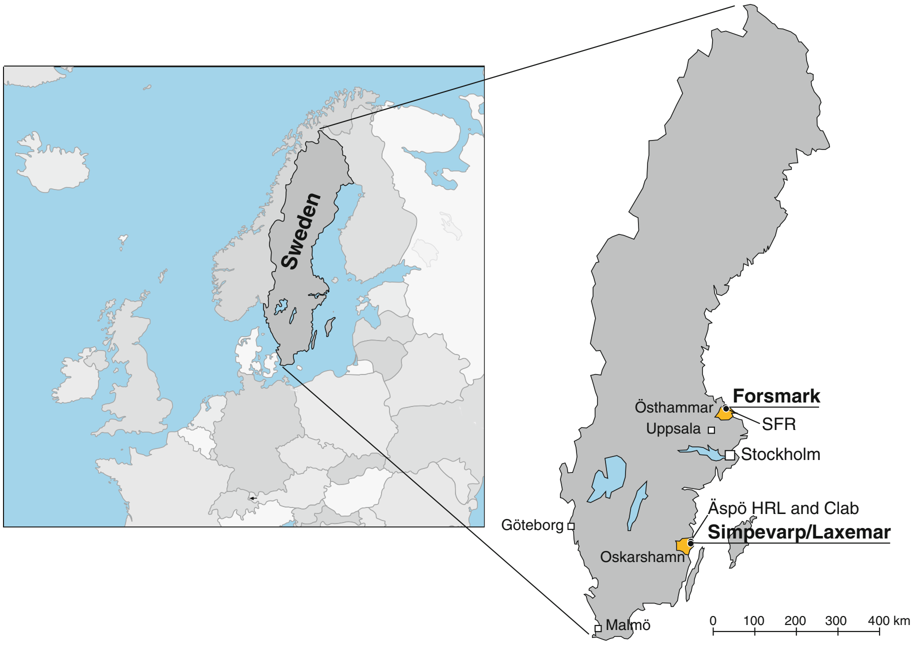

Fig. 2 The locations of the two sites, Forsmark and Simpevarp/Laxemar, which have been subjected to site investigations. Also indicated are the central interim storage for spent nuclear fuel (Clab) and the underground Äspö Hard Rock Laboratory near Oskarshamn, and the final repository for short-lived radioactive waste (SFR) off Forsmark

Stripa Project (Gnirk 1993; Olsson and Gale 1995) and the SKB Äspö Hard Rock Laboratory (Banwart et al. 1997) served as important input in this process.

Site-descriptive modelling (SDM) provides the necessary site understanding, including interpretation and transfer of the information from the quality-assured databases produced by the site investigations to discipline-specific descriptions applicable to various subdivisions of the system made up of surfaces and volumes. The underlying information used in the SDM is in its nature often point-wise, varying both spatially and temporally. Evaluation of uncertainties in values of parameters describing the material properties and states of the studied system and the realism in the subdivision of the studied system are central in the analyses. Basic background data and knowledge from reference sites[1] (SKB 2010b) provide additional support to the modelling.

Included in the SDM work is the necessary control of primary data, e.g. chemical analyses of core samples emerging from the surface-based site investigations, followed by disciplinary and interdisciplinary integrated modelling (Andersson 2003) providing basic geometrical descriptions and parameterisations of the bedrock and the surface system. Repository engineering makes use of the SDM for producing the basic layout and design of the repository. The latter is a basic input to the safety analysis which makes use of both the layout and the SDM models and associated parameterisations in the analysis of the long-term safety of the repository. The core element of the SDM modelling is an integrated multidisciplinary approach applied to databases made available at pre-defined points in time, typically with a 1–2 year separation in time. Accounting for and assessing remaining uncertainties was part of the delivery of each version of the SDM, which provided a transparent record of the successive building of confidence in the models and descriptions produced. A central issue of the work is whether it is possible to construct an integrated, mutually consistent, three-dimensional SDM encompassing the scientific disciplines in order to satisfy the needs of design and assessment of long-term safety of a geological repository. Other issues are how to ascertain overall confidence in the model/-s developed, assess associated uncertainties and evaluate alternative interpretations on the basis of data from surface-based investigations.

Principal deliveries at the conclusion of the complete site investigation stage (CSI) included the site-descriptive models developed for the two sites, denoted SDM-Site (SKB 2008a, 2009b), which were used for defining layouts D2 (SKB 2009a, c) and for the safety analysis SR-Site (SKB 2011). This documentation provided the basis and arguments for the site selection (SKB 2010a) and for the subsequent formal application to the government to construct the repository. The surface ecology models provided the basis for an environmental impact assessment and estimates of dose to the biosphere.

The methodology and associated models described in this paper account for the present-day situation and understanding of the historic evolution of the site. This

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[1] In this context “reference sites” refer to other sites investigated by SKB during the last 30 years, representing different geographical locations, geological conditions and level of ambition in investigations performed.

constitutes the basis for repository design and foundation for assessment of future site evolution and analysis of long-term safety.

Study site

The Forsmark site is located in the northern part of the province of Uppland, within the municipality of Östhammar, about 150 km north of Stockholm (Fig. 2), and in the immediate vicinity of the Forsmark nuclear power plant and the currently operating offshore repository for short-lived radioactive waste (SFR). The candidate area at Forsmark (Fig. 3) is flat and low-lying (most elevated parts of the candidate area are located some 10 m above sea level), about 10 km^2 in size, where the dominant rock is composed of a metamorphosed medium-grained granite to granodiorite (metagranite). However, the regional model area of the SDM covers about 165 km^2.

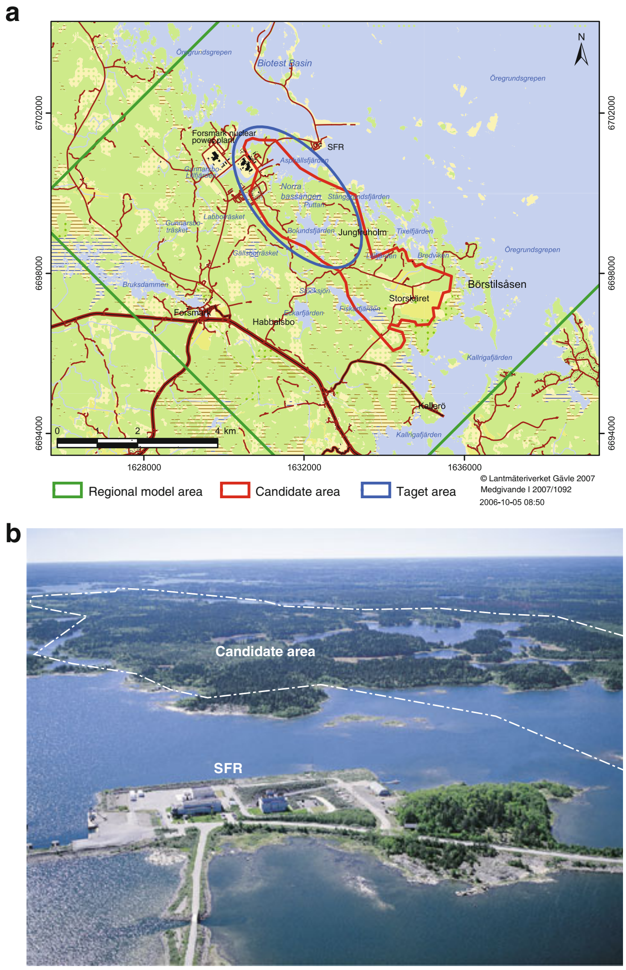

Fig. 3 **a** Outlines of "candidate area" (*red*) and "target area" (*blue*) and partial outline of the "regional model area" (*green*) at Forsmark. **b** Photograph showing the flat topography at Forsmark (perspective view to the west). Modified after (SKB 2008a)

Most of the bedrock was formed some 1,900 million years ago and has been subjected to both ductile and brittle deformation. As a consequence of glacial isostasy, almost the whole candidate area was covered by the sea until some 800 years ago, after which the process of land uplift led to the gradual formation of islands in what is now a coastal area. The landscape of today contains many small shallow lakes and bays. The northern part of the candidate area was in 2005 selected as the target area for the concluding phase of the site investigations—the CSI.

Site investigations and modelling methods

Data collection

The site investigations were performed in a staged manner where site investigation data at a particular time (data freeze) were used to develop models and integrated descriptions of the current situation at the site at predefined times during the site investigations. By employing a staged approach, an effective feedback was established regarding remaining uncertainties and need of additional data.

Basic requirements and preferences (criteria) placed on bedrock conditions and properties applicable to a KBS-3 repository at a depth of 400–700 m were defined by SKB prior to the start of the site investigations (Andersson et al. 2000). The stipulated requirements relate to ore potential, positioning of the repository and canisters in relation to interpreted deformation zones, rock strength and rock stresses, salt content and non-existence of dissolved oxygen in the groundwater. Fulfilment of all listed preferences (as opposed to the requirements) is not a definite must, but would if satisfied entail improved safety margins or imply an easier and less costly adaptation of the repository to site conditions (Andersson et al. 2000).

The site investigations included investigations which characterise the basic geometry, state variables [stress and hydraulic pressure (potential)] and parameters/properties relevant to repository layout/design and assessment of long-term safety. The latter included data to describe; distributions of rock types, geometry and properties of deformation zones, thermal conductivity, rock strength and deformation, frequency of conductive fractures and distribution of fracture transmissivity, groundwater chemical entities, bedrock transport and retention properties and surface ecosystem properties.

The site investigations carried out included surface and airborne surveys as well as drilling of a large number of boreholes in which various types of investigations were made. The information from surface investigations (geological mapping, elevation models and various airborne and detailed surface-based geophysical logs) provided the primary basis for constructing maps of bedrock lithology and lineaments (Munier et al. 2003). The drilling programme included cored boreholes to variable depths and percussion boreholes primarily aimed at shallow depths. Important borehole logs included borehole TV imaging (BIPS) and flow logs (PFL) which enabled discrete identification and quantification of individual conductive fractures. The latter information constitutes the cornerstones when developing discrete fracture network (DFN) models (Munier 2004). Borehole data in support of the Forsmark site description come from 25 core-drilled boreholes at 12 drill sites. These boreholes range in depth down to approximately 1,000 m and have an accumulated borehole length of some 17,800 m.

Site-descriptive modelling

The SDM was conducted by a multidisciplinary project. The project was manned with individuals responsible for the respective scientific discipline, providing a multi-disciplinary team composition and work mode, operating under unified management. The surface ecological modelling was conducted by a separate project group interacting with the SDM project. The geoscientific disciplines forming the base for the SDM models included geology, thermal properties, rock mechanics, bedrock hydrogeology, bedrock hydrogeochemistry, bedrock transport properties and surface ecology (Fig. 4).

Furthermore, the staged modelling process applied, with new and updated model versions associated with defined data freezes at specified times, has proven to be a suitable strategy for the site-descriptive modelling. This strategy enabled early identification of critical issues and need of additional important new data to handle these issues. The production of a succession of model versions has also provided opportunity for verification and successive refinement of the models as new data became available. The process applied also gave project members and clients the opportunity to follow the process towards more mature and refined site models and descriptions.

Geological description

The point of departure for the SDM modelling is the lithology of the bedrock (distribution of rock types) and the occurrence of zones of deformed bedrock. A common geometric platform for the modelling work of other disciplines is thereby provided by Geology through the rock domain model and the model of deterministic deformation zones (Munier et al. 2003). The three-dimensional rock domain model makes distinction between rock units showing similar characteristics, whereas the three-dimensional deformation zone model provides a deterministic description of zones (position, geometry and properties) with an interpreted surface expression longer than 1,000 m (Fig. 5). The remaining zones and fractures of length less than 1,000 m are described stochastically by DFN models developed for defined so-called fracture domains with similar fracturing characteristics and properties (Munier 2004).

Rock mechanics

Rock mechanical properties (incl. strength and deformation) of intact matrix rock were intimately linked to individual rock types, whereas corresponding properties of the fractured rock mass between deformation zones were related to defined fracture domains. Mechanical and deformation properties of fractures and deformation zones were also assessed according to the methodology outlined in Andersson et al. (2002). Modelling of rock stresses involved integration of performed rock stress measurements in boreholes and indirect stress indicators provided by indications of borehole fall outs and core disking. The resulting description included orientation and magnitude intervals for the major horizontal stress (Glamheden et al. 2007).

Thermal properties

The thermal conductivity of the bedrock, which in part governs the distance between disposed canisters, was closely linked to lithology through the rock domain model. The thermal property modelling also honoured the effects

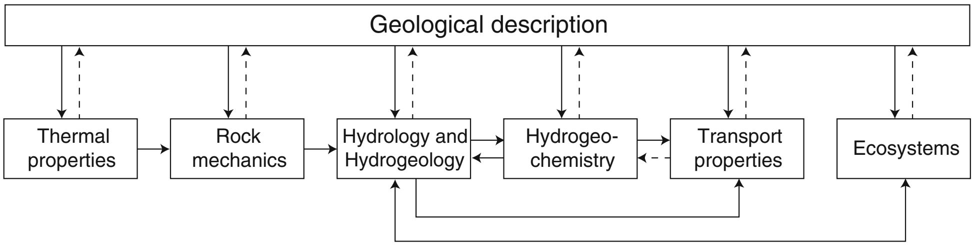

Fig. 4 The different discipline descriptions in the SDM are interrelated by several feedback loops with geology providing the essential geometrical framework

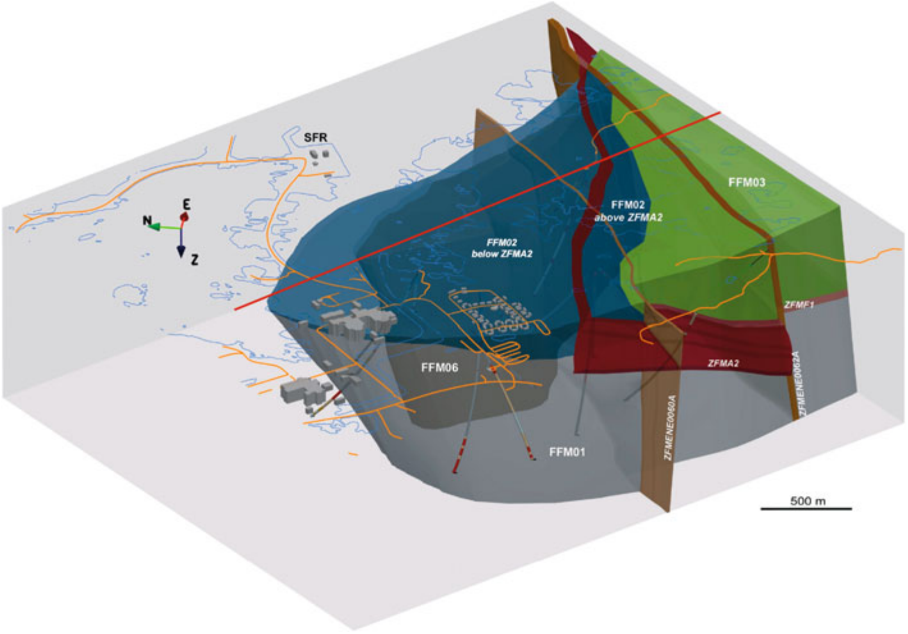

Fig. 5 Perspective three-dimensional view of fracture domains and their relation to the gently dipping deformation zone ZFMA2 and ZMF1 and steeply dipping zones ZFMNE0060A and ZFMENE0062A in the northern part of the tectonic lens. The profile (*red*) of the model sections shown in Fig. 6 is indicated. Modified after (SKB 2008a)

of lithological heterogeneity through a stochastic analysis scheme (Sundberg et al. 2009). Also the methodology to determine the distribution of thermal properties (thermal conductivity) based on a limited number of core sample data has been developed (Back and Sundberg 2007). The model depends primarily on the lithological modelling, through the correlation between rock type and thermal properties, although the thermal conductivity could also vary within a given rock type due to variation in mineral assembly.

The geological lithological modelling determines rock domains as distinct geometrical bodies. With respect to thermal properties, the lithological variation within the rock domains could still be substantial, especially in very heterogeneous rocks. Previous work indicates that the statistical distribution of thermal conductivity at domain level is far from normally distributed, which means that mean and standard deviation are not sufficient to characterise the distribution.

The applied methodology is to model the spatial correlation and perform stochastic simulation to produce a spatial thermal conductivity distribution that can be used to predict various statistical parameters of the thermal conductivity distribution. This is achieved in three steps. First, the lithological variation within the rock domains are described as a Markov process that describes the likelihood that a certain rock type within the domain will change to another rock type when making a lateral incremental spatial step in the model. From this description, different realisations of rock type distributions within a rock domain can be simulated. Secondly, the spatial variation of thermal properties within a given rock type is described geostatistically, using variograms. This generates realisations of the spatial distribution of thermal properties within each rock type. Thirdly, the different realisations are combined, following the realisations of rock types, in order to produce a realisation of the thermal properties within the rock domain.

Hydrology and hydrogeology

The modelled bedrock fractures and deformation zones constituted the geometrical basis for the hydrogeological modelling. Groundwater movement, residence times and flow rates are governed by the transmissivities of fractures and zones, their interconnectivity and the acting hydraulic driving forces. The hydrogeological work also involved analysis of performed hydraulic tests in boreholes, providing quantification of fracture domains in terms of parameterised hydraulic DFN models and of deformation zones in terms of different transmissivity–depth relationships, in some cases made zone-specific. The primary working hypothesis from site data was that below ca. 400 m depth, the rock planned to host the repository, has very low hydraulic conductivity and is only intersected by very few conductive fractures. The hydrogeological descriptive models and parameterisations were introduced in three-dimensional flow models describing the bedrock and overburden. Specified head boundary conditions were assigned offshore and flux conditions were applied on shore. Initial calibration steps included matching results to registrations of hydraulic head in the various borehole arrays. This was followed by a calibration to cross-hole test data and a forward calculation of the transient evolution of the hydrogeochemical situation from the latest glaciation till present, taking into account projections made regarding the evolution of the salinity of the Baltic and the inferred shoreline displacement due to glacial rebound. The calculated present time groundwater chemistry was compared with that measured in boreholes, and model parameters were adjusted accordingly to achieve an improved match (see e.g. Follin et al. 2007).

Initially, the hydrogeological modelling focused on fitting a hydraulic DFN to borehole hydraulic tests data, the former having very high spatial resolution including discrete stochastic representation of individual fractures. The subsequent modelling, exploring to what extent past evolution of groundwater flow can explain the current groundwater chemical composition of the site, was motivated by the fact that it is the local flow field as well as the composition of the groundwater interacting with the engineered barrier system that are of key importance for the long-term performance of the repository. While these preferences were still valid, experience showed that a more top–down approach, emphasising data analysis and conceptual modelling, was necessary in order to enhance confidence in the final model output.

The basic principle of the new approach was to develop an overall conceptual model that first established the main flowing features (typically deterministically modelled deformation zones) and then gradually approached the determination of the hydraulic properties of the rock mass between these deformation zones in the potential repository volume. The approach puts more emphasis on data analysis and testing of alternative interpretations and less on numerical simulation and calibration. Before extensive (and costly) simulations were made, it needed to be clearly explored and understood what could be the potential gain of carrying them out.

Hydrogeochemistry

Sampled and analysed groundwaters were interpreted hydrogeochemically in relation to their composition, origin and evolution. Integration with hydrogeology provided support for the palaeohydrogeological description of the sites. Chemical reaction modelling, different isotope ratios and measurements of Eh, pH and microbial activity provided additional support for the understanding of processes. By analysing the mineral assemblies on fracture surfaces it was possible to assess the chemical conditions in the bedrock during different time periods, including assessments of radionuclide retention, and to establish historic records of the penetration of oxygenated waters at depth. An account of the applied methodology is provided in Gascoyne and Laaksoharju (2008).

Bedrock transport properties

Modelling of bedrock transport properties (Crawford 2008) included assessments of both retention material properties (diffusion and sorption) of different geological materials as well as flow-related retention parameters. Whereas the former can be regarded as intrinsic to the geological materials along the flow paths, the latter are in part dependent on the applicable boundary conditions for groundwater flow.

Ecosystems

The surface ecology modelling resulted in perhaps the most comprehensive ecosystem description made so far in Sweden, unique in its integrated approach, covering hydrology, oceanography, Quaternary geology, chemistry, ecology of terrestrial, limnic and marine systems, and land use. The employed strategy involved descriptions of the ecosystem functions and processes at the potential repository sites using coupled discipline-specific models. The resulting models described the landscape properties, the distributed ecosystems and their properties and processes needed to follow transport of matter (Lindborg et al. 2006).

Results

In the following, the SDM modelling at Forsmark is used to exemplify important modelling steps and results. Overall, the lessons learnt related to the site-descriptive modelling of the Forsmark site are valid also for that of the Laxemar–Simpevarp site.

Geology

Resulting model

The Forsmark site is hosted in a so-called tectonic lens (less deformed rock) where the bedrock has been preserved relatively unaltered during a period of nearly 1,900 Ma, surrounded by major regional shear zones characterised by intense deformation (Stephens et al. 2007). The major rock domains consist of reddish-grey metamorphic (altered) granite with high quartz content, and a more altered (albitised) granite variety with more amphibolite. Despite poor surface expression of the bedrock, the folding of the bedrock within the tectonic lens at Forsmark simplified the geological modelling (Fig. 5). The resolution threshold ($L > 1{,}000$ m) introduced for defining deterministic structures in the deformation zone model (Fig. 6), where the geological DFN model describes statistically the features below this threshold, implies an important interaction

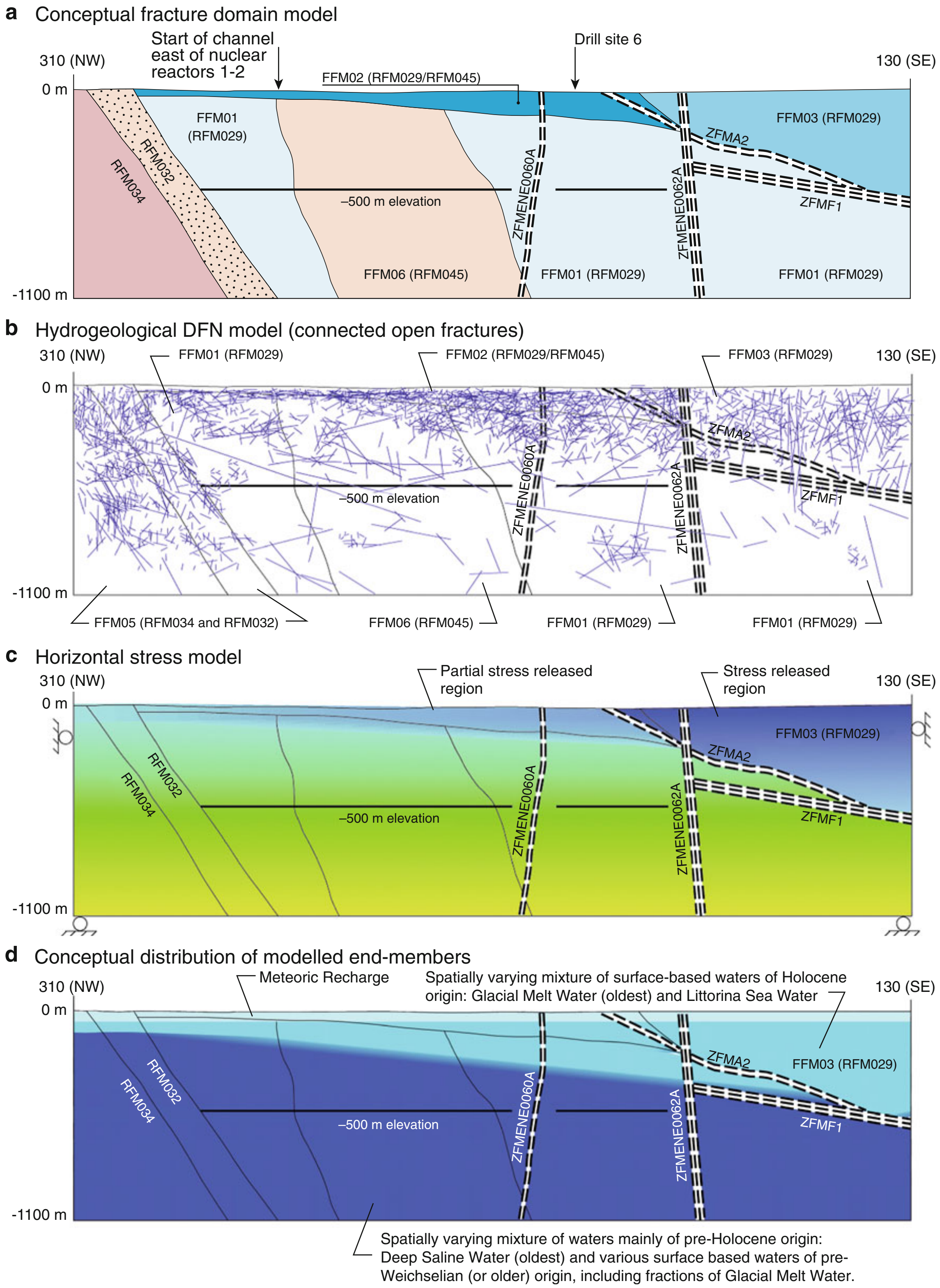

Fig. 6 Comparison of **a** fracture domain, **b** hydrogeological DFN and **c** maximum horizontal stress, **d** present-day distribution of waters of different signature along a NW–SE profile in the north-western part of the candidate volume. The location of the common section is indicated in Fig. 5. Modified after (SKB 2008a)

between the geological sub-models, as primary data needed to be addressed in the appropriate manner to establish this subdivision. Moreover, other disciplines were dependent on the assumptions and decisions made in the overall geological modelling work.

Already during work on early model versions, significant spatial variability in the fracturing was observed. The gently dipping deformation zone ZFMA2 (Fig. 6) was identified as a major structural feature governing both the fracture properties and the hydrogeological properties at the site (SKB 2005). Moreover, the conditions close to the ground surface in the north-western part of the model volume appeared different compared with conditions observed at depth. The variability was considered significant enough to further subdivide the model volume in sub-volumes, primarily for the analysis and modelling of geological and hydrogeological properties.

In preparation for the CSI modelling of the Forsmark site it was therefore decided to (1) identify and describe fracture domains at the site on the basis of geological data (Figs. 5, 6), so as to specify the set of data to be used for deformation zone modelling work and the set of data to be used in geological DFN modelling work, and to (2) compile hydrogeological, hydrogeochemical and rock mechanical data within each fracture domain and address the implications of this integration activity.

This allowed presentation of an overview of the available primary data and the compilation constituted a firm basis for the subsequent geological DFN and other modelling work by defining the different sub-domains in which the geological DFN should be developed. The fracture domain concept, based on compiling and visualising investigation data, thus constituted an important means to subdivide the rock. Based on the outcome of the statistical analyses in relation to the potentially controlling geological parameters, the definitions of the fracture domains could easily be modified, and/or complementary sub-domains recognised.

Implications for the SDM

The above considerations provided the basis for a conceptual model for fracture domains at Forsmark consisting of six separate domains. A NW–SE cross-section along the candidate volume[2] is shown in Fig. 6a. The fracture domains defined in this model were considered large enough not to overly constrain the analyses of the DFN. Furthermore, the fracture domains also acted as useful vehicles for presenting in situ data on geology, hydrogeology, hydrogeochemistry and rock mechanics. Correlations between data and modelling results from the different disciplines could thus be detected.

Hydrology and hydrogeology

Resulting model

The conceptual model for groundwater flow in Forsmark is developed based on the difference in fracture characteristics and groundwater chemical characteristics observed between different sub-volumes of the rock at the site. The intensity of conductive fractures shows a dramatic depth trend (SKB 2008a). Below ca. 400 m depth, the fracture domain FFM01 planned to host the repository shows very low hydraulic conductivity and very few conductive fractures. The noted decrease in hydraulic properties is in line with observations previously reported in the literature. Furthermore, highly transmissive subhorizontal features in the near-surface rock (fracture domain FFM02 and upper parts of fracture domain FFM01) together with outcropping gently dipping deformation zones (close to FFM03) act to compartmentalise (isolate hydraulically) the rock at depth in the north-western part of the candidate area in the "footwall" of the gently dipping deformation zone ZFMA2 (FFM01/FFM06) (Fig. 6b), see also Follin et al. (2007). This implies that recharge of meteoric water from above is short-circuited by these high permeability features and domains and that the subhorizontal fractures in the near-surface rock constitute the actual discharge routes for some of the deeper discharging groundwaters. The high coverage of boreholes in fracture domain FFM01 and the fact that they all show very few conductive fractures below ca. 400 m depth (Fig. 7) constitute key support for the model of hydraulic properties at depth.

The following observations support the conceptual model of the shallow flow system: (1) exceptionally high well yields were noted for percussion holes drilled inside the candidate area, with a median yield of ca. 12,000 L/h, which is ca. 20 times higher than in the nearby domestic wells outside the candidate area (2) hydraulic head data showing no, or very small, hydraulic gradient across the north-western part of the candidate area, demonstrating the equilibrating effect of the superficial highly permeable parts of this area (3) significant and rapid cross-hole test pressure responses over large distances in the north-western part of the candidate area (4) fairly fresh groundwater at shallow depths of 100–200 m, on top of relatively saline waters consistent with present-day marine (Baltic Sea) and older marine (Littorina Sea) water that covered the area between some 9,500–5,000 years ago (Laaksoharju et al.

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[2] The candidate volume refers to the volume outlined on ground surface by the area (ca. 10 km^2) around Forsmark originally designated for site investigations. This area encompasses the smaller "target area" (ca. 3 km^2) which at depth include the foreseen deposition volumes of the repository, see also Fig. 3a for geographical reference.

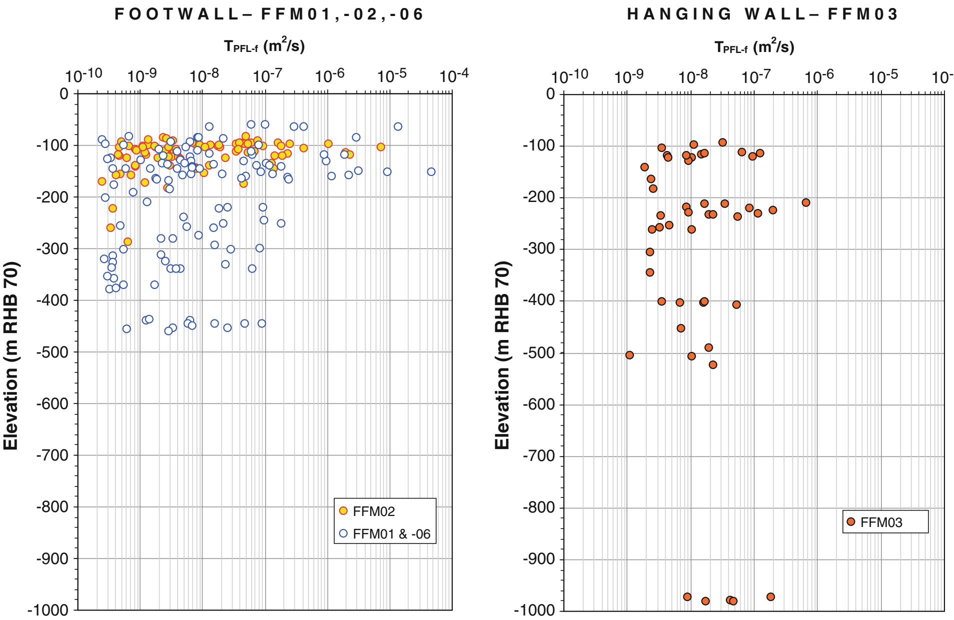

Fig. 7 Examples of transmissivities of open connected fractures evaluated from PFL-f flow logs compiled from boreholes in fracture domains FFM01/FFM06 (data from 10 boreholes) and FFM02 (data from 4 boreholes) representing the footwall (*left*) and those in fracture domain FFM03 representing the hanging wall of ZFM02, cf. Fig. 6. Notable is the absence of permeable fractures at depth in FFM01 and FFM06. Modified after (SKB 2008a)

2008) (5) another important support for the concept is the documentation of the occurrence of extensive superficial horizontal structures encountered during the siting and construction of the neighbouring nuclear reactors at Forsmark (Follin et al. 2008).

Implications for the SDM

The high-conductive parts of the bedrock above 200 m provide effective attenuation of the topographically induced hydraulic gradient and result in low driving forces for groundwater flow at depth. This in combination with the established low frequency of conductive fractures implies low groundwater flow at depth. Use of groundwater chemistry in constraining the parameterisation of the model has increased confidence in the developed conceptual and numerical models describing groundwater flow.

Thermal properties

Resulting model

Typically the rock types making up the potential deposition area at Forsmark have a thermal conductivity λ in the order of 3.5 W/mK on a 1 m scale (Back et al. 2007). This thermal conductivity, reflecting the mineralogy of the bedrock, is favourable to the repository since it allows a relatively small (~6–7 m) distance between the canisters.

Implications for the SDM

In one of the rock domains (FFM045) hosting the planned deposition areas, the tailing of the distribution of thermal conductivity is more pronounced. This tailing is attributed to the existence of minor bodies of amphibolite, characterised by low thermal conductivity. One of the challenges during construction of the repository is to map out these bodies and optimize the distance between canisters.

Rock stress

Resulting model

The stress evolution at Forsmark is closely related to the deformation history of the site. The early establishment of the deformation zones (ca. 900 Ma ago) and their subsequent responses to various tectonic events, loading/unloading cycles associated with burial/denudation of overlying sedimentary rocks and glaciation/deglaciation have all played important roles in the evolution of the rock stresses in the Forsmark bedrock. The stress model for the target volume is developed on the basis of data from overcoring stress measurements and evaluations of indirect observations (core disking and/or borehole fall-outs) combined with due consideration of the geological evolution history, topography, crustal thickness and glacial rebound (Glamheden et al. 2007).

Implications for the SDM

In accordance with site data and site understanding the stress model implies that horizontal stresses in fracture domains FFM01 and FFM06 (Fig. 6) are greater than the vertical stress magnitude (Martin 2007) (Fig. 8). The increase in the horizontal stress magnitudes with depth is correlated with an overall decrease in fracture frequency with depth and a corresponding increase in the rock mass stiffness (Fig. 6a–c). Notable is that these changes are also accompanied by a reduced hydraulic conductivity (Fig. 7).

Groundwater composition and its historic evolution

Although the data set is rather limited, the results of groundwater sampling/analysis have revealed that the current groundwater composition in general supports the occurrences of different hydrogeological regimes in the candidate volume. This is because the distribution of different water types in part depends on the relative salinity, and also on the hydraulic properties of the bedrock. At Forsmark, four distinct water signatures are typically identified (Fig. 6d): (1) meteoric water (which can be of young origin) (2) Littorina water (remnants of the Littorina sea—a predecessor to the Baltic) (3) glacial melt water (remnants from the latest glaciation) (4) highly saline water (dominant at great depth).

Simulated palaeo-evolution of the groundwater composition at Forsmark during the last 10,000 years (i.e. during Holocene) shows a fair agreement with measured concentrations of chloride, the bromide/chloride ratio, $\delta^{18}O$ and bicarbonate (SKB 2008a). Furthermore, the model predicts deeper penetration of Littorina water along the gently dipping fracture zones of FFM03 than in the steeply dipping deformation zones of FFM01 (Fig. 6d). Although not matching the exact concentrations, the model also predicts higher salinity in the fracture water than in the matrix pore water, which is consistent with observations.

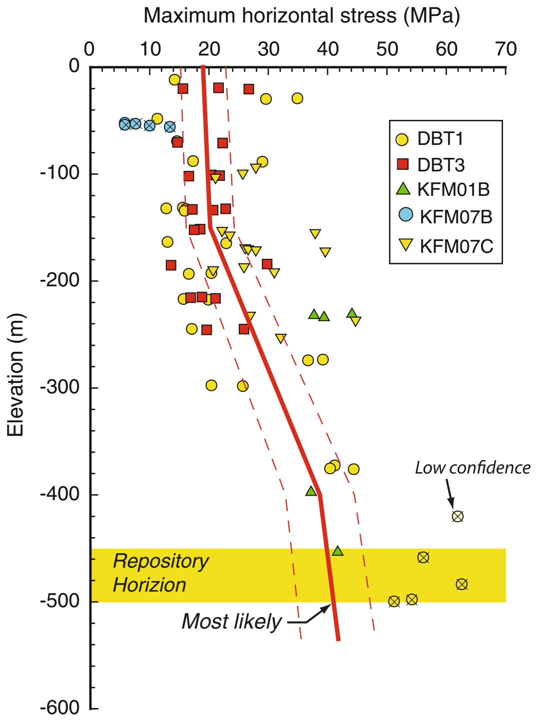

Fig. 8 Rock stresses at Forsmark. Summary of data and interpretations (SKB 2008a)

Implications for the SDM

The hydrogeochemical modelling has provided a description of present time groundwater chemistry in terms of groundwater types with characteristic chemical signatures and defined spatial distributions. This description has provided a highly valuable conditioning data set for simulation of the (non-reactive) evolution of groundwater chemistry, which has also provided additional calibration and verification to the groundwater flow models (Follin et al. 2007, 2008).

Bedrock transport properties

The limited data available indicate no significant differences in bedrock retardation properties (immobile zone porosity, effective diffusivity and linear sorption coefficient) between the rock domains planned to host the repository. Solute transport is conceptualized to occur in flow channels developed in fractures and deformation zones where matrix diffusion coupled with sorption acts as the main control of the rate of transport. In this context, the flow-wetted surface to flow ratio (denoted "F-factor") is the key parameter while retardation (residence times) is shown to scale quadratically with the F-factor. The F-factor depends on the flow distribution in the rock, here assessed jointly through a deterministic description of major deformation zones and a stochastic description of the rock by way of hydrogeological DFN models.

Implications for the SDM

The models describing transport and retention have developed considerably during the course of the SDM work. The results can be considered as important conceptual mid-way results which were ennobled further as part of the subsequent safety assessment work (SKB 2011).

Ecosystems

The surface system, or the integrated models of hydrology, geology, chemistry and ecology above the bedrock, was divided into a hierarchic structure (Lindborg et al. 2006). In short, the description was based on a number of descriptive models of abiotic and biotic entities (Fig. 9). These models were then integrated into system descriptions of the major ecosystems present, e.g. lakes, sea and terrestrial areas. Finally, these ecosystems were linked together in the landscape to enable the description of transport and accumulation of matter at the site (see Lindborg et al. 2006; Lindborg 2008). All this was subsequently used in the safety assessment to build and evaluate the dose models and the evolution of the landscape with time (Lindborg 2010; Lindborg et al. 2013).

Implications for the SDM

One important challenge, described in detail by Berglund et al. (2009), was the integration of numerical bedrock groundwater flow models covering the deeper rock but extending to the ground surface with corresponding hydrogeological and hydrological models covering the near-surface bedrock and overburden and surface waterways. Whereas the former models included deformation zones, the latter included lakes, water courses and overland water. The geological and topographical setting in combination with on-going land rise and associated shoreline displacement has a strong influence on both the locations and evolutions of potential discharge areas from the repository and for the development of the surface ecosystems.

Overall, a substantial improvement in the surface system modelling and its association to the deeper bedrock system was attained, providing the site understanding needed for subsequent safety assessment and environmental impact assessment.

Discussion

An integrated site-descriptive model of the Forsmark site has been established and documented at the conclusion of the CSI. The associated descriptions are supported by a large number of data, results and analyses which have been shown to be mutually supportive and consistent. This shows that a basic understanding of current states and natural processes in Forsmark has been established, from the ground surface to depths well below the projected repository depth. The SDM provides the understanding of the site and constitutes the base on which subsequent repository design and assessment of long-term safety is established. Furthermore, the outcome of the three successive processes constitutes the platform for the planning of detailed site investigations during construction of repository accesses and deposition areas. In the following, the outcome of the SDM work is discussed in light of results obtained and central issues posed.

A prerequisite for successful and relevant modelling is the use of high quality data. The site investigation data used were subject to extensive quality checks and could only be entered into the investigation databases after passing established clearance procedures. This said, the site modellers could not readily assume that all data in the database were without flaws. Consequently, a check of the plausibility of the investigation data in an integrated comparative context was key to ensuring the quality of the final model/-s. For example, such data delivery controls revealed non-systematic errors in borehole geometry obtained from surveying. Once found, this made it necessary to reassess and correct all orientation data of planar geological objects and associated modelling. The handling and correction of these errors were indeed costly, but small compared to the overall consequences implied by not identifying this error, which could distort results and jeopardise the confidence in the site-descriptive model as a whole.

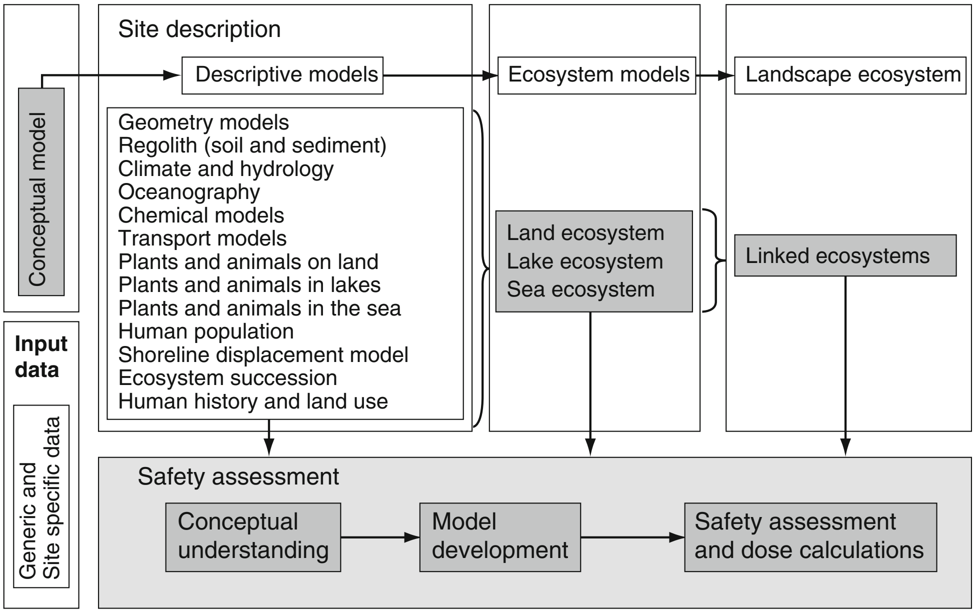

Fig. 9 Surface system modelling procedure (Lindborg et al. 2006)

The discipline-based SDM modelling, as exemplified by key findings in this paper, demonstrates that it is possible to produce, in an integrated and iterative manner, consistent and mutually supporting model descriptions providing the necessary data and descriptions for carrying out the subsequent steps in realizing the final repository. Geology has in this context provided the overall geometrical context for analysis conducted by other disciplines, whereas hydrogeology has provided the principal platform for integrated analysis involving also hydrogeochemistry and solute transport. To the knowledge of the authors, the site-descriptive models devised by SKB are the first ones to produce a unified comprehensive synthesis of this nature and with such broad (discipline) coverage. Furthermore, it is noted that the ecosystems descriptions produced constitute an entirely novel component, allowing more realistic descriptions of inputs to the bedrock system and of releases of radionuclides from the bedrock system to the biosphere. Notable is also that the SDMs produced by SKB are decoupled from the safety analysis. The advantages of this modular approach are easy address using alternative safety assessment concepts and tools and easy transfer of the SDM to other parties, e.g. regulatory agencies.

A site-descriptive model will always contain uncertainties, but an exhaustive understanding of the site is not required. Rather, the site characterisation should continue until the reliability and confidence of the site-descriptive model has reached such a level that the body of data and understanding are sufficient for the purpose 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 were progressively refined during the course of the SDM (SKB 2008b, c) including assessments whether all data had been considered and understood, identification of main uncertainties and their cause, possible alternative models and their handling, and consistency between disciplines. The assessment then formed the basis for an overall confidence statement for the given SDM model version. Only few of the uncertainties in the SDM are indeed essential for safety assessment or repository engineering, or important for the overall site understanding. The importance of remaining uncertainties was thus assessed relative to the further use of the models. At the conclusion of the surface-based investigations it was also essential to assess whether remaining, and still relevant, uncertainties would allow going ahead with detailed site investigations underground. It was therefore assessed whether the identified uncertainties associated with potential deposition volumes could be bounded (e.g. by alternative conceptual models), or concerned details that would, or could, be better resolved by investigations from the underground.

Review of the documentation is judged as an essential part of the quality assurance of the SDMs. Prior to publication, all reports were reviewed by SKB management and an internal group of internationally renowned experts. This reviewing process proved to be an essential step in enhancing the clarity of the documents. Furthermore, once published, the reports were subsequently reviewed by two international review teams, INSITE (Chapman et al. 2005) and OVERSITE established by the regulatory authorities in Sweden,[3] SKI (the Swedish Nuclear Power Inspectorate) and SSI (the Swedish Radiation Protection Institute), respectively. A “Tracking Issues List (TIL)” was maintained by INSITE, to which SKB provided written responses to different issues brought up by the reviewers. Thereby the SDM project was informed about potential regulatory expectations and, due to the iterative publication process, starting with very early versions of the reports, actions could be taken to ensure that expectations expressed by the authorities were better addressed in the final versions of the SDM reports.

The field investigations were managed by a site office, whereas the SDM was organised as a SDM project managed by the SKB central office in Stockholm. This division of work was necessary given the workload and the fact that two different sites, Forsmark (described in this paper) and Laxemar–Simpevarp, at two different locations in Sweden were investigated simultaneously, but it was early recognised that this organisation also implied several integration challenges.

In order to unify the modelling work, joint methodology reports and plans as a basis for the work were prepared. Some key technical staff members, like the site geologist from the site office were involved as members of the site modelling project. Furthermore, discipline-specific expert groups (“NET-groups”), where all staff, i.e. from both sites and both SDM projects, from a given specific discipline met and assessed modelling conducted within their discipline. Additional measures included organizing site-specific modelling project meetings devoted to cross-discipline interaction and organising special workshops and meetings focusing on different integration aspects.

The site-descriptive model is used as input to repository design and safety assessment. However, the information transfer from site-descriptive models to these applications involves different interpretation steps. A repository design including a site-specific layout is developed based on the site-descriptive model. However, experience from a preliminary step showed that construction engineers had difficulties comprehending the, sometimes, quite scientific presentation in the SDM. For this reason, SKB developed

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[3] SKI and SSI merged in 2008 to form the Swedish Radiation Protection Authority (SSM).

Site Engineering Reports (SER) interpreting the site-descriptive model of Forsmark for the design engineers (SKB 2008d). The main purpose of the SER is to present rationale and guidelines for the design that are focused on constructing the repository, operational issues and safety assessment issues that impact construction and operations. Design parameters that are recommended in the SER are based on the site-descriptive model, but may be modified to reflect engineering practice. The SER also assesses geological conditions that may impose constraints on the layout from the safety assessment point of view. Furthermore, it was found that the site-descriptive model could not be directly used in the subsequent safety assessment. There existed a need to also consider non-site-specific information, to add judgments on how to handle the uncertainties identified in the site-descriptive model and to make final selections of model input data. While the site-descriptive model aims at describing uncertainties, safety assessment requires further quantification and can also accept conservative assumptions. For this reason, all site data used in safety assessment were assessed in a designated data report, using the site-descriptive model as input (SKB 2010c).

Conclusions and outlook

Overall, the site-descriptive modelling work has followed the plans and strategies developed before the start of the site investigation phase. Still, the modelling approaches have developed and there are several lessons learnt of different nature. The modelling methodology has developed for most disciplines—with even stronger focus on early data assessment, visualisation and conceptual model building. Quality assurance and expert review have proved to be essential for maintaining and successively improving the confidence in the products. Handling the integration between investigations managed from two site offices, the SDM organised as two different projects, and between different disciplines, has been a challenge, but succeeded by ensuring strategic overlaps in personnel between some key activities and by organising various types of integration groups and activities.

The site-descriptive model reports have followed a standardised outline. However, in the last version, much more emphasis is put on supporting documents covering the main disciplines, whereas the main document, the site-descriptive model report, summaries the evaluation and results and then focuses on synthesising the information in order to present the integrated model and associated descriptions.

The site-descriptive model is used as input to repository design and safety assessment. However, the information transfer from site-descriptive models to these applications involves different interpretation steps. For this purpose SKB developed SER interpreting the site-descriptive models for the designing engineers. This was in turn used for developing site-specific layouts. For safety assessment all site data used are assessed in a data report, using the site-descriptive model as input.

Finally, the methodology applied within the framework of the SDM project constitutes a unique tool to describe a site. Mutually supportive descriptions have been produced that rely on scientific understanding of past and current site behaviour and that provide solid support for the assessments and preparations made to file an application for building a repository for spent nuclear fuel.

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